

Properties of intertidal marsh sediment mobilized by rainfall

Raymond Torres, Mwasi J. Mwamba, and Miguel A. Goñi

Department of Geological Sciences, University of South Carolina, Columbia, South Carolina 29208

Abstract

We conducted sprinkler irrigation experiments on a low-tide marsh to investigate the effects of rainfall on the redistribution of organic matter (OM) and nutrients in the intertidal zone. We irrigated 1- × 2-m plots at high-marsh, low-marsh, and channel bank sites and flood-irrigated 1- × 3-m plots in the high marsh and low marsh. We measured particulate density, OM content, organic carbon (OC) content, and nitrogen (N) content and calculated OM particulate density and atomic C:N ratios. The content of OM, OC, and N in rainfall-mobilized sediment was consistently higher than in the substrate. C:N ratios ranged from 13 to 15 and were consistently lower than the sediment substrate (16–21). These observations indicate that rainfall can mobilize N preferentially over OC; hence, rainfall events deplete the marsh substrate of OM, OC, and nutrients. Despite variability in the density of mobilized particulates, the calculated OM densities and the C:N ratios remained unchanged during the irrigation experiments. These results indicate that rainfall runoff processes preferentially and consistently mobilize OM-rich particulates with low C:N ratios, characteristic of mixed algal or vascular plant sources. The short-term OC fluxes during these rainfall experiments represent 3–20% of annual primary productivity.

Salt marshes are among the most highly productive ecosystems in the world, producing more organic matter per unit area than forests, grasslands, or cultivated fields (Schlesinger 1977). High marsh productivity is facilitated by biogenic and physical processes that interact to recycle nutrient-rich sediment. The physical processes that drive intertidal salt marsh sediment cycling result from both marine and subaerial forcing; therefore, rainfall during low tide might be an important facet of intertidal marsh sediment redistribution. For example, Anderson and Meyer (1984) determined that rainfall onto the low-tide substrate accounts for 50% of the suspended sediment concentration in a small cove. Also, Settlemyer and Gardner (1975) showed that low tide storms increase suspended sediment concentrations in tidal creeks by up to three orders of magnitude. Moreover, Mwamba and Torres (2002) estimated that a single thunderstorm could mobilize >67,000 kg sediment km⁻² salt marsh.

Low-tide rainstorms could also affect the accumulation, turnover, transformation, and redistribution of marsh organic matter and nutrients. For example, Oertel (1976) measured increases in suspended sediment concentrations during spring tides and rainstorms and found that the mobilized organic matter had a marsh rather than terrestrial source. Correll (1981) showed that rainfall events transfer organic matter and nutrients from marsh to estuarine systems. Chalmers et al. (1985) reasoned that rainfall-induced erosion of the salt marsh and subsequent sediment redistribution by tidal action are important processes that control the cycling of organic carbon in estuaries fringed with extensive salt marsh. Also, Dame and Kenny (1986) found that rainfall-induced

nutrient redistribution increased primary productivity. Together, these studies indicate that the sediment and organic matter cycling in estuaries can be affected by low-tide rainstorms, a potentially important subaerial process that is currently unaccounted for in estuarine biogeochemical models.

We hypothesize that low-tide rainfall runoff processes facilitate the fractionation of marsh sediments through preferential turnover of some particulate matter. In this study, we ask: What is the composition of intertidal marsh sediment entrained by low-tide rainfall events? To address this question, we measured several physical and chemical properties of sediment mobilized during simulated rainfall experiments over marsh plots. Subsequent data and analyses were combined to identify possible sources of rainfall-mobilized organic matter (OM) and nutrients and to describe the physical processes that lead to the entrainment of OM and nutrients in response to low-tide rainstorms.

Location and site description

Plot irrigation experiments were conducted at North Inlet marsh near Georgetown, South Carolina (UTM coordinates 667705, 3691015). North Inlet is a 32-km² bar-built, ebb-dominated, relatively pristine estuary with an extensive salt marsh. With the exception of the northernmost tip, the area around the salt marsh is maritime forest held in conservation. North Inlet has a subtropical climate with average monthly temperatures ranging between 9 and 27°C and annual rainfall of 1.4 m, with frequent high-intensity, low-duration cyclonic and convective storms (National Climatic Data Center COOPID 383468). For example, when tropical storm Kyle (October 2002) passed over the study site, one particular shower lasted 34 min and delivered 26.8 mm of rainfall, but during the most intense interval, 4.3 mm fell in 2 min. Other showers produced maximum hourly intensities of 94.5 mm h⁻¹ for 6 min and 103.6 mm h⁻¹ for 8 min.

We conducted sprinkler and flood irrigation experiments in the high marsh, low marsh, and channel bank areas, designated HM, LM, and CB, respectively. At each site, we

Acknowledgments

This research was supported by U.S. Environmental Protection Agency (R-828677) and National Science Foundation (EAR 00-1393) awards to R. Torres. Heather Aceves performed the elemental analyses and L.R. Gardner provided helpful commentary on the experiments and analyses. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government.

selected the study plots with the goal of having them as identical as possible based on substrate characteristics, vegetation density, and composition. Microtopography within the plots was <4 cm, but the CB plots had the greatest total relief—0.50 m at the channel-levee interface.

The HM and LM areas appeared to be undisturbed. The HM site was located on an accumulation of dune sand, the remnant of an eroded beach ridge. The ground was firm and sandy with dispersed accumulations of <2 -mm fecal pellets and 10–15-mm crab burrows. Landward, the HM vegetation transitions from tall to short *Spartina alterniflora*, to *Salicornia virginica*, to *Juncus roemerianus*. The LM study site was within the slightly convergent topography of a first-order intertidal channel, the maximum headward extent of the local tidal channel network. Vegetation included short and tall *S. alterniflora* growing in mud. The CB site was along a straight, dredged trench (dredged in 1958, Dennis Allen pers. comm.) now acting as a tidal channel; CB site selection was limited by access and logistical concerns. The CB site had tall *S. alterniflora* growing along the channel levee and short *S. alterniflora* along the banks. The regularly inundated channel substrate was muddy and unvegetated.

