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Seasonal Variations in Sedimentation and Organic Content in Five Plant Associations on a Chesapeake Bay Tidal Freshwater Delta

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Research on sedimentation processes in tidal freshwater marshes is lagging far behind that for salt marshes despite the importance of tidal freshwater systems for understanding impacts of watershed land use on estuarine habitats and water quality. From September 1996 to November 1997, biweekly sedimentation rates were monitored at 30 sites spanning 5 distinct habitat types across the intertidal zone of the tidal freshwater delta at the head of the Bush River tributary to upper Chesapeake Bay. These data were used to determine the spatio-temporal dynamics of sedimentation and erosion in the delta as well as the role of vegetation in seasonal to interannual physical processes. The observed mean net sedimentation rate was $1{\cdot}00\ \mathrm{g\ cm^{-2}\ yr^{-1}}$, with a range of $-74{\cdot}15$ to $145{\cdot}2\ \mathrm{g\ cm^{-2}\ yr^{-1}}$. No relations between delta sedimentation rate and total precipitation, peak precipitation intensity, or watershed discharge were found over time. Instead, three distinct temporal regimes in the data predominantly reflected seasonal patterns in vegetation life cycle. With regard to spatial patterns, nonparametric statistical tests demonstrated that each habitat had a unique cycle of sedimentation and erosion. When sedimentation rates were multiplied by habitat area, the floating leaf habitat was found to have sequestered $6370\ \mathrm{t\ yr^{-1}}$. In contrast, the high marsh lost $624\ \mathrm{t\ yr^{-1}}$. These data indicate that the greater diversity of plant species in tidal freshwater marshes generates a wider variation in geomorphic processes than is possible for salt marshes.

Keywords: tidal freshwater wetlands; marsh sedimentation; organic content; delta sediment processes; Chesapeake Bay

Introduction

Extensive fieldwork has been conducted over the last decade to develop an understanding of tidal salt marsh sedimentation and accretion. A wide variety of techniques has been used to carry out this work, including sediment cores (Nydick *et al.*, 1995; Anisfeld *et al.*, 1999), marker horizons (e.g., Wood *et al.*, 1989; Stoddart *et al.*, 1989), stage rods (Yang, 1998), sedimentation-erosion tables (e.g., Cahoon *et al.*, 1995; Childers *et al.*, 1993), filter paper (e.g., Reed, 1989; Leonard, 1997), buried metal plates (Allen & Duffy, 1998), and triangular stake arrays (Allen & Duffy, 1998). The outcome of tidal salt marsh research has been the quantification of rates, patterns, and mechanisms of marsh morphodynamics. For example, several investigators, including Letzsch and Frey (1980), Reed (1989), and Leonard (1997), have shown that tidal salt marshes exhibit seasonal cycles in sediment deposition which are responses to changing hydrology and sediment supply. Many researchers have used a variety of statistical methods to relate sedimentation patterns to vegetation growth (Eisma & Dijkema, 1997), marsh geometry (Stoddart *et al.*, 1989), wind forcing (Allen & Duffy, 1998), and more. Friedrichs and Perry (in press) recently reviewed this extensive literature and indicated that there now exists a strong understanding of the dynamic equilibrium among sediment supply, vegetative growth, and relative sea level for tidal salt marshes.

In sharp contrast to tidal salt-marsh sedimentation and accretion processes, similar questions about tidal freshwater marshes have received far less attention. Whereas salt-marsh research is largely driven by management issues relating to sea-level rise, the landscape position of tidal freshwater marshes makes them ideal for studying the impacts of watershed land use on estuarine habitats and water quality. For example, Pasternack *et al.* (in press) modelled marsh habitat

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succession in response to extreme rates of watershed sediment loading and Knight and Pasternack (2000) presented geochemical data illustrating how a tidal freshwater marsh acts as a critical buffer protecting upper Chesapeake Bay from metal pollution. Also, the difference in landscape position necessitates a different geomorphic emphasis. Instead of assessing marsh accretion and elevation change over monthly to decadal time scales, which is critical to explaining sea-level rise in salt marshes, the focus in many tidal freshwater systems should be on the short term processes of surficial particulate deposition and erosion which control delta evolution (Fowler, 1957; Miall, 1979; Syvitski *et al.*, 1988; Pasternack *et al.*, in press).

