



# Sediment Deposition and Accretion in a Mid-Atlantic (U.S.A.) Tidal Freshwater Marsh

S. C. Neubauer<sup>a,b,\*</sup>, I. C. Anderson<sup>a</sup>, J. A. Constantine<sup>c,d</sup> and S. A. Kuehl<sup>a</sup>

<sup>a</sup>Virginia Institute of Marine Science, School of Marine Science, College of William and Mary, Gloucester Point VA 23062, U.S.A.

<sup>b</sup>Present address: Smithsonian Environmental Research Center, P.O. Box 28, Edgewater MD 21037, U.S.A.

<sup>c</sup>College of William and Mary, Department of Geology, Williamsburg VA 23187, U.S.A.

<sup>d</sup>Present address: University of California at Davis, Department of Land, Air and Water Resources, Davis CA 95616, U.S.A.

Received 21 December 2000 and accepted in revised form 14 May 2001

Sediment deposition and accretion rates in a Virginia tidal freshwater marsh were measured to provide insight to the processes and time scales that are important for maintaining marsh surface elevation. Short-term sediment deposition rates (biweekly to monthly) measured using sediment collection tiles were spatially and temporally variable. Rates were greatest near a tidal creek and decreased along a transect extending toward the marsh interior. When integrated across the entire marsh, annual sediment deposition (as organic carbon) averaged  $517 \pm 353 \text{ g C m}^{-2} \text{ y}^{-1}$  and was sufficient to balance the effects of existing relative sea level rise and marsh respiration rates. At the creekbank, the highest deposition rates were measured during summer although rates were relatively constant over time at the interior sites. Similar spatial and temporal patterns were obtained when deposition rates were calculated from <sup>7</sup>Be inventories (monthly time scale). Sediment inventories of <sup>7</sup>Be were greater than those supported atmospherically, indicating that the spatial patterns of sedimentation were not due to sediment erosion and redistribution within the marsh. Accretion rates calculated from <sup>137</sup>Cs (decadal scale) and <sup>14</sup>C dating (centuries to millennia) were substantially less than annual deposition rates, with a decrease in accretion rate with increasing time scale. Mineralization rates of recently deposited sediments (measured as O<sub>2</sub> consumption) indicated that sediment metabolism could potentially remove ~30% of recently deposited carbon within one month of deposition. The metabolism of a labile sediment fraction could explain a portion of the observed decrease in accretion rate with increasing time scale, with the remainder due to periodic storm-induced erosion and historical variability in sediment deposition rates.

© 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** sedimentation; accretion; respiration; beryllium-7; cesium-137; carbon-14; tidal freshwater marsh; Virginia

## Introduction

Because of their location at the head of estuaries where watershed influences are concentrated, tidal freshwater marshes are among the first systems to interact with, and potentially remove watershed-derived sediments, nutrients, and pollutants. Sediment deposition onto the marsh surface occurs when water column turbulent energy is reduced following flooding of the marsh itself (Leonard & Luther, 1995), while removal of dissolved materials can take place via direct uptake by organisms in the marsh or sorption onto sediment particles with subsequent deposition (Olsen *et al.*, 1982; Froelich, 1988; Hedges & Keil, 1999). In contrast to infrequently flooded marshes where the retention of autochthonous production is responsible for the bulk of vertical accretion, marshes

that are regularly inundated rely on both autochthonous production and the deposition of mineral sediments to maintain marsh elevation relative to a rising sea level (Bricker-Urso *et al.*, 1989; Craft *et al.*, 1993).

While tidal salt marsh sedimentation has been well studied (see reviews in Frey & Basan, 1985; Stevenson *et al.*, 1988; Friedrichs & Perry, 2000), relatively few studies have examined sediment dynamics in tidal freshwater wetlands. Pasternack and Brush (1998) measured seasonal patterns in sediment deposition across freshwater marsh habitat types using sediment collection tiles, while Ledwin (1988) studied annual deposition and erosion rates using a combination of marker horizons, sediment traps and graduated stakes. Childers *et al.* (1993) used sedimentation-erosion tables (SET) to examine spatial and temporal variability in sedimentation along an estuarine gradient.

\*Corresponding author: [neubauer@serc.si.edu](mailto:neubauer@serc.si.edu)

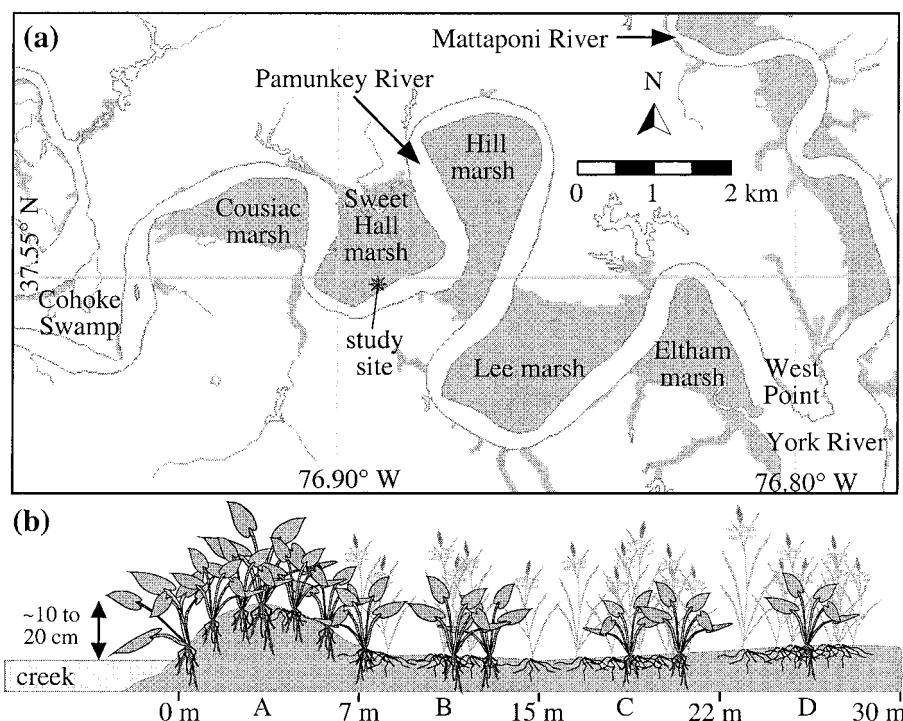


FIGURE 1. (a) Map of Pamunkey River, Virginia showing location of Sweet Hall and other tidal marshes (shaded areas). Tidal marsh areas were redrawn from Doumlele (1979) and Silberhorn and Zacherle (1987). Approximately 2400 ha of tidal marsh in the Pamunkey River (out of 3000 ha total) are shown on this map; the remainder are farther upriver. (b) Generalized cross-section of study site showing 10 to 20 cm elevated creekbank levee and location of sampling blocks across the marsh transect. Not to scale.

Short-term measurements, which are usually collected at relatively high frequency (i.e. weekly to monthly), are useful in determining seasonal patterns in sediment deposition due to variations in sediment supply or marsh sediment trapping efficiency. Sediment accretion rates (decades to centuries) in tidal freshwater marshes have been calculated using palynology (pollen analysis; e.g. Orson *et al.*, 1990, 1992; Khan & Brush, 1994), modelling (Morris & Bowden, 1986), and  $^{137}\text{Cs}$ ,  $^{210}\text{Pb}$ , and  $^{14}\text{C}$  radioisotope dating (e.g. Orson *et al.*, 1990; Campana, 1998; Cornwell & Zelenke, 1998). Unlike short-term deposition rates, long-term accretion rates integrate processes that occur over many years and can therefore be useful in detecting historical patterns in sedimentation due to changes in land use and sediment delivery from the watershed.

Rates of sediment deposition (the settling of material onto a marsh surface) and accretion (the net balance between deposition and removal processes) are linked. For instance, greater rates of sediment deposition can lead to enhanced preservation and accretion (Hedges & Keil, 1995). Similarly, sediment accretion rates influence the frequency and duration of tidal flooding which subsequently affects deposition

rates (Bricker-Urso *et al.*, 1989; Cahoon & Reed, 1995; Leonard, 1997). Examining sedimentation rates over a range of time scales provides insight into the factors that control marsh elevation and sedimentation processes. In this study, biweekly to monthly measurements of deposition onto sediment collection tiles were used to estimate annual sediment deposition rates for a mid-Atlantic (Virginia) tidal freshwater marsh. Depth profiles of  $^{137}\text{Cs}$  were used to calculate decadal accretion rates, while longer-term rates (centuries to millennia) were estimated using  $^{14}\text{C}$  dating. Sediment inventories of the radioisotope  $^7\text{Be}$  (i.e. the total depth integrated activity of  $^7\text{Be}$  per unit area) were used to assess the role of erosion in marsh sediment dynamics, and seasonal measurements of sediment respiration examined the importance of biological utilization of sediment-associated carbon in controlling sedimentation rates.

### Study area

Our study area was located on the Pamunkey River which drains 3768 km<sup>2</sup> in southeastern Virginia before converging with the Mattaponi River at West Point, Virginia to form the York River [Figure 1(a)].

The Pamunkey River watershed is predominately undeveloped (65% forested, 6% tidal + non-tidal wetlands), with 27% as grass and croplands and <2% urbanized (EPA, 1996). Tidal marshes along the lower Pamunkey River range in size from small pocket and fringing marshes less than 0.5 ha to expansive marshes up to 587 ha (Doumlele, 1979; Silberhorn & Zacherle, 1987). Global eustatic sea level rise is occurring at 1 to 1.5 mm y<sup>-1</sup> (Gornitz *et al.*, 1982; Gornitz & Lebedeff, 1987). When combined with locally high rates of subsidence (3 to 5 mm y<sup>-1</sup>; Holdahl & Morrison, 1974) due to groundwater withdrawal and post-glacial crustal rebound, relative sea level in the lower Pamunkey River is rising at a rate of 4 to 6.5 mm y<sup>-1</sup>.