Materials and methods

Experimental design—Three months prior to the experiments, wooden boardwalks were constructed around the LM and CB plots, providing plot access with negligible disturbance; the ground around the HM plots was firm and did not require boardwalks. Plots were isolated with lengths of 0.25-m-wide by 0.5-m-thick aluminum flashing pushed into the substrate along the plot perimeter. The flashing was supported with wooden stakes, and the resulting aluminum wall was about 0.15 m high. Concurrently, a 0.4–0.5-m-deep trench was dug along the downslope end of each plot to collect runoff, and we installed angled flashing over the exposed trench lip to prevent lip erosion. Rain gutters (0.12-m opening) were placed just below the overhanging flashing and slanted toward the runoff collection position. A 12-V sump pump prevented trench flooding by plot runoff and shallow ground water.

After plot preparation, a portable frame-mounted sprinkler was positioned over the plot. The sprinkler system was constructed with industrial spray nozzles mounted 2 m above the ground surface and pointed upward to enhance spray distribution. The nozzles produce drop sizes comparable to those of natural rainfall when operated at $\sim 4 \times 10^{-3}$ Pa (Booker 1989). The irrigation rates were ~ 100 mm h^{-1} , and the durations were 25–60 min. The first 10 min of our simulated rainstorms were equivalent to rainfall events with a 2–10-yr recurrence interval (Mwamba 2001).

Flood irrigations were conducted on 1×3 -m plots to emulate tidal sheetflow for comparison with the simulated rainfall effects. Flood irrigation plot preparation was identical to the sprinkler plots. During the flood experiments, designated FL, we pumped estuary water directly into the plot through an upslope fixed bundle ($1 \times 0.5 \times 0.3$ m) of dry *S. alterniflora* stalks to dissipate pump energy. We did not conduct flood irrigation experiments on the channel bank

Table 1. Field experiment schedule and plot description.

Study site	Water	Method	Date, time	Symbol
High marsh	Fresh	Rain	15 Apr 00, 1124 h	HMF _W
	Salt	Rain	15 Apr 00, 1715 h	HMS _W
	Salt	Flood	16 Apr 00, 1110 h	HMFL
Low marsh	Fresh	Rain	27 May 00, 1110 h	LMF _W
	Salt	Rain	28 May 00, 1011 h	LMS _W
	Salt	Flood	28 May 00, 1155 h	LMFL
Channel bank	Fresh	Rain	24 Jun 00, 0941 h	CBF _W
	Salt	Rain	25 Jun 00, 0902 h	CBS _W

site because the resulting artificial sheetflow conditions would not have a natural counterpart.

A total of eight plots were irrigated: three each in the HM and LM and two on the CB. Each plot was oriented normal to the topographic contour as determined by topographic survey. Experiments between plot sites were conducted about 1 month apart (Table 1). Therefore, temporal differences between experiments can affect our results through the concomitant variations in the life cycle of marsh flora and fauna. This translates to, among other things, variable vegetation protection of the sediment substrate from raindrop impacts. Hence, the sediment transport rates associated with the later experiments could be lower because of increased canopy protection.

We used tap water (0 ppt), designated FW for freshwater, and estuary water (30 ppt), designated SW for salt water (Table 1). Although the salinity of natural rainfall is ~ 0 , we irrigated with estuary water to distinguish between the effects from the impact of raindrops and those of freshwater dilution on sediment entrainment. Estuary water used in the FL and SW experiments was filtered through fine sand. Plot runoff delivered sediment to the collection trough and water sediment samples were collected at 0.25–10 min intervals in 0.96-liter plastic containers. After collection, the containers were sealed and placed in a cold room set at 2°C. After 1–2 d, the samples were packed in ice for the ~ 3 -h trip to our main laboratory. The samples were then placed in a second cold room also set at 2°C. After 1–2 d we separated the solid and liquid fractions by centrifugation. Each runoff sample was poured into multiple 50-ml centrifuge tubes and centrifuged at 3,600 rpm for 10–15 min, forming easily removed sediment pellets of 0.01–30 g in clear water. The sediment pellets were oven dried at 105°C, crushed, sieved through a 0.212- μm mesh and stored in glass vials.

Prior to the irrigation experiments, eight substrate samples were taken using 2-cm-deep, 8.5-cm-diameter cylinders. The cylinders were pushed into the sediment near each plot, avoiding compaction, and the substrate was cut from the marsh surface, covered, and placed in cold storage (2°C) for 1–3 d. Thereafter, the samples were oven dried and processing of the dry substrate samples was identical to that for the dried runoff samples. We assume that these eight samples cut from the marsh substrate represent the bulk-averaged initial physical and geochemical conditions preceding the irrigation experiments.

OM content—Depending on sample size, up to 100% of the sieved sample was poured into 20-ml crucibles, oven dried for 1 h at 105°C, and cooled in a desiccator for 0.3 h. The samples were reweighed and placed in a muffle furnace for 3 h at 550°C and weighed after combustion (*after* Howard and Howard 1989). The weight loss is assumed to be total OM content. Because the HM sample sizes were so small (<0.5 g), 100% of each was consumed in this procedure and none was available for subsequent analyses.

Particulate density—Combusted and uncombusted sediment samples of 0.5–5 g were oven dried at 105°C for 24 h, and volumes were measured using a pycnometer (AccuPyc 1330) with an accuracy of $\pm 0.005 \text{ cm}^3$. Using weight and volume of sediments, we estimated the particulate density of combusted and uncombusted samples. We did not attempt to separate organic from inorganic matter, but we estimated OM density (ρ_o) from the uncombusted and combusted data according to Eq. 1.

$$\rho_o = \frac{\text{OMC}}{\rho_u^{-1} - \rho_c^{-1}(1 - \text{OMC})} \quad (1)$$

where ρ_u is the density of uncombusted solids, ρ_c is the density of combusted solids, and OMC is the OM content by weight.

C and N element analyses—We measured weight percentage of organic carbon (OC) and N using the procedure of Hedges and Stern (1984). Briefly, oven-dried sediment samples were homogenized and weighed (2–5 mg) in silver boats, placed in a vacuum desiccator, and vapor acidified for 24 h to remove inorganic carbon. The silver boats were inserted into tin boats, folded, and loaded into a Carlo Erba NC 2400 elemental analyzer for OC and N analyses. The samples were analyzed using a combustion temperature of 1,020°C and reduction temperature of 640°C. Replicate analyses of the same sample resulted in analytical errors of $\pm 2\%$ of the measured value for OC and N. Atomic C:N ratios were calculated from the OC and N weight percent data.