The existing literature on sedimentation processes in tidal freshwater marshes stems from a few thorough case studies. Serodes and Troude (1984) used vertical stakes and subsequently anchored aluminium plates to monitor monthly sediment deposition and erosion in a marsh fringing the St. Lawrence Estuary. They reported two erosional periods during May and in October–November, with a period of rapid deposition in between. In that system, vegetation growth cycles and snow geese played important roles in controlling net deposition.

Coring and suspended sediment flux studies of tidal freshwater marshes in upper Delaware River were conducted by Orson *et al.* (1990, 1992). This research showed that tidal freshwater marshes may be formed entirely as a result of inorganic sedimentation induced by changes in land use. Also, a conceptual model for seasonal cycles of sedimentation and erosion was hypothesized, but no data were available to corroborate it.

Tidal freshwater marshes downstream of urbanizing basins in Chesapeake Bay tributaries have been studied for indications of watershed–estuary interactions. Khan and Brush (1994) and Hilgartner (pers. comm.) found that Jug Bay marsh on Patuxent River and Otter Point Creek marsh on Bush River, respectively, both formed in response to historic land clearance. Prior to 1600 A. D. both systems were deepwater habitats with submerged aquatic vegetation; today these areas are forests and marshes. Recently, Pasternack *et al.* (in press) went a step further and used data from sediment cores to calibrate an inverse boundary value model of tidal freshwater delta evolution that is capable of quantifying the impact of historic land-use change on sediment loadings and resulting habitat succession at Otter Point Creek.

New field studies have generated important results on short-term tidal freshwater marsh sedimentation processes. Pasternack and Brush (1998), Knight and Pasternack (2000), and Pasternack *et al.* (2000) monitored inorganic, organic, and toxic metal erosion and deposition in a small marsh in the Bush River tributary of upper Chesapeake Bay. These studies identified sources, transport pathways, and spatio-temporal distributions of sediment as well as seasonal to interannual geomorphic controls on sedimentation. Coops *et al.* (1999) also monitored sedimentation dynamics in a tidal freshwater system, and focused on the role of wind and tidal processes at the channel-marsh surface interface. Finally, Constantine (pers. comm.) studied sedimentation in a pristine tidal freshwater marsh in lower Chesapeake Bay and observed sedimentation processes similar to those reported by Pasternack and Brush (1998).

Despite these very recent developments in research on tidal freshwater marshes, there still is a dearth of data on surficial sedimentation and erosion processes, especially for larger systems. In many instances in Chesapeake Bay, tidal freshwater marshes may constitute the entire intertidal zone of an estuarine delta such as at the heads of branches of Elk River, Bohemia River, Sassafras River, and Bush River. For Gulf coast estuaries, tidal freshwater marshes are an important component among a mosaic of wetland types on each delta. In the research reported in this paper, field monitoring across the entire vegetated intertidal zone of the delta at the head of Bush River, Maryland, was conducted to determine the spatio-temporal dynamics of sedimentation and erosion on a vegetated delta and the role of vegetation, if any, in the delta's seasonal to interannual physical processes. To identify mechanisms responsible for delta evolution, sedimentation and erosion time-series data collected in the intertidal zone were assessed for nonrandom cycles, seasonal variations within and among habitats, habitat-stratified total loadings, and relationships with precipitation, watershed runoff, and vegetation growth cycles using multiple types of data analyses. Other geological and biological processes responsible for elevation change at a site over years to centuries are not considered in this paper.

Materials and methods

Study site

The Otter Point Creek tidal fresh water delta (OPC) at the head of Bush River in upper Chesapeake Bay (Figure 1) has been the focus of an interdisciplinary research programme addressing ecological, paleoecological, geomorphic, and geochemical issues relevant to Chesapeake Bay management (Hilgartner,