This study was conducted at Sweet Hall, a 401 ha tidal freshwater marsh located 35 km by river from West Point, VA [Figure 1(a)]. The marsh is a site within the Chesapeake Bay National Estuarine Research Reserve System in Virginia (CB-NERRVA). Long-term average salinity at Sweet Hall is 0.5 (Brooks, 1983) although the average salinity in 1999 was 2.8 (range 0.0 to 15.9; CB-NERRVA unpublished data). High salinity and the increasing presence of the oligohaline species *Spartina cynosuroides* in the marsh may be indicative of a long-term shift from freshwater to oligohaline conditions (Perry & Hershner, 1999). At Sweet Hall, the Pamunkey River is microtidal, with a mean tidal range of 70 cm (neap tide) to 90 cm (spring tide). To minimize disturbance to the marsh surface, all sampling was conducted from three boardwalks (30 m) that extended roughly perpendicular to the western branch of Hill's Ditch, a tidal creek draining the southern portion of the marsh. Each boardwalk traversed a creekside levee (~10 to 20 cm elevated above the surrounding marsh) before extending into the marsh interior [Figure 1(b)].

## Materials and methods

### Sedimentation measurements

(1) *Sediment collection tiles*: Between February 1998 and August 1999, net rates of marsh sediment deposition were measured using 117 cm<sup>2</sup> ceramic sedimentation tiles positioned flush with the marsh surface (after Pasternack & Brush, 1998; Christiansen *et al.*, 2000). Tiles were deployed along one 30 m transect, the transect was divided into four blocks (0 to 7, 7 to 15, 15 to 22, and 22 to 30 m from the creekside); [Figure 1(b)], and four tiles were positioned at a random location in each block (total of 16 tiles). Tile deployment and retrieval took place when the marsh surface was exposed to air and

occurred every other week during the summer of 1998 and monthly thereafter. After removing fallen dead stems and roots from each tile, deposited sediments were scraped and washed with deionized water into clean, preweighed plastic specimen cups. Samples were dried at 50 °C and weighed to calculate mass sedimentation rates. Subsamples were processed for organic content and percent carbon and nitrogen as described below.

(2) *Beryllium-7*: Sediment inventories of <sup>7</sup>Be (t<sub>1/2</sub> = 53.3 d) were used to estimate marsh sediment deposition and erosion rates on a time scale of months (after He & Walling, 1996; Goodbred & Kuehl, 1998). The inventory approach assumes that any radioisotope activity above that supplied by atmospheric fallout is due to sediment input (Walling *et al.*, 1992) and that atmospheric inputs are evenly distributed across the study area (i.e. there is no 'focusing' of fallout <sup>7</sup>Be due to land topography). In June and October 1998 and January 1999, 15.2 cm diameter sediment cores were taken to a depth of ~15 cm. To avoid influencing the sediment collection tiles, all cores for radioisotope dating were collected from a transect located approximately 60 m downstream of the one used for the sediment collection tiles. Each core was sectioned at 1 to 5 cm intervals, each section was homogenized and a subsample was gamma counted (477 keV) for 24 h using a high-purity germanium detector. Total core <sup>7</sup>Be inventories (I<sub>total</sub>; dpm cm<sup>-2</sup>; dpm = decays per minute) were calculated as:

$$I_{\text{total}} = \frac{\sum_{i=1}^n (A_i \times W_i)}{SA}, \quad (1)$$

where n is the number of intervals between the sediment surface and base of the core; A<sub>i</sub> is the specific activity of interval i (dpm g<sup>-1</sup>; W<sub>i</sub> is the total dry mass of interval i (g) and SA is the core surface area (cm<sup>2</sup>). The sediment accumulation rate (R; g cm<sup>-2</sup> d<sup>-1</sup>) is calculated as:

$$R = \lambda_{\text{Be}} \times \left( \frac{I_{\text{total}} - I_{\text{atm}}}{A_{\text{catch}}} \right), \quad (2)$$

where λ<sub>Be</sub> is the <sup>7</sup>Be decay constant (0.013 d<sup>-1</sup>); I<sub>total</sub> is total sediment <sup>7</sup>Be inventory (dpm cm<sup>-2</sup>; from Equation 1); I<sub>atm</sub> is local atmospheric fallout inventory (dpm cm<sup>-2</sup>); and A<sub>catch</sub> is a mean <sup>7</sup>Be activity for catchment derived sediments (dpm g<sup>-1</sup>). Total atmospheric <sup>7</sup>Be deposition (wet + dry) has been measured at the Virginia Institute of Marine

Science (VIMS; ~50 km from Sweet Hall marsh) since April 1997 (S.A.K., unpublished data). At Sweet Hall, the marsh is flooded for an average of 12 to 13 h d<sup>-1</sup>. Therefore, we assumed that the actual <sup>7</sup>Be deposition ( $I_{\text{atm}}$ ) to the marsh surface was 50 to 100% of that measured at VIMS. This range represents the extremes of no fallout (50% case) or all fallout (100% case) reaching the sediment when the marsh is flooded. In October and November 1998, particle specific <sup>7</sup>Be activity ( $A_{\text{catch}}$ ) was estimated by concentrating (via settling and centrifugation) and measuring the <sup>7</sup>Be activity of particles in approximately 70 l of creek water collected adjacent to the marsh study site near low tide.

(3) *Cesium-137*: The <sup>137</sup>Cs profile ( $t_{1/2}=30.17$  y) in a marsh core was used to determine sediment accretion rates over the last 30 to 50 years. In February 1998, a core was taken to a depth of 1.3 m using a 10.2 cm diameter PVC tube. Total compaction of 8 cm (6%) over the length of the core was measured; no corrections for this compaction were made in subsequent calculation. 1 cm thick sections of the core were gamma counted for 24 h using a high-purity germanium detector. The area of the <sup>137</sup>Cs photopeak (661.62 keV) was quantified and converted to <sup>137</sup>Cs activity (dpm g<sup>-1</sup>) using known detector efficiency factors. The depths corresponding to the first appearance (1954) and maximum activity (1963) of <sup>137</sup>Cs were identified and average annual accretion rates calculated (DeLaune *et al.*, 1978). Vertical accretion (mm y<sup>-1</sup>) was converted to a carbon accretion rate using measured sediment bulk densities and carbon content:

$$CA = \frac{\sum_{i=1}^n (d_i \times B_i \times C_i)}{t}, \quad (3)$$

where CA is carbon accretion (g C m<sup>-2</sup> y<sup>-1</sup>); n is the number of intervals between the sediment surface and the <sup>137</sup>Cs peak;  $d_i$  is thickness of interval  $i$  (m);  $B_i$  is interval bulk density (g sediment m<sup>-3</sup>),  $C_i$  is interval percent carbon, and  $t$  is time since <sup>137</sup>Cs peak horizon deposition (34 y). For intervals where bulk density and percent carbon were not measured (see 'sediment characterization' section), these properties were estimated by averaging adjacent intervals. Shallow <sup>7</sup>Be sediment penetration depths (<2 cm) and the absence of fiddler crabs from the marsh interior indicated low vertical mixing rates. Therefore, a bioturbation term was not included in the accretion rate calculations.

(4) *Carbon-14*: In November 1998, an aluminum core tube (7.5 cm diameter) was driven into the marsh to a

depth of 6.7 m using a vibracorer. Compaction was minimal (15.3 cm or 2%) and no corrections were made in accretion calculations. Samples from 3.1 and 6.5 m were sent to Beta Analytic, Inc. (Miami, FL) for <sup>14</sup>C dating. Additional samples were taken every 15 cm for analysis of organic content and percents carbon and nitrogen as described below, and the entire core was described for colour, texture, and the character of visible organic detritus.

#### *Sediment characterization*

Sediment bulk density and organic and carbon contents were measured over the course of the study. Surface samples (0 to 0.5 cm) were collected using 2 cm diameter core tubes at all locations and times when sedimentation tiles were retrieved. Deeper sediments (to 30 cm) were collected in June, August, and November 1996 and April 1997 using 4.2 cm diameter core tubes. These cores were collected from five locations along each of three parallel 30 m transects (15 cores per season) and sectioned at 0 to 2, 2 to 5, 10 to 13, 18 to 21, and 27 to 30 cm intervals. Samples were dried at 50 °C and weighed to calculate dry bulk density (g cm<sup>-3</sup>).

A fraction of each dried sediment sample from the tiles and cores was combusted at 500 °C for 5 h and reweighed. Organic content was calculated as the weight loss-on-ignition. A second fraction of each dried sediment sample was ground in a Wiley mill (#40 screen) or by mortar and pestle for determination of carbon and nitrogen content. A portion of dried, ground sediments was weighed into ashed silver cups, acidified with 1 to 2 drops of 30% HCl to remove carbonates, and redried overnight at 50 °C. Organic carbon and total nitrogen were measured using a Fison model EA 1108 elemental analyser. The average precision for duplicate samples was ± 0.08% C and ± 0.02% N.

#### *Sediment lability*

In June, August, and November 1999, the reactivity of freshly deposited sediment was examined. Four sediment traps (plastic specimen cups; 7.7 cm diameter opening, 150 ml) were deployed around a randomly selected point in each block (16 traps total). To reduce bed load transport of sediments into the traps, each trap was pushed into the sediments so the lip of the trap was slightly (<5 mm) above the surface of the marsh. Furthermore, each trap was filled with marsh creek water to minimize turbulence effects on deposition during marsh flooding. After 24 h, the traps were recovered and returned to the lab.