Results

Sediment concentration—High marsh: HMF_W runoff had an initial maximum concentration of 1,097 mg L⁻¹, but within 12 min it decreased to $\sim 200 \text{ mg L}^{-1}$ and continued to decline asymptotically until the end of irrigation (Fig. 1A). Thereafter, concentrations were highly variable but less than 300 mg L⁻¹. The HMS_W concentration showed three distinct peaks of 2,380, 1,385, and 1,510 mg L⁻¹. Two HMFL experiments were conducted; the first experiment was terminated early because the discharge overwhelmed our ability to sample it. In a subsequent run, we reduced the discharge by 17%. During the first run, the initial runoff sample had 1,258 mg L⁻¹ but abruptly declined to <100 mg L⁻¹. During the second run, initial concentration was 1,580 mg L⁻¹ but decreased to <100 mg L⁻¹ until the end of experiment. Greater variability in the HM response could have resulted from bed load transport of the sandy substrate.

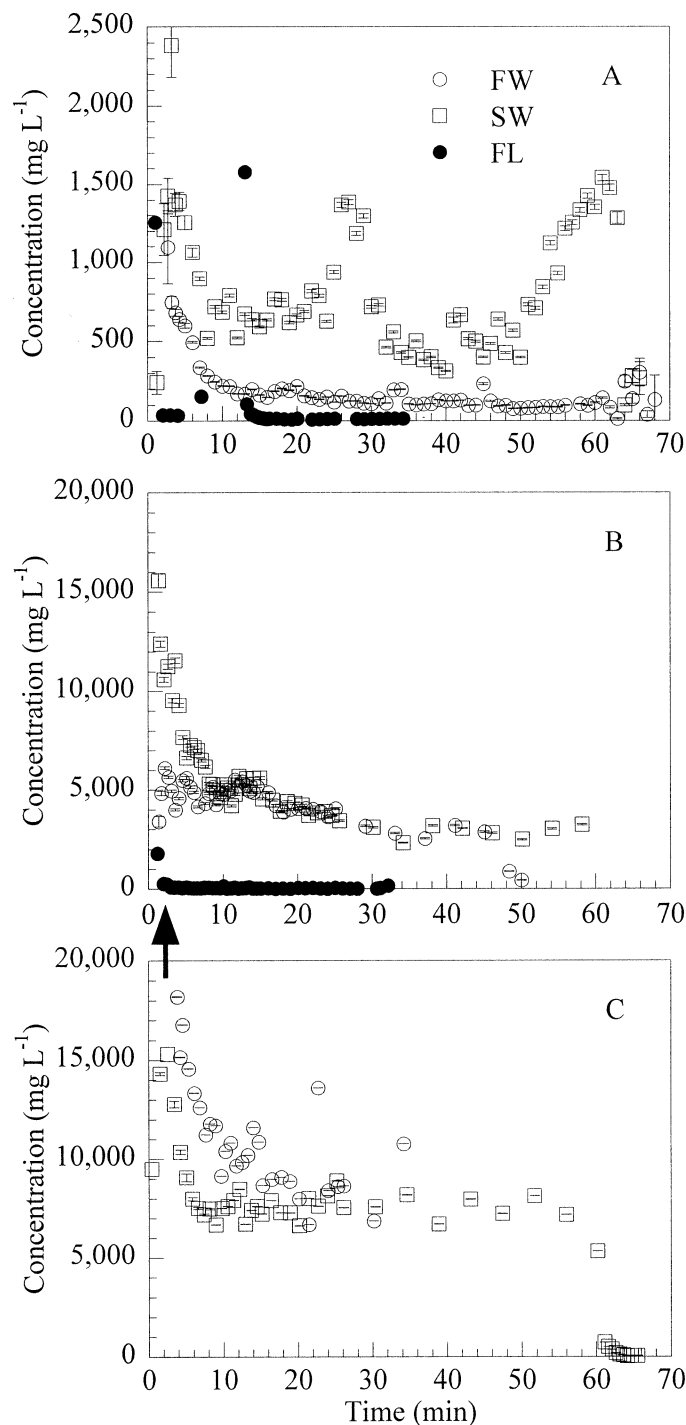


Fig. 1. Time series of sediment concentration in plot runoff for the (A) high marsh (HM), (B) low marsh (LM), and (C) channel bank (CB). Irrigation methods are freshwater sprinkler irrigation (FW), saltwater sprinkler irrigation (SW), and saltwater flood irrigation (FL). The arrow on panel C indicates that a single measurement at 1 min approached 36,000 mg L⁻¹. Also, note the different y-axis scales. Error bars depict analytical uncertainty in measurements.

Table 2. OM (%) determined by loss on ignition. Values are percentage by weight.

	HMFW	HMSW	HMFL	HM _{substrate}	LMFW	LMSW	LMFL	LM _{substrate}	CBFW	CBSW	CB _{substrate}
Mean	22.39	8.49	20.1	1.66	20.4	19.0	15.0	15.0	11.8	11.3	4.43
SD	5.30	4.93	7.66	0.19	0.39	2.29	9.95	0.89	2.11	3.53	1.08
n	60	62	32	3	16	7	49	2	16	12	3

Low marsh: The LMFW experiment showed an initial concentration of 3,402 mg L⁻¹, which increased to a maximum of 6,120 mg L⁻¹ at 2 min (Fig. 1B). Thereafter, values fluctuated between 4,000 and 6,000 mg L⁻¹ and then decreased to a minimum of 2,546 mg L⁻¹ at 37 min. At the end of irrigation, concentrations increased slightly before declining to 440 mg L⁻¹ at 50 min. The initial LMSW concentration reached 15,580 mg L⁻¹ but decreased to ~5,000 mg L⁻¹ at 8 min and remained there until 12 min. After 12 min, values declined asymptotically toward 3,000 mg L⁻¹. In the LMFL experiments, sediment concentrations started at 2,150 mg L⁻¹ but decreased to <200 mg L⁻¹ at 3 min and continued to decline to <100 mg L⁻¹.

Channel bank: CBFW concentrations peaked at 35,876 mg L⁻¹ and decreased asymptotically toward 9,000 mg L⁻¹ (Fig. 1C). The SW discharge concentrations started at ~9,000 mg L⁻¹ and peaked at 15,035 mg L⁻¹ within 2 min. This was followed by a decrease to ~7,500 mg L⁻¹ at 8 min that persisted until irrigation was stopped at 60 min. Thereafter, sediment concentration decreased from ~5,000 mg L⁻¹ to <1,000 mg L⁻¹.

Together, these observations show that low-tide rainfall can entrain ~10 times more sediment from the low marsh and channel bank plots compared to the high marsh. Also, rainfall-driven sediment fluxes were typically 5–100 times greater than that from flood irrigation experiments designed to emulate ebb tide forcing. Hence, the simulated rainfall runoff processes entrained more sediment than the simulated tidal flows.