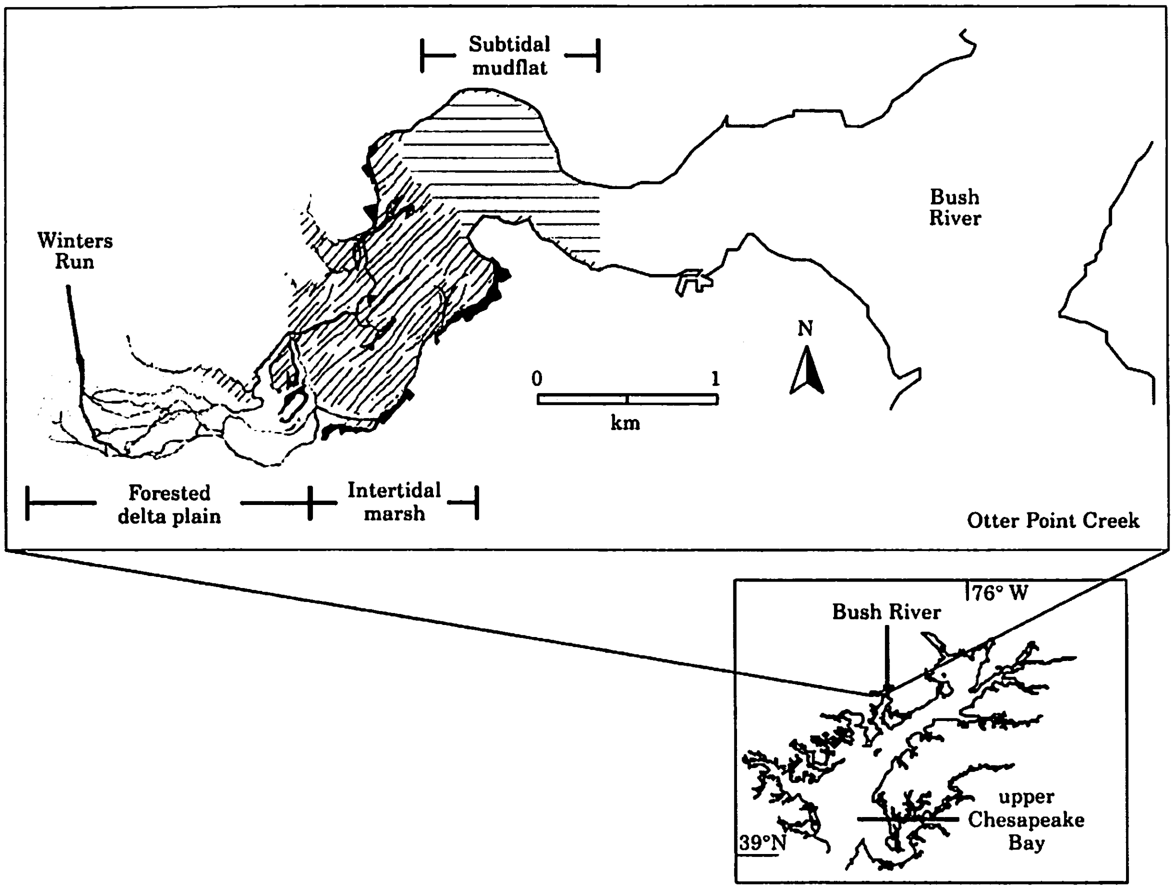

FIGURE 1. Map showing the location and geomorphic zonation of the Otter Point Creek delta at the head of Bush River in upper Chesapeake Bay.

pers. comm.; Pasternack & Brush, 1998; Pasternack *et al.*, 2000; Knight & Pasternack, 2000; Pasternack *et al.*, in press). The delta consists of a 54.4-ha forested delta plain, an 84-ha intertidal marsh, and a large subtidal mudflat. Historic land clearance and land use prior to dam building in the late 1930s is responsible for a 7.5 times increase in delta size relative to pre-settlement conditions (Pasternack *et al.*, in press). Ecological succession associated with long-term delta progradation has been thoroughly documented by Hilgartner (pers. comm.). Data from this paleoecological study served as an important guide for designing the conceptual framework underlying the overall research programme.

To assess seasonal variations in sedimentation on the OPC delta, monitoring was carried out during a 60-week period from 6 September 1996 to 30 October 1997. Thirty sites spanning five distinct habitat types were selected from a very large area across the delta for intensive monitoring (Figure 2). All sites were accessed by canoe via channels and then walking along designated trails. Care was taken not to disturb soils or vegetation in the vicinity of study sites. Because of the marsh's fragility and the need for systematic accessibility to study sites during the ~4-hour low tide period, neither a completely random nor square grid sampling scheme could be used. Since the area covered was far too large to construct boardwalks, 23 of the sites were placed along randomly located transects established in a 1991–1992 comprehensive vegetation mapping study (Hilgartner, pers. comm.; Pasternack *et al.*, 2000). One of these sites (5-P7) was lost due to distributary bank erosion during a storm. The other seven sites were located in predetermined plant associations at randomly selected sites to generate more samples in those plant associations. Detailed procedures for measuring each variable and parameter described below are provided in Pasternack and Brush (1998), and Pasternack *et al.* (2000).