Collected sediments from each block were combined and filtered through window screening (six to seven meshes  $\text{cm}^{-1}$ ) to remove large detritus. Window-screen filtered marsh creek water was added to the sediments to bring the total volume to  $\sim 1200$  ml. This sediment-water slurry was subdivided among three 300 ml darkened biological oxygen demand (BOD) bottles per block. Triplicate BOD bottles were filled with creek water to serve as a water blank. Duplicate 100 ml samples from each block and the creek were filtered through precombusted GF/F filters and weighed when dry to calculate total sediment mass per bottle. A subsample of each filter was analysed for percents carbon and nitrogen using a Fison model EA 1108 elemental analyser.

All BOD bottles were incubated in the dark at ambient sediment temperatures (June: 21 °C; August: 29 °C; November: 13 °C) for 5 days (June, August) or >1 month (November). To prevent oxygen gradients within the BOD bottles, all samples were gently mixed (170 rpm) throughout the incubation. Dissolved oxygen concentrations were regularly measured in each BOD bottle using an Orbisphere model 2604 multichannel oxygen probe (Orbisphere Laboratories, Geneva, Switzerland). Dissolved oxygen levels over the course of each incubation were fit to the exponential decay equation:

$$\text{DO}_t = a \times (1 - e^{-b \times t}) + c, \quad (4)$$

where  $\text{DO}_t$  is dissolved oxygen concentration ( $\text{mg l}^{-1}$ ) at time  $t$ , and  $a$ ,  $b$ , and  $c$  are empirically determined constants. Oxygen utilization rates over five days (all months) and 30 days (November only) were calculated and corrected for water blank oxygen utilization. Rates were converted to carbon units assuming a respiratory quotient of one (1 mole  $\text{CO}_2$  produced per 1 mole  $\text{O}_2$  consumed) and normalized to the mass of carbon in each BOD bottle at the start of the incubation.

## Results

### Sedimentation rates

(1) *Sediment collection tiles*: Direct measures of deposition using ceramic tiles revealed considerable spatial and temporal variability (Figure 2). Deposition rates were consistently higher on the creekbank (block A) than at the three interior sampling blocks (B, C, D), especially during the growing season (roughly April to October). Average rates on the creekbank ranged from  $0.1 \text{ g sediment m}^{-2} \text{ d}^{-1}$  during winter (November 1998 to January 1999) to  $284.2 \text{ g sediment m}^{-2} \text{ d}^{-1}$  for July to August 1999.

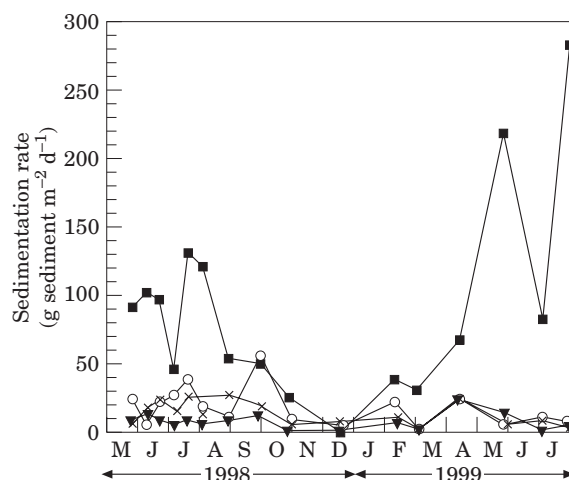


FIGURE 2. Sediment deposition rates onto ceramic tiles deployed in marsh for 2 to 4 week periods. Data are plotted at the midpoint of each sampling period. All points are the mean of 4 plates, with error bars omitted for clarity. The median coefficient of variation (standard deviation/mean) for all samples was 36% (range 6 to 171%). ■ A (Creekbank); ○ B; × C; ▼ D (Interior).

In the marsh interior, sediment accumulation rates were more consistent between stations and over the course of the year. Mean rates ranged from  $1.2 \text{ g sediment m}^{-2} \text{ d}^{-1}$  between February and March 1999 (block D) to  $56.5 \text{ g sediment m}^{-2} \text{ d}^{-1}$  for September to October 1998 (block B). Although all tiles in a given block were within 0.5 m of each other, deposition rates within a block were highly variable with coefficients of variation (standard deviation/mean) ranging from 6 to 171% (median=36%). The carbon content of recently deposited sediments averaged  $5.96 \pm 0.95\% \text{ C}$  and was lowest at the creekbank site ( $5.31 \pm 0.43\% \text{ C}$ ; ANOVA,  $P < 1 \times 10^{-7}$ ; Tukey's HSD,  $P < 0.001$ ). Surface (0 to 5 mm) sediment bulk density for all months averaged  $0.324 \pm 0.095 \text{ g sed cm}^{-3}$  (Table 1). Creekbank bulk density ( $0.407 \pm 0.095 \text{ g sed cm}^{-3}$ ) was significantly higher than at the interior sites ( $0.289$  to  $0.303 \text{ g sed cm}^{-3}$ ; ANOVA,  $P < 1 \times 10^{-7}$ ; Tukey's HSD,  $P < 0.00001$ ). There were no significant effects of transect number on shallow (0 to 5 cm) sediment bulk density or organic content (ANOVA,  $P > 0.05$ ).

Sediment deposition rates were combined with the carbon content of each sample and surface sediment bulk density to calculate annual rates of carbon deposition and vertical marsh accretion, respectively. To account for interannual variability in deposition on the marsh, rates were integrated from May 1998 (start of study) to April 1999, and September 1998 to August 1999 (end of study). Additionally, average 1998 and 1999 summer (May to August) deposition

TABLE 1. Sediment bulk density, percent organic matter (loss-on-ignition) and organic carbon content. Values are means  $\pm$  1 standard deviation and have been averaged across season and location in marsh. For 0 to 0.5 cm, bulk density was measured on 2 cm diameter cores while percents organic matter and carbon are from sediments collected on tiles.

Depth interval (cm)	Bulk density		Percent organic		Percent carbon	
	n	(g cm <sup>-3</sup> )	n	(%)	n	(%)
0 to 0.5	172	0.324 $\pm$ 0.095	259	16.48 $\pm$ 2.07	257	5.96 $\pm$ 0.95
0 to 2	60	0.353 $\pm$ 0.125	60	20.73 $\pm$ 12.34	19	5.81 $\pm$ 1.44
2 to 5	59	0.380 $\pm$ 0.132	59	17.00 $\pm$ 2.75	20	5.57 $\pm$ 1.11
10 to 13	60	0.427 $\pm$ 0.153	60	18.37 $\pm$ 3.98	4	5.97 $\pm$ 1.73
18 to 21	59	0.433 $\pm$ 0.143	59	21.06 $\pm$ 5.75	4	7.44 $\pm$ 3.31
27 to 30	56	0.393 $\pm$ 0.144	56	20.81 $\pm$ 5.02	4	7.36 $\pm$ 3.29

TABLE 2. Annual marsh carbon accumulation and vertical accretion rates for blocks A (creekbank) to D (marsh interior).

Time period	A	B	C	D	Transect mean
Carbon accumulation (g C m <sup>-2</sup> y <sup>-1</sup> )					
May 1998 to Apr 1999	1096 $\pm$ 145 <sup>a</sup>	395 $\pm$ 56	300 $\pm$ 37	210 $\pm$ 40	500 $\pm$ 164
Sep 1998 to Aug 1999	1413 $\pm$ 248	290 $\pm$ 54	197 $\pm$ 29	181 $\pm$ 38	521 $\pm$ 258
summer average	1293 $\pm$ 161	350 $\pm$ 54	267 $\pm$ 31	205 $\pm$ 37	529 $\pm$ 176
Average, all intervals	1268 $\pm$ 329	345 $\pm$ 94	255 $\pm$ 56	199 $\pm$ 67	517 $\pm$ 353
Vertical accretion (mm y <sup>-1</sup> )					
May 1998 to Apr 1999	51.5 $\pm$ 7.7	23.7 $\pm$ 4.4	17.6 $\pm$ 2.6	10.6 $\pm$ 2.2	25.9 $\pm$ 9.5
Sep 1998 to Aug 1999	77.7 $\pm$ 15.1	19.9 $\pm$ 4.2	15.0 $\pm$ 2.3	10.6 $\pm$ 2.0	30.8 $\pm$ 16.0
summer average	65.0 $\pm$ 8.9	21.8 $\pm$ 4.2	16.4 $\pm$ 2.3	10.7 $\pm$ 2.0	28.5 $\pm$ 10.3
Average, all intervals	64.7 $\pm$ 19.2	21.8 $\pm$ 7.4	16.4 $\pm$ 4.2	10.6 $\pm$ 3.7	28.4 $\pm$ 21.3

<sup>a</sup>Values are means  $\pm$  1 standard deviation and were calculated by propagating errors associated with seasonal sediment deposition rates, carbon content and surface sediment bulk density.

rates plus measured rates for the remainder of the year (September 1998 to April 1999) were used to provide a third estimate of annual deposition. Errors for annual rate calculations due to variations in deposition rates, carbon content, and bulk density were propagated following Skoog and West (1963). Average carbon accumulation rates onto ceramic tiles ranged from 1268  $\pm$  329 g C m<sup>-2</sup> y<sup>-1</sup> at the creekbank to 199  $\pm$  67 g C m<sup>-2</sup> y<sup>-1</sup> at site D. Vertical accretion ranged from 64.7  $\pm$  19.2 mm y<sup>-1</sup> at the creekbank to 10.6  $\pm$  3.7 mm y<sup>-1</sup> at site D (Table 2). Regardless of the time period of integration, sedimentation and vertical accretion rates were greatest at the creekbank with a gradual decrease from sites B through D. When averaged across all locations and calculation periods, carbon accumulation and vertical accretion were 517  $\pm$  353 g C m<sup>-2</sup> y<sup>-1</sup> and 28.4  $\pm$  21.3 mm y<sup>-1</sup>, respectively.