In subsequent analyses, we examined differences between study sites, and between treatments. To facilitate these comparisons, we used analysis of variance between groups of data. Unless otherwise stated, the null hypothesis—sample means are not significantly different—will be valid. In most cases the data sets were unbalanced; we made use of the concept of least significant difference and set the significance indicator to 0.05 ($\alpha = 0.05$). To reduce the likelihood of type I error, we use the Tukey-Kramer HSD approach.

OM content—High marsh: The upper 2 cm of the HM substrate had an OM content of $1.66 \pm 0.19\%$ by weight (Table 2). The HMFW sprinkler experiments entrained sediment with OM content of 20% (Fig. 2A), although the analytical error with the latter measurements increased because of declining sample size (see Fig. 1). Three samples (at 33, 34, and 45 min) had <10% OM, perhaps because of intermittent increases of the inorganic fraction. These observations show that the OM flux was nearly constant throughout the experiment, but the sediment concentration declined asymptotically.

The OM content time series for the HMSW plot showed

two types of variability. First, there was a general decline in OM content from 17% at the start of the experiment to 1% at the end (Fig. 2B). The second type of variability is superimposed on this general decline and is associated with nonuniform changes that yield peaks and troughs. The peaks and troughs in OM content were out of phase with the fluctuations in sediment concentration (Fig. 1A). The broad minimum between 20 and 30 min (Fig. 2B) coincided with a peak in sediment concentration (Fig. 1A). Together, these observations show that rainfall processes at the HM can mobilize OM, entraining sediment with a ~10-fold greater OM content than was found in the HM substrate. This indicates that rainfall runoff on a low-tide marsh could deplete or preferentially recycle marsh OM.

The HMFL data showed high variability in OM content (Fig. 2C). The OM values ranged from 2 to 40%, and uncertainty in these measurements reached 15% because of small sample sizes associated with the lower sediment yield (see Fig. 1). Variability in the HMFL response was distinct from the HM sprinkler results, perhaps reflecting variability in the sediment entrainment process facilitated by the impact of raindrops versus sheetflow alone. Also, the average OM content of $20 \pm 7.5\%$ was significantly higher than the substrate (1.7%).

Low marsh: The LM plot surfaces were muddy, and the OM content of the upper 2 cm was $15 \pm 0.89\%$ (Table 2). The LMFW OM content time series was nearly constant at about 20% for the duration of the applied rainfall (Fig. 2D). The two values after the irrigation interval showed a 4% decline, but these OM content measurements were still greater than that of the substrate value.

The LMSW time series showed a steady decline in OM content from an initial high of 21% to a low of 15% (Fig. 2E). The decline was similar to the general decline observed in the HMSW experiment. On the other hand, we did not observe fluctuations similar to those of the HMSW plot (Fig. 2B). Sediment mobilized during this experiment had significantly higher OM content compared to the sediment substrate.

The OM content of the LMFL samples ranged from 3 to 25% (Fig. 2F), with greater variability than either of the LM sprinkler irrigation treatments. Hence, as was the case in the HM experiments, the LMFL treatment produced a highly variable response relative to the sprinkler irrigations. The average OM content of $15 \pm 4.2\%$ was comparable to the substrate average of $15 \pm 0.90\%$.

Channel bank: The CB substrate samples contained a mixture of silt and mud with an OM content of $4.4 \pm 1.1\%$. The coarser sediment and low OM content might be artifacts of the 1958 dredging disturbance (e.g., mixing). Time series