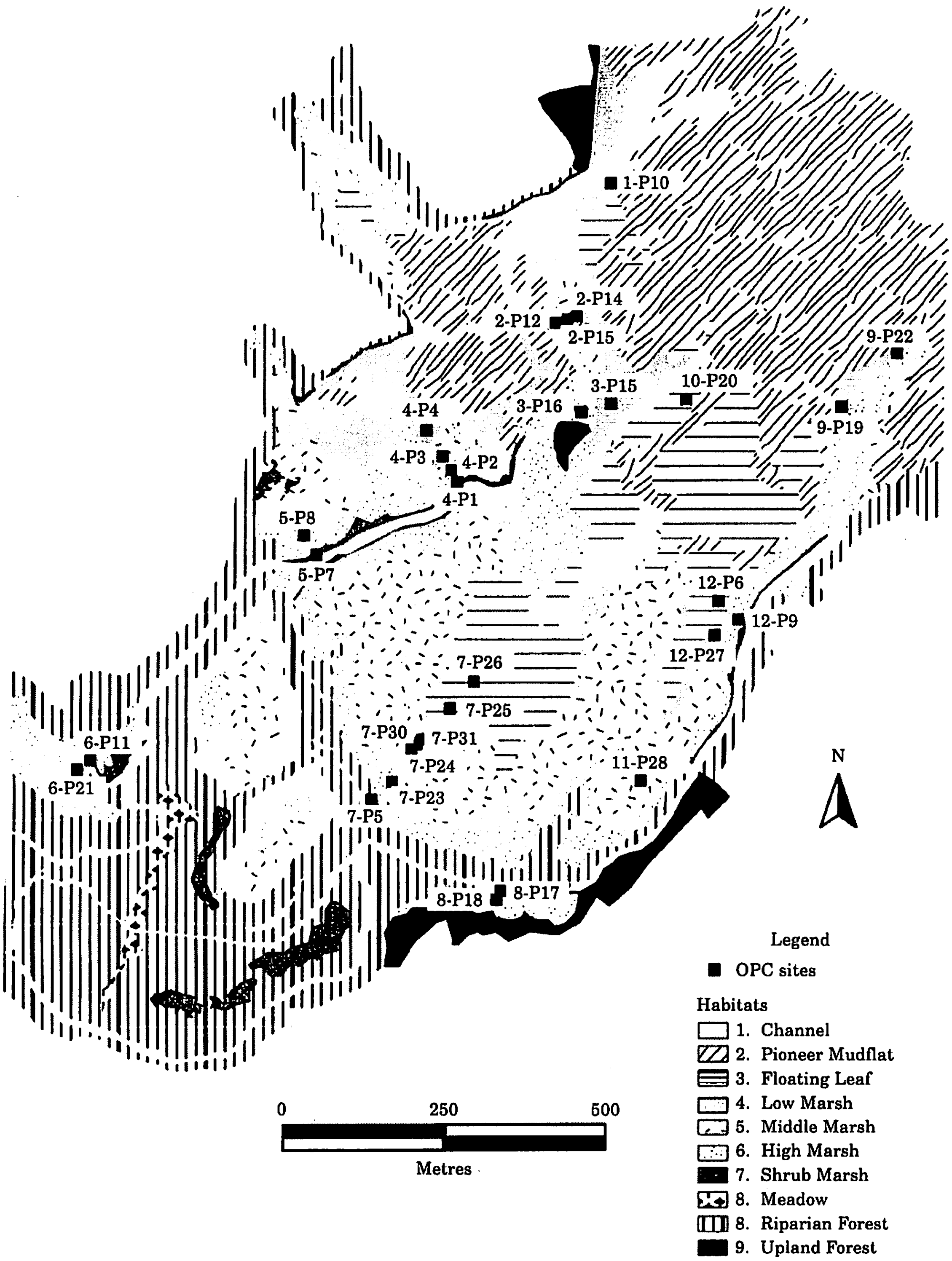

FIGURE 2. Map of the intertidal zone of the OPC delta showing habitats and study sites (■).