(2) *Beryllium-7*: Average sediment <sup>7</sup>Be inventories ranged from 1.8 to 16.5 dpm cm<sup>-2</sup> and varied with

season and transect location (Table 3). The study period was characterized by lower than average atmospheric <sup>7</sup>Be fallout, with atmospherically supported inventories at VIMS ranging from 1.29 to 2.41 dpm cm<sup>-2</sup> versus a longer-term average of 2.52  $\pm$  1.30 dpm cm<sup>-2</sup> (July 1997 to December 1999; S.A.K. unpublished data). In 9 out of 11 cores, the sediment <sup>7</sup>Be inventory was greater than could be supported by atmospheric fallout onto the marsh surface, indicating net sediment deposition (exceptions: June and October cores at 25 m from creekbank). In October and November 1998, we measured suspended particle specific <sup>7</sup>Be activities of 2.26 and 9.13 dpm g<sup>-1</sup>. Because <sup>7</sup>Be activities on particles can vary twofold or more over a single tidal cycle (S.A.K. & T. Dellapenna, unpublished data) and show a much wider range over several months (e.g. Olsen *et al.*, 1986; Dibb & Rice, 1989; Baskaran *et al.*, 1997), we calculated a median value of 14.3 dpm g<sup>-1</sup> (4.2 to 21.5 for 25th to 75th percentiles) for suspended particles (this study; S.A.K. & T. Dellapenna

TABLE 3. Calculated beryllium-7 sedimentation rates, including sediment and atmospheric inventories, by month and distance from creekbank.

Date	Distance (m)	n	$I_{\text{total}}$ (dpm cm <sup>-2</sup> )	$I_{\text{atm}}$ <sup>a</sup> (dpm cm <sup>-2</sup> )	Sedimentation rate <sup>b</sup> (g sed m <sup>-2</sup> d <sup>-1</sup> )
29 Jun 1998	2.4	1	16.45	1.21 to 2.41	128.0 to 139.0
	13.7	1	3.19	1.21 to 2.41	7.1 to 18.0
	25.0	1	1.80	1.21 to 2.41	-5.6 to 5.4
15 Oct 1998	1.5	3	5.16 ± 1.94 <sup>c</sup>	0.75 to 1.51	33.3 to 40.2 ± 17.7 <sup>c</sup>
	11.6	2	2.24 ± 0.11	0.75 to 1.51	6.6 to 13.5 ± 1.0
	25.3	2	3.46 ± 4.28	0.75 to 1.51	17.8 to 24.7 ± 39.0
25 Jan 1999	1.2	1	4.47	0.64 to 1.29	29.0 to 34.9

<sup>a</sup>Range in  $I_{\text{atm}}$  assumes that 50 to 100% of <sup>7</sup>Be fallout measured at Virginia Institute of Marine Science directly reaches the marsh surface, with reductions due to interception of fallout by tidal waters during marsh flooding (12 to 13 hr d<sup>-1</sup>).

<sup>b</sup>Calculated using Equation 2, with  $A_{\text{catch}}$  estimated as 14.3 dpm g<sup>-1</sup>, the median particle-specific <sup>7</sup>Be activity reported in the literature for particles and recently deposited sediments in estuarine and shallow coastal systems. Range in sedimentation rates is due to the range in  $I_{\text{atm}}$ . Positive rates indicate net deposition; negative rates indicate erosion.

<sup>c</sup>Mean ± standard deviation for replicate cores. The median counting error for  $I_{\text{total}}$  was ± 0.03 dpm cm<sup>-2</sup>.

unpublished; Olsen *et al.*, 1986; Dibb & Rice, 1989; Baskaran *et al.*, 1997) and recently deposited sediments (Canuel *et al.*, 1990) in estuarine and shallow coastal waters. Using this median value, we calculated deposition rates of -6 to 139 g sed m<sup>-2</sup> d<sup>-1</sup> in June 1998, 7 to 40 g m<sup>-2</sup> d<sup>-1</sup> in October 1998, and 29 to 35 g m<sup>-2</sup> d<sup>-1</sup> in January 1999 (Table 3).

(3) *Cesium-137*: Cesium-137 activities ranged from undetectable below 37 cm to a maximum of 3.21 dpm g<sup>-1</sup> at 29 cm, for average accretion rates of 8.4 and 8.5 mm y<sup>-1</sup> since 1954 and 1963, respectively. Sediment bulk density was significantly higher in the 10 to 13 cm and 18 to 21 cm intervals than in surface and deeper sediments (Table 1; ANOVA,  $P=0.01$ ; Tukey's HSD,  $P<0.05$ ). There was a general but non-significant trend (ANOVA,  $P=0.17$ ) of increasing percent carbon with increasing depth (Table 1). Organic content was significantly higher in the 0 to 2 cm interval than the 2 to 5 cm section (ANOVA,  $P=0.003$ ; Tukey's HSD,  $P<0.05$ ), perhaps due to inputs of organic detritus or the presence of shallow adventitious roots. Between 10 and 30 cm depth, there were no significant differences in organic content (Tukey's HSD,  $P>0.30$ ). Using Equation 3, we calculated an average carbon accretion rate of 224 ± 45 g C m<sup>-2</sup> y<sup>-1</sup> since 1963.

(4) *Vibracore and carbon-14*: In the marsh vibracore, organic content and percent carbon in the root zone (0 to ~125 cm; Booth, 1989; S.C.N. field observations) were relatively constant (Figure 3; 13.50 ± 1.35% and 4.78 ± 0.35%, respectively).

Below this depth, to about 250 cm, organic and carbon concentrations were homogenous (11.30 ± 0.60% and 3.34 ± 0.36%, respectively), but significantly lower than in the root zone ( $t$ -test,  $P<0.001$ ). From 250 cm to the base of the core, there were large variations in both organic matter (12.49 to 55.82%) and carbon content (4.48 to 34.31%). Throughout the core, organic matter and carbon contents were highly correlated ( $r^2=0.94$ ). Sediment C/N ratios (molar) averaged 16.3 (± 2.3) from 0 to 250 cm with no difference between the 0 to 125 and 125 to 250 cm intervals ( $t$ -test,  $P=0.15$ ). Carbon to nitrogen ratios were higher below 250 cm (23.9 ± 3.4;  $t$ -test,  $P<1 \times 10^{-10}$ ). Sediment colour varied from light to medium brown in surface sediments through grey to black at the base of the core. In the upper 3 m of the core, organic matter was disseminated through the sediments or preserved as fibrous material. A high density of wood fragments was observed between 106 and 140 cm. Below 323 cm, the sediment matrix was densely fibrous with wood fragments present from 366 to 665 cm. A more complete description of core colour, organic content, and texture is available from the authors. Based on radiocarbon dating of samples from 3.1 m (630 ± 70 y BP) and 6.5 m (3640 ± 80 y BP), average accretion rates were 4.3 to 5.5 mm y<sup>-1</sup> (0 to 3.1 m) and 1.5 to 1.7 mm y<sup>-1</sup> (0 to 6.5 m).

#### Sediment lability

Oxygen levels during sediment incubations decreased exponentially (Equation 4) with regression

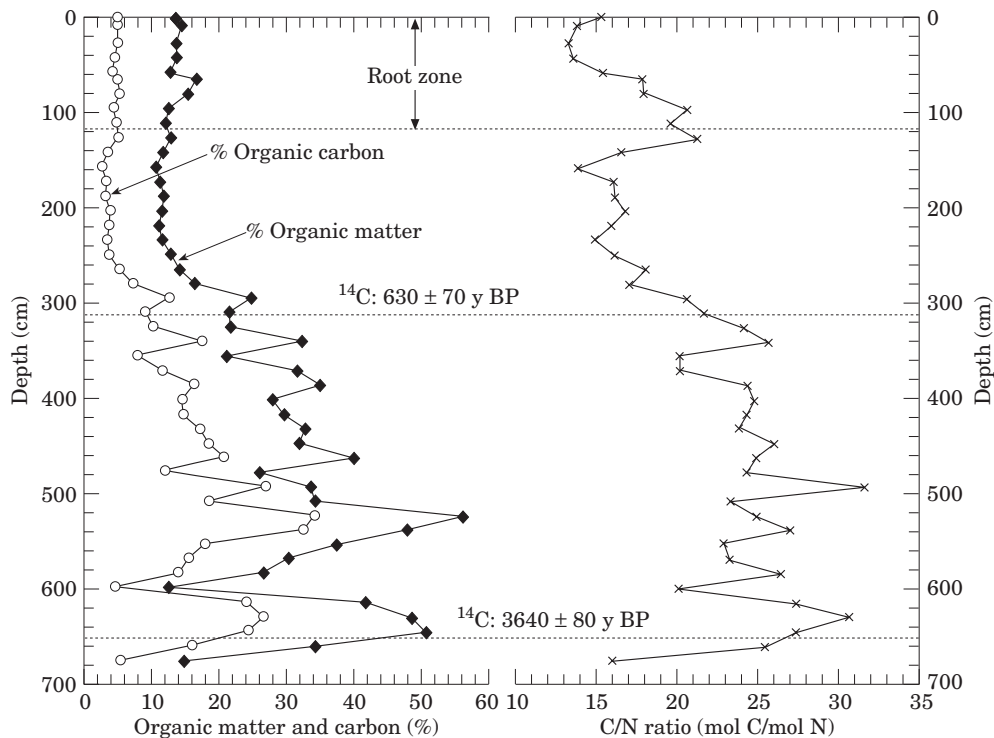


FIGURE 3. Marsh vibrocore characterization with sediment organic content, percent carbon, molar carbon to nitrogen ratios and  $^{14}\text{C}$  dates.

coefficients ( $r^2$ ) of 0.95 to 1.00. Due to variations in marsh sedimentation rates, the amount of sediment in each BOD bottle varied along the transect as well as between months (June: 65 to 188; August: 61 to 286; and November: 20 to 216 mg dry sediment bottle $^{-1}$ ). Incubated sediments averaged  $5.8 \pm 1.1\%$  carbon and did not significantly vary by date or transect block (2-way ANOVA,  $P=0.09$  for date;  $P=0.32$  for block). Sediment C/N ratios ranged from 7.7 to 10.6 (molar) and did not vary consistently along the transect or from season to season. In all months, average respiration rates for the first 5 days of the incubation were lowest at the creekbank site (ca.  $0.04$  mg C respired (mg sediment C) $^{-1}$ , or 4% sediment C respired; Figure 4). The implicit time scale for these mineralization rates is the length of each incubation (i.e. 5 or 30 d; that is, the units for five day rates are mg C respired (mg sediment C) $^{-1}$  (5 d) $^{-1}$ ). Overall, mean five day respiration rates increased from June ( $\bar{x}=4.8 \pm 2.3\%$  C respired) to November ( $\bar{x}=12.6 \pm 7.5\%$  C respired; Figure 4). When calculated over 30 days, respiration rates in November ranged from 5.9 to 45.4% C respired ( $\bar{x}=27.5 \pm 11.1\%$  C respired), an average increase of 209% compared to five day rates.