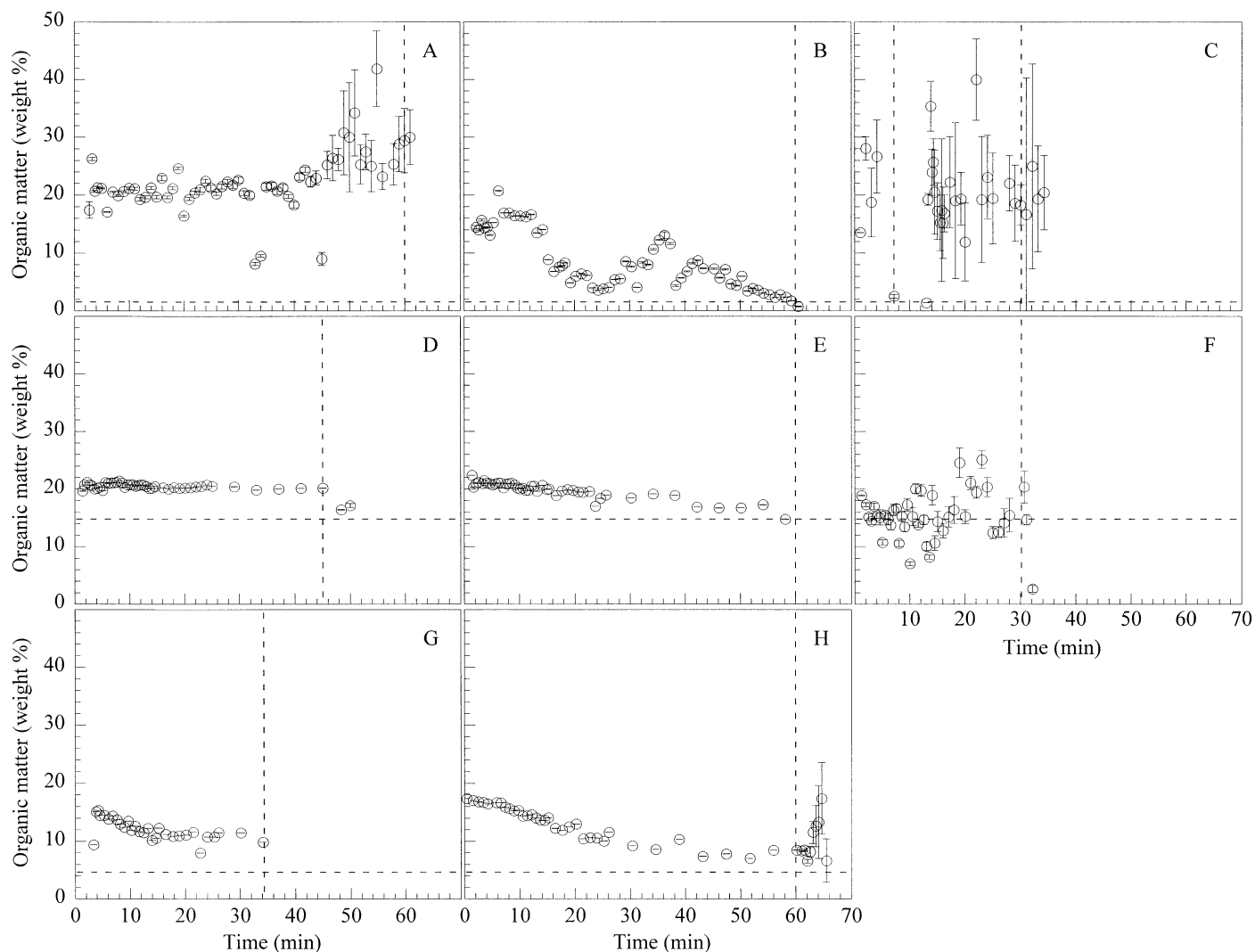


Fig. 2. OM content (weight percent) in rainfall-entrained sediment under different treatments: (A) HMFW, (B) HMSW, (C) HMFL, (D) LMFW, (E) LMSW, (F) LMFL, (G) CBFW, and (H) CBSW. Vertical dashed lines indicate end of irrigation, and horizontal dashed line indicates average OM content of surface sediment. The HMFL run #2 started at 13 min. FW, freshwater sprinkler irrigation; SW, saltwater sprinkler irrigation; FL, saltwater flood irrigation.

of CBFW OM content showed a uniform decline from 16 to 11% during the first 15 min of irrigation, but from 15 to 35 min, the response was steady at $\sim 11\%$ (Fig. 2G). The experiment was terminated at 35 min when the plot was inundated at high tide.

The CBSW OM content declined from 18 to 7% during the first 35 min (Fig. 2H) and remained nearly steady at 7% until the end of irrigation. After irrigation, sample values and measurement uncertainty fluctuated greatly. In both CB experiments, the OM content was up to five times greater than the average substrate OM content.

Overall, the HM, LM, and CB experiments show that rainfall preferentially mobilizes sediment with higher OM content than their respective sediment substrates. The sediments mobilized by FW rainfall irrigation maintained elevated OM content throughout the experiments. In contrast, the OM content of sediment entrained during SW rainfall decreased from the start to the end of the experiments. The CB OM

content time series appeared to represent a combination of the FW and SW responses, with an initial decline followed by a nearly steady interval. These observations indicate that rainfall runoff processes preferentially entrain OM, but enhanced floc formation resulting from the higher salinity water might partially offset this effect.

Particulate density: Bulk average and inorganic matter— Here we focus on the LM and CB sprinkler-derived sediment sample densities because the HM plots and FL treatments provided little sediment, precluding reliable sediment volume estimates. All combusted sample densities average $2.63 \pm 0.026 \text{ g cm}^{-3}$, and this value is significantly different from the uncombusted sample average of $2.41 \pm 0.079 \text{ g cm}^{-3}$. Also, combusted and uncombusted substrate averages at each site and between sites are significantly different. Results reported below indicate uncombusted sediment samples

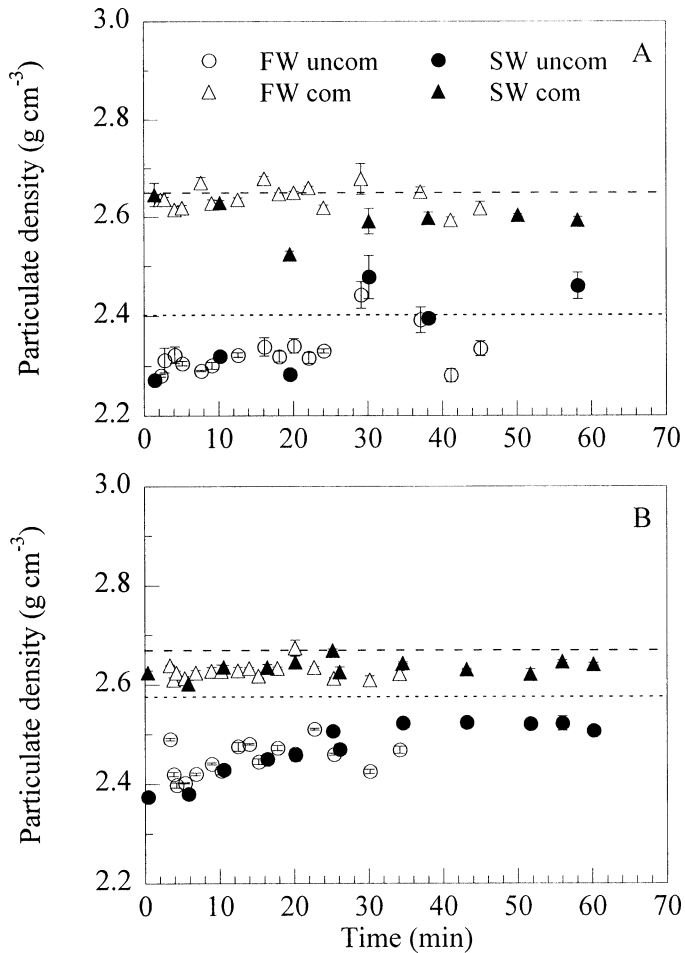


Fig. 3. Particulate densities of sediment in runoff samples from the (A) low marsh sprinkler irrigations and (B) channel bank sprinkler irrigations. The long-dash horizontal lines indicate the average substrate density of combusted samples. The short-dash horizontal lines indicate the uncombusted substrate density. com, combusted samples; uncom, uncombusted samples; FW, freshwater irrigations; SW, saltwater irrigations. Error bars depict analytical uncertainty in measurements.

with the subscript u and combusted sediment samples with the subscript c.

Low marsh: The LM_u substrate density averaged $2.40 \pm 0.015 \text{ g cm}^{-3}$. The LMF_u densities varied an average of $2.33 \pm 0.041 \text{ g cm}^{-3}$, with no clear trend in the time series (Fig. 3A). Higher densities occurred at 29 and 37 min, and there were no corresponding maxima or minima in the sediment concentration or for OM content (Figs. 1B, 2B). Densities of the LMF_c samples (inorganic particulates) showed slight fluctuations about a mean of $2.64 \pm 0.024 \text{ g cm}^{-3}$, with no clear trend. These values are comparable to the LM_c substrate mean of $2.65 \pm 0.04 \text{ g cm}^{-3}$.

LMSW_u samples averaged $2.37 \pm 0.090 \text{ g cm}^{-3}$, slightly lower than the substrate average of $2.40 \pm 0.02 \text{ g cm}^{-3}$. On the other hand, the LMSW_u time series depicts a clear density increase from 2.28 to 2.47 g cm^{-3} (Fig. 3A). The LMSW_c density decreased over the first 20 min, from 2.62

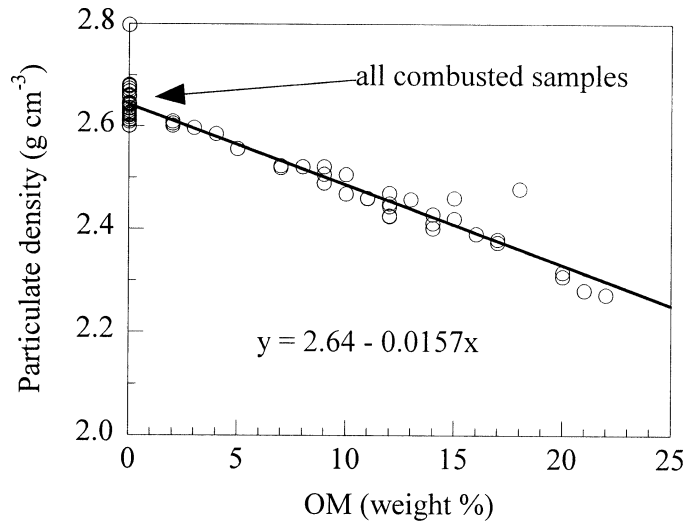


Fig. 4. Correlation between bulk sample density and OM content with OM (weight percent) determined by loss on ignition (x), and combusted sample density estimated from sample volume estimates (y). We assume all combusted samples have 0% OM.

to 2.51 g cm^{-3} , but thereafter remained nearly constant at 2.60 g cm^{-3} .

Channel bank: The CB_u substrate averaged $2.58 \pm 0.02 \text{ g cm}^{-3}$ and was significantly higher than the CBF_u average of $2.45 \pm 0.03 \text{ g cm}^{-3}$. CBF_u densities ranged from 2.40 to 2.51 g cm^{-3} with no systematic variation (Fig. 3B). Conversely, time series of CBF_c particulate density showed a nearly steady response of $\sim 2.63 \text{ g cm}^{-3}$.

The CBSW_u densities ranged from 2.37 to 2.52 g cm^{-3} with an average of $2.47 \pm 0.055 \text{ g cm}^{-3}$, significantly lower than the substrate. Also, the time series exhibited an increasing trend from 2.39 to 2.52 g cm^{-3} before settling to a near steady response at 34 min (Fig. 3B).

Overall, the density of inorganic particulate matter, represented by the combusted samples, ranged from 2.52 to 2.68 g cm^{-3} . The average value of these samples ($2.63 \pm 0.026 \text{ g cm}^{-3}$) is within the range of quartz and kaolinite, two common minerals in estuarine mud. Conversely, the uncombusted samples averaged $2.40 \pm 0.079 \text{ g cm}^{-3}$. Moreover, the bulk average uncombusted particulate density was highly correlated ($r^2 = 0.96$) with the OM content (Fig. 4), indicating that variations in OM content control the bulk density of sediment samples. The particulate densities from the CBF_u site were significantly higher than the LMF_u sites, which could be caused by the preferential deposition of higher density sediments near the channel bank or levee, typically associated with recurrent marsh inundation. As expected from the trends in OM content (Fig. 2), bulk average particulate densities increased with time at the SW plots, but not at the FW plots (Fig. 3).

Particulate density: Organic matter—We estimated OM density with the relationships between inorganic (combusted) and bulk particulate (uncombusted) density expressed in Eq. 1. Based on these calculations, the OM density from the

Table 3. Density (ρ) of uncombusted (u), combusted (c), and OM samples (g cm^{-3}).

	HM _{substrate}	LMFW	LMSW	LM _{substrate}	CBFW	CBSW	CB _{substrate}
ρ_u							
Mean	2.61	2.33	2.37	2.40	2.45	2.47	2.58
SD	0.004	0.041	0.090	0.015	0.033	0.055	0.021
<i>n</i>	3	16	6	2	16	12	3
ρ_c							
Mean	2.65	2.64	2.60	2.65	2.63	2.64	2.68
SD	0.011	0.024	0.038	0.039	0.015	0.017	0.0068
<i>n</i>	3	16	7	2	16	12	3
ρ_{OM}							
Mean	1.39	1.59	1.75	1.57	1.63	1.66	1.46
SD	0.148	0.081	0.211	0.08	0.054	0.026	0.021
<i>n</i>	3	16	6	2	16	12	3

eight substrate samples ranged from 1.22 to 1.62 g cm^{-3} with averages of 1.39, 1.57, and 1.46 g cm^{-3} at the HM, LM, and CB sites, respectively (Table 3). The OM densities of the LMFW and CBFW sites are significantly different from all others.

Low marsh: Time series of LMFW OM density ranged from 1.51 to 1.82 g cm^{-3} , fluctuating about a mean of 1.59 \pm 0.081 g cm^{-3} (Fig. 5A). From 0 to 20 min, most OM densities were lower than the substrate OM density, but from 20 to 60 min, densities were generally higher. The OM densities found in LMSW samples show a clear and significant increase with time, going from 1.52 to 1.90, and averaging 1.75 \pm 0.21 g cm^{-3} (Fig. 5B). This clear increase did not occur in the other OM density time series.

Channel bank: The CBFW OM density time series fluctuated about a mean of 1.63 \pm 0.054 g cm^{-3} , with a range of 1.50–1.72 g cm^{-3} (Fig. 5B); the fluctuations showed no consistent trend. CBSW OM densities were less variable, ranging between 1.61 and 1.68 g cm^{-3} with a mean of 1.66 \pm 0.026 g cm^{-3} (Fig. 5B). Also, the OM densities from the CB, FW, and SW plots were significantly higher than the CB substrate average of 1.46 \pm 0.021 g cm^{-3} . Comparing Figs. 3 and 5 shows that SW irrigations produced increasing trends in particulate density and OM density in three of four plots, CBSW being the exception (Fig. 5).