## Discussion

### *Sediment deposition*

Tidal marshes can be sites of active yet spatially and temporally variable sedimentation. Across marsh habitat types (e.g. low marsh to high marsh), sediment deposition rates are largely a function of the duration of inundation: sites that are flooded more frequently and for a longer time tend to exhibit higher deposition rates (Reed, 1990; Cahoon & Reed, 1995; Leonard, 1997). Flooding frequency, and therefore deposition rates, can vary spatially across the marsh and over time due to seasonal or interannual variations in sea level. Near tidal creeks, the typical inundation versus deposition relationship breaks down and highest rates are measured on topographically elevated levees immediately adjacent to the creek (French & Spencer, 1993; Esselink *et al.*, 1998). This occurs because the rapid decrease in turbulent energy as water starts to flood the marsh causes sediments to fall out of suspension close to the creekbank. At Sweet Hall, this pattern was especially pronounced from April to November (Figure 2) when plant stems further reduced water velocities and enhanced deposition



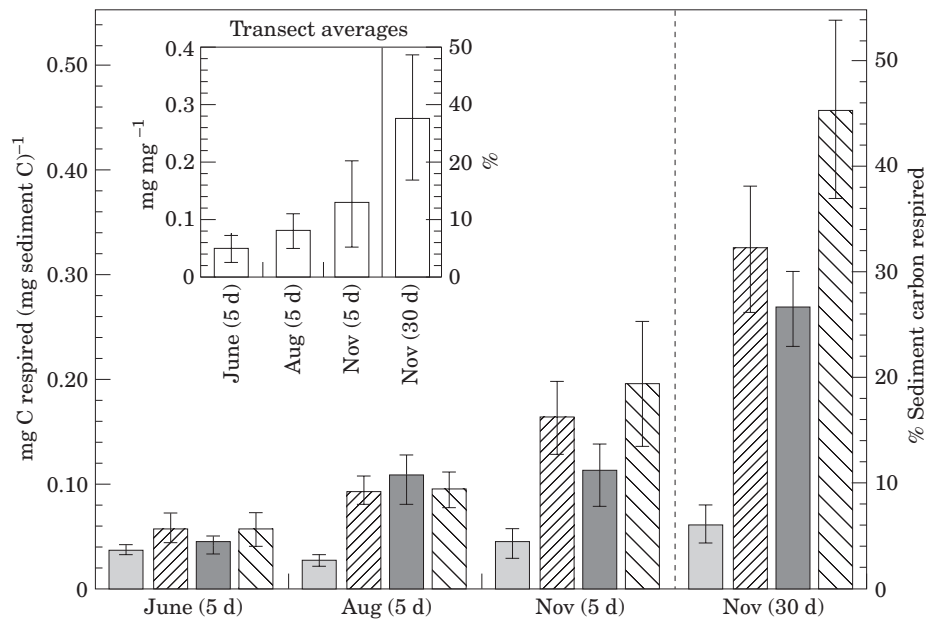


FIGURE 4. Average sediment respiration rates by date and location. Samples were collected along a 30 m transect from block A (creekbank) to D (marsh interior). Values are mean rates for 3 replicate incubations  $\pm$  1 standard deviation. Inset shows seasonal respiration rates averaged across all locations ( $n=12$ ). The implicit time scale for the mineralization rates is the length of each incubation (i.e. 5 or 30 d; that is, the units for 5 d respiration rates are  $\text{mg C respired (mg sediment C)}^{-1} (5 \text{ d})^{-1}$ ).  $\square$  A;  $\text{\textbackslash}$  B;  $\blacksquare$  C;  $\text{\textbackslash}$  D.

(Leonard *et al.*, 1995; Leonard & Luther, 1995). We did not observe the same dependence of sedimentation on time of year at the interior sites. In part, plant production was lower at these stations (S.C.N., unpublished data) so there was less frictional resistance to sediment transport (Leonard *et al.*, 1995). Also, and perhaps more importantly, the interior sites are farther from the sediment source (i.e. the creek). Although the marsh interior was flooded first and for a longer period than the creekbank levee, water that floods the marsh interior must first travel through small channels that incise the levee and then across the inner marsh flat. During this transport from creek to channel to marsh interior, sediments were constantly being deposited (French & Spencer, 1993; Leonard, 1997). By the time the interior marsh floods, suspended sediment concentrations and flood water velocity were low enough that additional frictional resistance from plant stems did not significantly affect deposition rates.

Marsh fauna also influence patterns of sediment deposition. Burrow excavation by fiddler crabs (*Uca* spp.) can bring buried sediments to the surface and increase the apparent sedimentation rate if these sediments are deposited on a collection tile. However, deposition rates calculated from  $^7\text{Be}$  inventories would not be affected by vertical sediment mixing. At Sweet Hall, fiddler crabs were most abundant near the

creekbank (S.C.N., pers. observation). In January 1999, several sedimentation tiles fell into a collapsed muskrat (*Ondatra zibethica*) tunnel and were buried by 6 to 10 cm sediment (versus  $\sim 2$  mm for all other tiles). These extreme results were not included in sedimentation calculations, but illustrate that marsh biology can influence total sedimentation rates by creating regions of intense deposition. Alternately, muskrat eatout of a dense marsh root mat can lower the marsh surface (Garbisch, 1994).

The magnitude and temporal patterns of sedimentation measured in this study are similar to those observed by Pasternack and Brush (1998) for a tidal freshwater marsh in Maryland, although Pasternack and Brush documented significant erosion ( $\sim 50$  to  $190 \text{ g sediment m}^{-2} \text{ d}^{-1}$ ) from low marsh sites during winter 1997. We suggest that erosion was not a significant factor during our study. During the growing season, when 70 to 90% of the annual sediment deposition occurs, high plant stem density slows water flow across the marsh (Leonard *et al.*, 1995; Shi *et al.*, 1996) so sediment erosion and redistribution across the marsh are unlikely (Christiansen *et al.*, 2000). Our seasonal  $^7\text{Be}$  inventories provide further evidence of net accretion throughout the year, as sediment inventories were greater than atmospherically supported  $^7\text{Be}$  inventories in 9 of 11 cores. In contrast, Ledwin (1988) measured net erosion of 0 to 8 mm

during a 14 month study at an exposed riverbank site at Sweet Hall and also observed local resuspension and redeposition of glitter placed on the sediment surface. This suggests that processes controlling sediment deposition and erosion can differ between an exposed high energy riverbank site (Ledwin, 1988) and a more protected creekbank site (this study) within the same marsh.

#### *Beryllium-7 sedimentation*

When calculated using a median particle activity of  $14.3 \text{ dpm g}^{-1}$ ,  $^7\text{Be}$ -based deposition rates were similar in magnitude to those measured using sediment tiles. For example, rates measured using sediment tiles at the creekbank site in June 1998 ranged from  $62$  to  $140 \text{ g sed m}^{-2} \text{ d}^{-1}$  versus  $128$  to  $139 \text{ g sed m}^{-2} \text{ d}^{-1}$  calculated from  $^7\text{Be}$  inventories. Some differences between methods were expected because  $^7\text{Be}$  inventories (Table 3) and sediment tile deposition rates (Figure 2) were measured on different transects and at different distances from the creekbank. Additionally,  $^7\text{Be}$  derived rates were integrated over several months (mean  $^7\text{Be}$  lifetime for radioactive decay,  $\tau$ , =77 d), while sediment tile measurements were averaged over 14 to 30 days. In spite of these differences, both methods reported greatest sedimentation rates at the creekbank with lower rates in the marsh interior. Additionally, deposition rates at the creekbank decreased from summer to winter with each technique.

The calculation of sedimentation rates using  $^7\text{Be}$  inventories is strongly influenced by estimates of particle specific  $^7\text{Be}$  activity ( $A_{\text{catch}}$ , Equation 2). In estuaries, there can be considerable spatial and temporal variability in particle associated  $^7\text{Be}$  activity due to variations in atmospheric  $^7\text{Be}$  fallout, suspended particle concentrations and residence time in the water column, water salinity, and pH (Olsen *et al.*, 1986; Dibb & Rice, 1989). The literature values of particle activity (median =  $14.3 \text{ dpm g}^{-1}$ ; range: undetectable to  $>150 \text{ dpm g}^{-1}$ ) that we used as an estimate of  $A_{\text{catch}}$  were greater than our October and November 1998 measurements of  $2.3$  and  $9.1 \text{ dpm g}^{-1}$ . In June the activity of surface sediments ranged from  $10.9 \text{ dpm g}^{-1}$  at the creekbank (0–2 cm) to  $8.8$  and  $2.7 \text{ dpm g}^{-1}$  in the marsh interior (0–1 cm). Based on our tile sedimentation measurements, we estimated that recent sediment deposition (within 1  $^7\text{Be}$  half-life of sampling) accounted for only 20 to 50% of the sediment in these surface intervals during June (and a smaller fraction in October and January). Because the total  $^7\text{Be}$  activity in the surface represented inputs from recently deposited

( $^7\text{Be}$ -enriched) as well as older ( $^7\text{Be}$ -depleted) sediments, the actual activity of recently deposited sediments must be greater than the mean  $^7\text{Be}$  activity in the upper centimetre(s) of marsh sediments. Therefore, we suggest that the mean activity of recently deposited sediments ( $A_{\text{catch}}$ ) was greater than the measured  $^7\text{Be}$  activity of suspended particles in the marsh tidal creek ( $2.3$  and  $9.1 \text{ dpm g}^{-1}$ ). Preferential binding of  $^7\text{Be}$  to inorganic over organic particles or fine-grained versus sandy particles may explain our relatively low particle-specific  $^7\text{Be}$  activities (Bloom & Creelius, 1983). At Sweet Hall, the maximum suspended particle concentrations and minimum percent of organic particles (20 to 25% organic; range for 10 tidal cycles) were measured approximately midway between slack tides – this was also near the time when the marsh was first flooded. Because we collected suspended particles near low tide when organic enrichment (23 to 52% organic) and possible dilution of activity by  $^7\text{Be}$ -depleted organic matter were greatest, our measures of  $A_{\text{catch}}$  may underestimate the actual activity of deposited particles.

Using  $^7\text{Be}$  inventories to calculate sedimentation rates also requires measuring atmospheric  $^7\text{Be}$  deposition. In intertidal systems, a fraction of  $^7\text{Be}$  fallout may be intercepted by tidal waters. Because Sweet Hall is flooded for  $12$  to  $13 \text{ hr d}^{-1}$ , we estimated the minimum atmospheric  $^7\text{Be}$  deposition to the marsh as 50% of that measured at the Virginia Institute of Marine Science ( $I_{\text{atm, Sweet Hall}} = 0.5 \times I_{\text{atm, VIMS}}$ ). Inherent in this estimation are the assumptions that  $^7\text{Be}$  fallout is evenly distributed between periods of high and low tide, and that fallout which occurs during high tide does not directly reach the marsh surface. If any atmospheric  $^7\text{Be}$  fallout during high tide sorbs to particles which then settle to the marsh surface, this input would be measured as sediment deposition. However, in a shallow, well-mixed water column (such as that overlying a microtidal marsh), a fraction of dissolved atmospheric beryllium may also directly sorb to submerged sediments (Olsen *et al.*, 1986; Dibb & Rice, 1989). Therefore, we estimated a maximum value for  $I_{\text{atm}}$  by assuming that atmospheric beryllium delivery was not affected by tidal stage (i.e.  $I_{\text{atm, Sweet Hall}} = I_{\text{atm, VIMS}}$ ). In all samples, this range in  $I_{\text{atm}}$  caused variability in calculated sedimentation rates of  $\sim 6$  to  $11 \text{ g sed m}^{-2} \text{ d}^{-1}$ , but did not cause a change from net deposition to erosion (exception: 25 m core from June 1998; Table 3).

Marsh plants may also intercept atmospheric fallout and reduce delivery to underlying sediments. Russell *et al.* (1981) estimated that forests with leaf area indices of 3 to 10 ( $\text{LAI} = \text{m}^2 \text{ leaf area per m}^2$ )

subtended land) can reduce atmospheric radionuclide flux by 5 to 20%. At Sweet Hall, we calculated a LAI of 3 to 11 in June 1996 and 0 to <2 in September (S.C.N., unpublished data) and suggest that atmospheric deposition of  $^7\text{Be}$  to the sediment surface may be further reduced during early to mid summer when macrophyte leaf area and biomass are greatest. By not accounting for this effect, we are effectively providing a conservative estimate of sediment deposition since further reducing the atmospheric flux to the marsh surface would increase calculated deposition rates (Equation 2).

#### *Sediment lability and marsh carbon budget*

Using a carbon gas flux model based on measured field fluxes of  $\text{CO}_2$  and  $\text{CH}_4$ , Neubauer *et al.* (2000) calculated rates of total community photosynthesis and respiration at Sweet Hall marsh. Annually, community respiration ( $1269 \text{ g C m}^{-2}$ ) exceeded gross photosynthesis ( $1062 \text{ g C m}^{-2}$ ). In the absence of an external carbon source, this 'excess' respiration implies that some fraction of sediment carbon is being mineralized to  $\text{CO}_2$  or  $\text{CH}_4$  and lost from the marsh. Simultaneously, a relative sea level rise of  $4$  to  $6.5 \text{ mm y}^{-1}$  may potentially lower marsh elevation relative to mean tidal level. Because tidal marsh plant zonation is affected by the frequency and depth of tidal flooding (Odum *et al.*, 1984; Perry, 1991) and the distribution of plant assemblages at Sweet Hall has not changed significantly since 1937 (Perry, 1991), we assume that the marsh imports enough carbon to overcome the combined effects of respiration and relative sea level rise on marsh elevation. Converting relative sea level (RSL) rise to carbon units using surface bulk density and percent carbon data, we estimate a required C input of  $284$  to  $332 \text{ g C m}^{-2} \text{ y}^{-1}$  ( $207 \text{ g C m}^{-2} \text{ y}^{-1}$  'excess' respiration +  $77$  to  $125 \text{ g C m}^{-2} \text{ y}^{-1}$  RSL) to balance these factors. Based on a measured annual sedimentation rate of  $517 \text{ g C m}^{-2} \text{ y}^{-1}$  (Table 2), the deposition of sediment-associated carbon during tidal flooding is sufficient to counteract the effects of respiratory marsh loss and relative sea level rise.

In order to explain measured respiration rates, freshly deposited sediments must contain a sufficient quantity of labile carbon. The spatial variability in sediment mineralization rates suggested that sediments deposited at the creekbank were less labile than those deposited in the marsh interior. While bulk C/N ratios do not support the idea of varying organic matter lability, there may have been spatial variability in the molecular composition of sediment organic matter (e.g. abundance of amino acids versus

carbohydrates versus lignin). Alternately, a proportionally greater fraction of the carbon may have been bound to mineral surfaces in creekbank sediments and therefore protected from microbial degradation. Regardless of the mechanism, lower respiration rates at the creekbank may ultimately contribute to higher long-term accretion rates.

We used average sediment mineralization rates (Figure 4) and annual deposition rates (Table 2) for each block to calculate that 22 to  $44 \text{ g C m}^{-2} \text{ y}^{-1}$  of recently deposited sediment organic carbon was mineralized on time scales less than 5 days, with 54 to  $71 \text{ g C m}^{-2} \text{ y}^{-1}$  metabolized within 30 days of deposition. This accounts for 26 to 35% of the measured 'excess' respiration of  $207 \text{ g C m}^{-2} \text{ y}^{-1}$ . An additional fraction can be explained by the turnover of sediment carbon on time scales longer than 1 month as natural sediment carbon is composed of compounds that are remineralized on time scales from hours (e.g. free amino acids:  $k > 7500 \text{ y}^{-1}$ ) to centuries (e.g. sterols:  $k = 0.015 \text{ y}^{-1}$ ) or longer (e.g. hydrocarbons:  $k < 0.001 \text{ y}^{-1}$ ; lignin:  $k = 0 \text{ y}^{-1}$ ; see references in Heinrichs, 1993). Inputs of relatively labile organic matter from marsh primary producers (macrophytes, microalgae) or sediment deposition may promote the degradation of more refractory organic matter due to the effects of co-metabolism. The mineralization of 'old' detritus from autotrophic production in previous years may account for some measured respiration, while anaerobic metabolism of sediment carbon is also likely to be important.

#### *Sediment accretion*

Our  $^{137}\text{Cs}$ -based estimates of sediment accretion rates ( $8.4$  to  $8.5 \text{ mm y}^{-1}$ ) are higher than estimated rates of relative sea level rise ( $4.5$  to  $6 \text{ mm y}^{-1}$ ) at Sweet Hall marsh. Working in *Spartina cynosuroides* and *Phragmites australis* stands elsewhere at Sweet Hall, Campana (1998) measured accretion rates of  $4.9$  to  $6.0 \text{ mm y}^{-1}$  using  $^{137}\text{Cs}$  activity profiles. The difference between our rates and those of Campana (1998) illustrates between habitat sedimentation differences. *S. cynosuroides* and *P. australis* grow at slightly higher elevations and are therefore flooded less frequently than *Peltandra virginica* and *Pontederia cordata*, the dominant species at our study site (Perry, 1991). Thus, sedimentation rates will be lower in these communities. The similarity between relative sea level rise and accretion rates in the *S. cynosuroides* and *P. australis* communities suggests that they are accreting sediments at rates similar to RSL, while our study site is growing vertically at a faster rate than sea level rise. Over time, this will reduce the flooding duration at

TABLE 4. Variations in Sweet Hall marsh accretion rates at different time scales.

Method	Time scale	Vertical accretion (mm y <sup>-1</sup> )	Mass accumulation (g C m <sup>-2</sup> y <sup>-1</sup> )
plates	annual	28.4 ± 21.3 <sup>a</sup>	517 ± 353 <sup>a</sup>
<sup>137</sup> Cs	decades	8.4, 8.5 <sup>b</sup>	224 ± 45
<sup>14</sup> C	centuries	4.3 to 5.5 <sup>c</sup>	— <sup>d</sup>
<sup>14</sup> C	millennia	1.5 to 1.7 <sup>c</sup>	— <sup>d</sup>

<sup>a</sup>Mean ± 1 standard deviation for entire transect.

<sup>b</sup>Based on depths of first appearance and maximum activity of <sup>137</sup>Cs, respectively.