OC and N analyses—Low marsh: The OC content in the LMFW samples was 7–9% (Table 4). These values were at least 14 times greater than the substrate composition. The LMFW N content was between 0.58 and 0.66%, whereas the substrate was significantly lower at 0.03%. Therefore, both OC content and N content in runoff sediment were greater than the substrate by a factor of \sim 13. The C:N ratios of

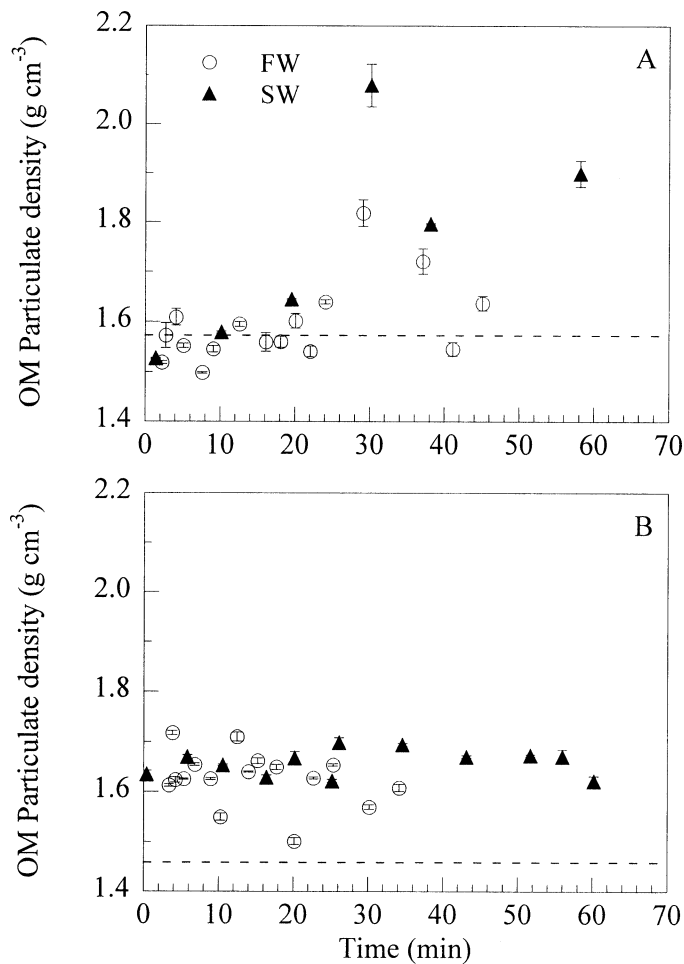


Fig. 5. Calculated particulate OM density from Eq. 1; (A) low marsh plot, (B) channel bank plot. The dashed horizontal lines depict average uncombusted substrate density. Note that the range on the density axis is 0.8 to facilitate comparison between figures.

Table 4. C and N elemental data.

	LMFW	LM _{substrate}	CBFW	CB _{substrate}
OC (wt %)				
Mean	7.7	0.6	3.4	1.5
SD	0.3		0.7	
ON (wt %)				
Mean	0.61	0.03	0.28	0.10
SD	0.04		0.07	
C:N (atomic)				
Mean	14.8	21.1	14.2	17.3
SD	0.6		0.9	
<i>n</i>	4	1	3	2

mobilized sediments were 14–15 (Table 4). In contrast, the substrate sediments were characterized by higher C:N ratios of 21. We did not analyze sediment from the SW plots in order to focus our efforts on evaluating the effects of natural rainfall on OC and N compositions. The LM OC and N concentrations averaged 279.7 ± 50.1 and 22.2 ± 4.7 mg L⁻¹ of runoff, respectively.

Channel bank: The OC content of CBFW samples ranged from 2 to 4% (Table 4). These values were approximately one half that for the LM sites but were still higher than the CB substrate range of 1.3–1.7%. The N content of CB sediments ranged from 0.21 to 0.36%, which was higher than the substrate content of 0.09–0.11% N. The C:N ratios of these samples ranged from 13 to 15 and were significantly lower than the substrate composition of 16–18. Although OC content and N content of the mobilized sediments varied between sites, the C:N ratios were not significantly different. The CB, OC, and N concentrations averaged 139.7 ± 94.0 and 11.8 ± 8.7 mg L⁻¹ of runoff, respectively. These values are significantly lower than the LM fluxes.

Based on the elemental data, there is little evidence that the trends in atomic C:N ratios are the result of ammonium incorporation into the mobilized sediments. For example, the measured N content and OC content of the 10 sediment samples analyzed show a strong linear correlation ($r^2 = 0.93$), with a positive intercept for OC at zero N content. This result is consistent with the idea that most of the N in these acid-treated samples is associated with organic matter and that there is little inorganic N present (Hedges et al. 1986; Goni and Thomas 2000).

Runoff sediment samples had higher OC content than the substrate and were within the 0.3–6.6% OC range measured by McCraith (1998) for the same region. The N content in runoff samples was also higher than in the substrate samples. The C:N ratios for runoff samples were lower than those for the substrate; therefore, the runoff sediment OM was compositionally different from that of the substrate. Although the total sediment concentrations in runoff from CBFW were an order of magnitude higher than those from LMFW, the OC concentrations were similar. This indicates that the rainfall-driven OC fluxes might be similar throughout the salt marsh.

Discussion

Physical controls on the cycling and residence time of sediment in marsh systems are important factors in carbon turnover and biogeochemical models. Moreover, physical processes controlling sediment accumulation and redistribution in the intertidal zone are typically assumed to have a marine origin. Here, we examine rainfall runoff as a type of terrestrial forcing on marsh sediment redistribution. Although the cycling effects of rainfall runoff can be considered short term, the cumulative effects of recurring short-term cycling events can produce physical and biogeochemical responses over longer temporal and spatial scales extending from the marsh, to estuaries, to the coastal ocean. Here, we examine low-tide, intertidal-zone rainfall

effects on sediment, carbon, and nutrient cycling because these effects are not well constrained.

Mobilization of organic matter—A comparison of Figs. 1A and 2B shows that variability in sediment concentration can produce a response in OM content, but not always. For example, asymptotic declines in Fig. 1 are not apparent in Figs. 2, 3, or 5; hence, an approximate fivefold decrease in concentration has negligible effect on OM content and density. Also, flood irrigations, with sediment concentrations approximately three orders of magnitude lower, entrained sediment with OM content greater than or equal to OM content of the substrate. Together, these observations suggest that the readily mobile fraction of marsh sediment is enriched in OM relative to the bulk composition of the substrate, thereby giving rise to a lower particulate density. Also, these data show that rainfall runoff processes deplete the substrate of OM. This preferential OM removal might have been facilitated by a combination of its lower density and dispersal by raindrop impact. We propose that this OM entrainment mechanism could account for the large OM increases observed in marsh channels during and after rainstorms (Oertel 1976; Chalmers et al. 1985).