<sup>c</sup>Range represents analytical uncertainty associated with radiocarbon dating and conversion to calendar age.

<sup>d</sup>Insufficient bulk density data to convert mm y<sup>-1</sup> to g C m<sup>-2</sup> y<sup>-1</sup>.

our site and may cause a reduction in sedimentation rates until a morphodynamic equilibrium between marsh elevation and sea level is reached.

Using <sup>14</sup>C dating, we calculated long-term average accretion rates of 4.3 to 5.5 mm y<sup>-1</sup> (0 to 3.1 m) and 1.5 to 1.7 mm y<sup>-1</sup> (0 to 6.5 m). The relative consistency in organic and carbon content above 250 cm (Figure 3) indicates that deposition and preservation conditions throughout this portion of the sediment profile were similar to those in the modern tidal freshwater marsh. We therefore estimate that Sweet Hall has been a tidal freshwater marsh for approximately 450 to 580 y (250 cm/0.43 to 0.55 cm y<sup>-1</sup> vertical accretion). Variability in sediment organic matter and carbon content below 250 cm, the increase in sediment C/N ratio (Figure 3), and the presence of wood fragments through much of the deep core suggest that Sweet Hall marsh may have been a non-tidal swamp or other wetland type in the past. Thus, caution must be applied when comparing accretion rates from this section of the core with shorter term measurements from the modern tidal freshwater marsh.

With this caveat in mind, we observed a decrease in sediment accumulation rate with increasing time scale, from years to decades to millennia (Table 4). Although our estimates of long-term accretion rates (<sup>137</sup>Cs and <sup>14</sup>C dating) were based on a limited number of cores, a review of other studies that have examined accretion rates over a range of time scales revealed that this trend is a common feature in Chesapeake Bay marshes (Figure 5) and in other sedimentary environments (e.g. McKee *et al.*, 1983). Due to the high spatial variability in short-term (annual) deposition rates, the most significant decrease in accretion rates occurs when comparing annual and decadal rates with those averaged over centuries and millennia. As rates are integrated over

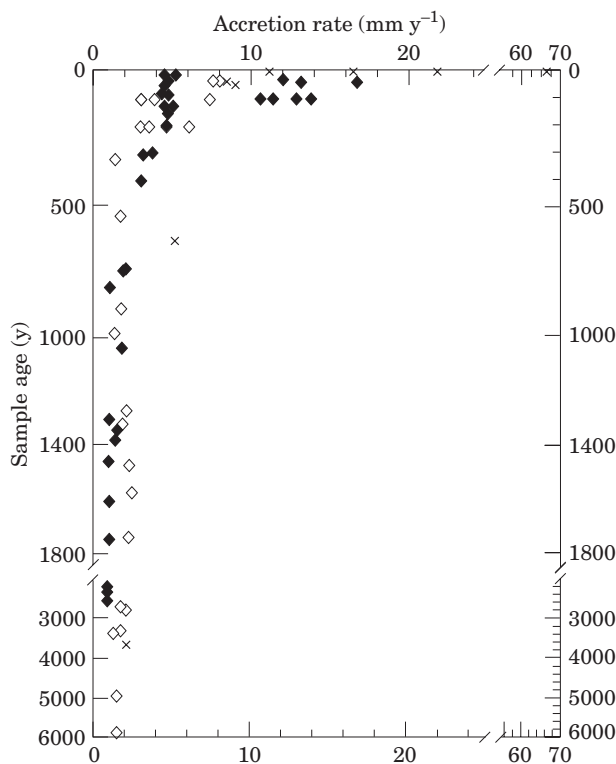


FIGURE 5. Accretion rate versus sample age for mid-Atlantic tidal marshes (U.S.A.). Data are presented from studies where accretion rates were measured over a range of time scales. Tidal freshwater marsh data points are from Orson *et al.* (1990; Delaware River), Khan and Brush (1994; Jug Bay, MD), and this study (Pamunkey River, VA). Salt marsh data points are from Ellison and Nichols (1976; James and Rappahannock Rivers, VA) and Kearney *et al.* (1994; Monie Bay, MD). × This study (tidal freshwater); ◆ Other tidal freshwater marshes; ◇ Tidal salt marshes.

longer time periods, there is a greater probability that the effects of significant sediment removal events (e.g. hurricanes and large storms) will be captured in the sediment record. An additional part of the difference in vertical accretion rates is likely due to compaction of deeper sediments. However, the concurrent reduction in carbon accumulation rate (this study, Table 4) indicates that compaction cannot be the sole mechanism as sediment bulk density is included (and therefore compaction accounted for; Equation 3) in the carbon accretion calculations. Land clearance associated with agricultural development in the 1600s increased sediment delivery to rivers and estuarine waters and may explain increased accretion rates in recent sediments (Brush, 1989; Orson *et al.*, 1990). Alternately, an increase in the frequency and duration of tidal inundation due to sea level rise or marsh subsidence could increase sedimentation rates (Bricker-Urso *et al.*, 1989; Cahoon & Reed, 1995; Leonard, 1997).

We suggest that a portion of the decrease in apparent accretion rate with increasing time scale is due to the respiration of labile sediment carbon following deposition (Figure 4). Additionally, we suggest that sediment metabolism continues at gradually decreasing rates over hundreds or thousands of years as the remaining sediment carbon becomes more refractory. The importance of carbon mineralization in the modern marsh over these time scales is reinforced by the significant decrease in carbon content from freshly deposited sediments (5.95% C) to sediments in the root zone (0–125 cm; 4.78% C) to deeper sediments (125–250 cm; 3.34% C; ANOVA,  $P < 1 \times 10^{-7}$ ; Tukey's HSD,  $P < 0.005$ ). Overall, we hypothesize that a combination of mechanisms (including periodic storm-induced erosion, historical variability in sediment deposition, and the metabolism of a labile sediment fraction) is responsible for the decrease in apparent accretion rates with increasing time scale.

### Conclusions

(1) Short-term sediment deposition rates in tidal freshwater marshes are spatially and temporally variable. Throughout the study period, rates were greatest near a tidal creek and progressively decreased into the marsh interior. At the creekbank, the highest deposition rates were observed during the growing season when the frictional effects of plant vegetation enhanced sediment deposition. Deposition rates were relatively constant throughout the year at the interior sites.

(2) An analysis of historical vegetation patterns at Sweet Hall marsh has suggested that the marsh has grown vertically at a rate similar to relative sea level rise. However, measurements of marsh community respiration and gross photosynthesis indicate that a fraction of sediment organic carbon is being metabolized and lost from the marsh. Therefore, there must be an additional source(s) of carbon to the marsh. When integrated over an entire year, sediment deposition provided sufficient carbon to the marsh to balance the effects of relative sea level rise and marsh respiration rates.

(3) Sediment inventories of  $^7\text{Be}$  were greater than atmospheric fallout inventories in 9 of 11 cores analysed, indicating net sediment deposition throughout the year. Sedimentation rates calculated using a median literature value for particle-specific  $^7\text{Be}$  activity were similar to those measured using sedimentation tiles, although direct comparisons are difficult because the methods integrate sediment deposition over different time scales. Both methods showed simi-

lar temporal and spatial trends in sediment deposition. (4) Depth profiles of  $^{137}\text{Cs}$  and  $^{14}\text{C}$  dating of deep sediments were used to calculate sediment accretion rates on decadal to millennial time scales. Long-term accretion rates were substantially less than annual deposition rates. Characterization of a deep (6.7 m) sediment core suggested that the modern marsh extends to  $\sim 250$  cm depth. The remainder of the core was highly variable in carbon and organic content, C/N ratios, and detritus character, indicating that the marsh may have been a non-tidal swamp or other wetland type in the past.

(5) Mineralization rates of recently deposited sediments were spatially and seasonally variable. Rates were consistently lowest in sediments from the creekbank site and, when averaged across all locations, increased from June to August to November. Within 30 days of sediment deposition, sediment metabolism can potentially remove  $\sim 30\%$  of recently deposited carbon. We suggest that part of the difference between sediment deposition and accretion rates is due to periodic storm-induced erosion and historical variability in sedimentation rates, with a portion also due to the respiration of sediment associated carbon following deposition.

### Acknowledgements

We thank Mike Campana, Matt Church, Alan Moore, Craig Tobias, and Denise Wilson for assistance in the field. Linda Meneghini helped with the  $^7\text{Be}$  and  $^{137}\text{Cs}$  radioisotope analyses, and Gerald Johnson assisted greatly with collection and processing of the vibracore. Critical reviews of earlier drafts of this manuscript were provided by Jim Bauer, Elizabeth Canuel, Gregory Pasternack, and Richard L. Wetzel. Comments by two anonymous reviewers also improved the manuscript. Funding to S.C.N. was provided by the National Estuarine Research Reserve system through a Graduate Research Fellowship. The National Science Foundation's Research Experience for Undergraduates program (grant NSF 99-87930 to Linda C. Schaffner) supported J.A.C. Additional funding was provided by NSF grant DEB-9411974 to the University of Virginia (subcontract to I.C.A.). This is contribution number 2410 of the Virginia Institute of Marine Science, School of Marine Science, College of William and Mary.

### References

- Baskaran, M., Ravichandran, M. & Bianchi, T. S. 1997 Cycling of  $^7\text{Be}$  and  $^{210}\text{Pb}$  in a high DOC, shallow, turbid estuary of south-east Texas. *Estuarine, Coastal and Shelf Science* **45**, 165–176/doi:10.1006/ecss.1996.0181.

- Bloom, N. & Crecelius, E. A. 1983 Solubility behaviour of atmospheric  $^7\text{Be}$  in the marine environment. *Marine Chemistry* **12**, 323–331.
- Booth, P. M. 1989 *Nitrogen and phosphorus cycling strategies in two tidal freshwater macrophytes, Peltandra virginica and Spartina cynosuroides*. Ph.D. dissertation, College of William and Mary, Virginia Institute of Marine Science, Gloucester Point.
- 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.
- Brooks, T. J. *Pamunkey River slack water data report: Temperature, salinity, dissolved oxygen 1970–1980*. Virginia Institute of Marine Science Data Report 20.
- Brush, G. S. 1989 Rates and patterns of estuarine sediment accumulation. *Limnology and Oceanography* **34**, 1235–1246.
- Cahoon, D. R. & Reed, D. J. 1995 Relationships among marsh surface topography, hydroperiod, and soil accretion in a deteriorating Louisiana salt marsh. *Journal of Coastal Research* **11**, 357–369.
- Campana, M. L. 1998 *The effect of Phragmites australis invasion on community processes in a tidal freshwater marsh*. M.S. Thesis, College of William and Mary, Virginia Institute of Marine Science, Gloucester Point.
- Canuel, E. A., Martens, C. S. & Benninger, L.K. 1990 Seasonal variations in  $^7\text{Be}$  activity in the sediments of Cape Lookout Bight, North Carolina. *Geochimica et Cosmochimica Acta* **54**, 237–245.
- Childers, D. L., Sklar, F. H., Drake, B. & Jordan, T. 1993 Seasonal measurements of sediment elevation in three mid-Atlantic estuaries. *Journal of Coastal Research* **9**, 986–1003.
- Christiansen, T., Wiberg, P. L. & Milligan, T. G. 2000 Flow and sediment transport on a tidal salt marsh surface. *Estuarine, Coastal and Shelf Science* **50**, 315–331/doi:10.1006/ecss.2000.0548.
- Cornwell, J. C. & Zelenke, J. L. 1998 The role of oligohaline marshes in estuarine nutrient cycling. *Concepts and controversies in tidal marsh ecology* conference, April 5–9, 1998, Vineland N.J.
- 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/doi:10.1006/ecss.1993.1062.
- DeLaune, R. D., Patrick, Jr, W. H. & Buresh, R. J. 1978 Sedimentation rates determined by  $^{137}\text{Cs}$  dating in a rapidly accreting salt marsh. *Nature* **275**, 532–533.
- Dibb, J. E. & Rice, D. L. 1989 The geochemistry of beryllium-7 in Chesapeake Bay. *Estuarine, Coastal and Shelf Science* **28**, 379–394.
- Doumlele, D. G. 1979 *New Kent County Tidal Marsh Inventory*. Special Report No. 208 in Applied Marine Science and Ocean Engineering. Virginia Institute of Marine Science, Gloucester Point, Virginia.
- Ellison, R. L. & Nichols, M. M. 1976 Modern and Holocene Foraminifera in the Chesapeake Bay Region. *First International Symposium on Benthic Foraminifera of Continental Margins*, Halifax, Nova Scotia, Canada. 131–151.
- EPA. 1996 *Region III Land Cover Data Set*. United States Environmental Protection Agency, Washington DC.
- Esselink, P., Dijkema, K. S., Reents, S. & Hageman, G. 1998 Vertical accretion and profile changes in abandoned man-made tidal marshes in the Dollard estuary, the Netherlands. *Journal of Coastal Research* **14**, 570–582.
- French, J. R. & Spencer, T. 1993 Dynamics of sedimentation in a tide-dominated backbarrier salt marsh, Norfolk, UK. *Marine Geology* **110**, 315–331.
- Frey, R. W. & Basan, P. B. 1985 Coastal salt marshes. In *Coastal Sedimentary Environments* (Davis, R. A., ed.). Springer-Verlag, New York, pp. 225–301.
- Friedrichs, C. T. & Perry III, J. E. 2000 Tidal salt marsh morphodynamics. In *Tidal wetlands: physical and ecological processes* (Goodwin, P. & Mehta, A. J., eds). *Journal of Coastal Research* special issue.
- Froelich, P. N. 1988 Kinetic control of dissolved phosphate in natural rivers and estuaries: A primer on the phosphate buffer mechanism. *Limnology and Oceanography* **33**, 649–668.
- Garbisch, E. 1994 The results of muskrat feeding on cattails in a tidal freshwater wetland. *Wetlands Journal* **6**, 14–15.
- Goodbred Jr, S. L. & Kuehl, S. A. 1998 Floodplain processes in the Bengal Basin and the storage of Ganges-Brahmaputra river sediment: An accretion study using  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  geochronology. *Sedimentary Geology* **121**, 239–258.
- Gornitz, V. & Lebedeff, S. 1987 Global sea level changes during the past century. In *Sea level fluctuation and coastal evolution* (Nummedal, D., Pilkey, O. H. & Howard, J. D., eds). Society of Economic Paleontologists and Mineralogists Special Publication 41, Tulsa, Oklahoma, pp. 3–16.
- Gornitz, V., Lebedeff, S. & Hansen, J. 1982 Global sea level trend in the past century. *Science* **215**, 1611–1614.
- He, Q. & Walling, E. 1996 Use of fallout Pb-210 measurements to investigate longer-term rates and patterns of overbank sediment deposition on the floodplains of lowland rivers. *Earth Surface Processes and Landforms* **21**, 141–154.
- Hedges, J. I. & Keil, R. G. 1995 Sedimentary organic matter preservation: an assessment and speculative synthesis. *Marine Chemistry* **49**, 81–115.
- Hedges, J. I. & Keil, R. G. 1999 Organic geochemical perspectives on estuarine processes: sorption reactions and consequences. *Marine Chemistry* **65**, 55–65.
- Henrichs, S. M. 1993 Early diagenesis of organic matter: The dynamics (rates) of cycling of organic compounds. In *Organic Geochemistry: Principles and Applications* Engel, M. H., Macko, S. A., eds). Plenum Press, New York, pp. 101–117.
- Holdahl, S. R. & Morrison, N. L. 1974 Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data. *Tectonophysics* **23**, 373–390.
- Kearney, M. S., Stevenson, J. C. & Ward, L. G. 1994 Spatial and Temporal Changes in Marsh Vertical Accretion Rates at Monie Bay: Implications for Sea-Level Rise. *Journal of Coastal Research* **10**, 1010–1020.
- Khan, H. & Brush, G. S. 1994 Nutrient and metal accumulation in a freshwater tidal marsh. *Estuaries* **9**, 310–319.
- Ledwin, J. M. 1988 *Sedimentation and its role in the nutrient dynamics of a tidal freshwater marsh*. M.A. Thesis, College of William and Mary, Virginia Institute of Marine Science, Gloucester Point.
- Leonard, L. A. & Luther, M. E. 1995 Flow hydrodynamics in tidal marsh canopies. *Limnology and Oceanography* **40**, 1474–1484.
- Leonard, L. A. 1997 Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina. *Wetlands* **17**, 263–274.
- 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.
- McKee, B. A., Nittrouer, C. A. & DeMaster, D. J. 1983 Concepts of sediment deposition and accumulation applied to the continental shelf near the mouth of the Yangtze River. *Geology* **11**, 631–633.
- 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.
- 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.
- 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*. United States Department of the Interior, Fish and Wildlife Service, FWS/OBS-83/17.
- Olsen, C. R., Cutshall, N. H. & Larsen, I. L. 1982 Pollutant-particle associations and dynamics in coastal marine environments: A review. *Marine Chemistry* **11**, 501–533.
- Olsen, C. R., Larsen, I. L., Lowry, P. D., Cutshall, N. H. & Nichols, M. M. 1986 Geochemistry and deposition of  $^7\text{Be}$  in river-estuarine and coastal waters. *Journal of Geophysical Research* **91**, 896–908.

- 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 The paleoecological development of a late-Holocene, tidal freshwater marsh of the upper Delaware River estuary. *Estuaries* **15**, 130–146.
- Pasternack, G. B. & Brush, G. S. 1998 Sedimentation cycles in a river-mouth tidal freshwater marsh. *Estuaries* **21**, 407–415.
- Perry III, J. E. & Hershner, C. 1999 Temporal changes in the vegetation pattern in a tidal freshwater marsh. *Wetlands* **19**, 90–99.
- Perry III, J. E. 1991 *Analysis of vegetation patterns in a tidal freshwater marsh*. Ph.D. dissertation, College of William and Mary, Virginia Institute of Marine Science, Gloucester Point.
- Reed, D. J. 1990 The impact of sea-level rise on coastal salt marshes. *Progress in Physical Geography* **14**, 465–481.
- Russell, I. J., Choquette, C. E., Fang, S. L., Dundulis, W. P., Pao, A. A. & Pszenny, A. A. P. 1981 Forest vegetation as a sink for atmospheric particulates: Quantitative studies in rain and dry deposition. *Journal of Geophysical Research* **86**, 5247–5363.
- Shi, Z., Pethick, J. S., Burd, F. & Murphy, B. 1996 Velocity profiles in a salt marsh canopy. *Geo-Marine Letters* **16**, 319–323.
- Silberhorn, G. M. & Zacherle, A. W. 1987 *King William County and Town of West Point Tidal Marsh Inventory*. Special Report No. 289 in Applied Marine Science and Ocean Engineering. Virginia Institute of Marine Science, Gloucester Point, Virginia.
- Skoog, D. A. & West, D. M. 1963 *Fundamentals of Analytical Chemistry*, 3rd edn. Holt, Rinehart and Winston, New York, pp. 71–78.
- Stevenson, J. C., Ward, L. G. & Kearney, M. S. 1988 Sediment transport and trapping in marsh systems: implications of tidal flux studies. *Marine Geology* **80**, 37–59.
- Walling, D. E., Quine, T. A. & He, Q. 1992 Investigating contemporary rates of floodplain sedimentation. In *Lowland floodplain rivers: Geomorphological perspectives* (Carling, P. A. & Petts, G. E., eds). John Wiley and Sons, New York, pp. 165–184.