Comparing the saltwater and freshwater responses yield further insight into sediment entrainment processes. The OM content response to saltwater irrigation (Fig. 2) shows a prolonged decline with time, whereas the freshwater response attains a uniform OM content relatively quickly. Conversely, the uncombusted density response to salt water (Fig. 3) shows a general increase with time, whereas the freshwater response shows irregular variability within some uniform range. These observations indicate that rainfall produces an ample supply of OM for transport, but the presence of salt water could promote flocculation following mobilization. Such a process is consistent with an observed decrease in OM content (Fig. 2) and the increasing density measured with time (Fig. 3). Hence, tidal inundation is less likely to facilitate OM removal from the marsh surface to the extent that rainfall runoff does.

Mobilization of OC and N—The elemental analyses show that mobilized sediments are significantly enriched in OC and N relative to the substrate (Table 4). For example, mobilized sediment samples were composed of 2–8% OC and 0.2–0.7% N. This was higher than the substrate values, which were 0.5–1.7% OC and 0.03–0.1% N. These observations indicate that low-tide rainfall could be an important mechanism affecting the removal or redistribution of OC and N. The data and analyses also show that residence time estimates and biogeochemical models of OC and N in the intertidal zone must account for the effects of low-tide rainfall export and redistribution.

Mobilized sediments were characterized by C:N ratios of ~14, whereas substrate sediment C:N ratios were >18. Although we observed differences between substrate C:N ratios from the LM and CB sites, the C:N ratios of mobilized sediment samples were not significantly different. We interpret this observation as evidence for the similarity in the type and source of mobilized OM from different parts of the salt marsh. Sediment from the CB *S. alterniflora* zone had

a higher OC and elemental N than the unvegetated lower half of the CB plots. Despite having a *S. alterniflora* zone with more OM, the difference in C:N ratios is negligible. This indicates that the lower and upper halves of the channel bank derive substrate OM from similar sources. The lower C:N ratios of the mobilized sediment are consistent with a mixed algal (C:N \approx 6.6) and *S. alterniflora* (C:N > 20) source of OM. Further analyses are needed to better define the sources and composition of the OM entrained by rainfall onto exposed marsh surfaces.

We also estimated rates of OC and N mobilization for the rainfall experiments. The results indicate a flux of 30 g C m⁻² h⁻¹. This represents 3–20% of salt marsh primary production as reported by Hatcher and Mann (1975), or 9–30% of annual benthic microalgal production in the vegetated zone at North Inlet (Pinckney 1992). Therefore, low-tide rainstorms, subsequent runoff, and sediment entrainment could be an important mechanism for the removal and redistribution of OM, C, and N in the salt marsh. Our main finding indicates that low-tide rainfall events result in the redistribution of OM-rich particulates with low C:N ratios that differ from the bulk sediment properties. Hence, rainfall events deplete marsh surface sediment of organic matter and nutrients.

References

- ANDERSON, F. E., AND L. M. MEYER. 1984. Seasonal and spatial variability of particulate matter of a muddy flood front. *Sedimentology* **31**: 383–394.
- BOOKER, F. A. 1989. Landscape and management response to wildfires in California. Master's thesis, Univ. of California, Berkeley.
- CHALMERS, G. C., R. G. WIEGERT, AND P. L. WOLF. 1985. Carbon balance in a salt marsh: Interactions of diffusive export, tidal deposition and rainfall-caused erosion. *Estuar. Coast. Shelf Sci.* **20–21**: 757–771.
- CORRELL, D. L. 1981. Nutrient mass balances for the watershed, headwaters, intertidal zone, and basin of the Rhode River estuary. *Limnol. Oceanogr.* **26**: 1142–1149.
- DAME, R. F., AND P. KENNY. 1986. Nutrient processing and the development of tidal creek ecosystems. *Mar. Chem.* **43**: 175–183.
- GONI, M. A., AND K. A. THOMAS. 2000. Sources and transformations of organic matter in surface soils and sediments from a tidal estuary (North Inlet, South Carolina, USA). *Estuaries* **23**: 548–564.
- HATCHER, B. G., AND K. H. MANN. 1975. Above-ground production of marsh cord grass (*Spartina alterniflora*) near the northern edge of its range. *J. Fish Res. Board Can.* **32**: 83–87.
- HEDGES, J. I., AND J. H. STERN. 1984. Carbon and nitrogen determinations of carbonate-containing solids. *Limnol. Oceanogr.* **29**: 657–663.
- , W. A. CLARK, P. D. QUAY, J. E. RICHEY, A. H. DEVOL, AND U. DE M. SANTOS. 1986. Compositions and fluxes of particulate organic material in the Amazon River. *Limnol. Oceanogr.* **31**: 717–738.
- HOWARD, P. J. A., AND D. M. HOWARD. 1989. Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. *Biol. Fertil. Soils* **9**: 306–310.
- MCCRAITH, B. J. 1998. The distribution and dynamics of fiddler crab burrowing and its effect on salt marsh sediment composition and chemistry in a southeastern salt marsh. Ph.D. dissertation, Univ. of South Carolina.
- MWAMBA, M. J. 2001. Rainfall enhanced sediment entrainment in the intertidal zone, North Inlet, SC, USA. Master's thesis, Univ. of South Carolina, Columbia.
- , AND R. TORRES. 2002. Rainfall effects on marsh sediment redistribution, North Inlet, South Carolina. *Mar. Geol.* **189**: 267–287.
- OERTEL, G. F. 1976. Characteristics of suspended sediments in estuaries and nearshore waters of Georgia. *Southeast. Geol.* **18**: 107–118.
- PINCKNEY, J. L. 1992. Ecology of intertidal benthic microalgal communities in North Inlet Estuary, South Carolina. Ph.D. dissertation, Univ. of South Carolina.
- SCHLESINGER, W. H. 1977. Carbon balance in terrestrial detritus. *Annu. Rev. Ecol. Syst.* **8**: 51–81.
- SETTLEMEYER, J. L., AND L. R. GARDNER. 1975. Low tide storm erosion in a salt marsh. *Southeast. Geol.* **16**: 205–212.

Received: 24 July 2002
Accepted: 3 December 2002
Amended: 2 January 2003