Biweekly sediment monitoring

Pasternack and Brush (1998) described an ' anchored tile ' method for monitoring sedimentation and erosion which is well suited for deltas experiencing significant spatial and temporal variability in transport processes. According to this approach, lightweight 1·22 m × 2·5 cm dia. (4′ × 1″) aluminium rods are sunk into the ground and capped with a detachable 20 × 20 cm (8 × 8″) ceramic tile flush with the marsh surface, as identified during low tide when the surface is exposed and there is no ponded water or fluidized mud layer present. Anchor rods are so firmly embedded into the soil that they are difficult to move or adjust by hand once installed. As OPC vegetation and sediment is not subjected to ice ' grazing ' or heaving, a force imposed by ice cannot lift the anchors. The detachment mechanism involves gluing a 5 cm long acrylic tube with a 2·5 cm inner diameter to the bottom of each tile. The ceramic tile/acrylic tube assembly caps the anchor rod and is not susceptible to motion unless subjected to extreme hydraulic lift forces.

The anchored tile at each of the 30 sites was visited once every 2 weeks during low tide and all accumulated materials on a tile were collected into pre-washed, pre-weighed glass jars. During the winter months, sampling was prevented because tiles were frozen into the marsh. Sedimentation rates were averaged over the last collection date in autumn and the first collection date after thawing. Tiles in areas of rapid accretion were raised by filling in their underlying acrylic tubes to maintain a position at the marsh surface. Surface samples adjacent to each tile were collected and analyzed for bulk density using the method of Pasternack and Brush (1998). While in the field, biweekly erosion was determined by measuring the height of each tile edge and the anchor rod above the marsh surface, averaging the measurements, and multiplying by bulk density. Local scour induced by tiles was observed to be negligible for all sites. Other potential sources of elevation change within the 1·22 m span of the anchor rod which might mimic erosion over long time scales, such as compaction due to respiration of organics or sediment consolidation, may be neglected due to their insignificance at the biweekly time scale. Respiration rates must be extremely low from November through March due to the cold and freezing climate. No sediment consolidation is possible when the marsh is frozen. Potential effects of compaction during the other seasons were considered on a site by site basis where erosion was significant, and those results are reported below.

Sediment samples were returned to the laboratory and processed to obtain wet weight, dry weight, water content, organic content, and deposition rate. When both erosion and deposition were evident, the two methods were combined to obtain a net sedimentation rate. Biweekly net sedimentation rates (g cm^{-2} 2 weeks^{-1}) were converted into annual rates (g cm^{-2} yr^{-1}) by simple multiplication by a constant (365/14) to facilitate comparison with other studies where different methods and different sampling intervals are used. However, biweekly values are not necessarily representative of the average annual deposition at a site, so care should be used in interpreting individual data points. Organic content is reported as percent weight loss-on-ignition using the method of Pasternack and Brush (1998).

Rainfall data

Letzsch and Frey (1980) reported that seasonal erosion on a salt marsh was not influenced by rainfall intensity, but it was important to verify that result for the case of biweekly erosion in the tidal freshwater setting. Because the marsh surface may have been exposed to rainfall erosion during the brief period of low tide at some sites where vegetation was sparse during some periods of the year, hourly precipitation data was obtained from a nearby station for comparison against biweekly sedimentation and erosion data. The precipitation data comes from a National Weather Service long-term weather station at Phillips Army Air Field in the U.S. Army Aberdeen Proving Ground, which is 10 km west of OPC. Hourly precipitation during the study period was recorded in increments of 2·54 mm (0·1″) at the station. The total number of days when precipitation occurred was determined from the Phillips record, whereas the number of sediment sampling days when precipitation occurred was determined by direct on-site observation. As rainfall erosivity is known to be directly proportional to rainfall intensity (Lal, 1988), the exceedence probability of peak hourly rainfall intensity was calculated, generating an estimate of the potential for erosion. Because water level was not monitored at every site, it was not possible to determine whether a tile was even exposed during these precipitation events, though low tide exposure typically lasts for only ~4 h in the open water zone (Pasternack, unpublished data). Also, most tiles were under the vegetation canopy, further reducing the likelihood of significant soil erosion. To test the significance of rainfall-induced erosion at the biweekly to interannual time scales, total biweekly and peak biweekly precipitation were correlated against net sedimentation on a site-by-site basis. The F-value and resulting P-value were used as an overall F test of the relationship between net sedimentation and each independent variable.

Watershed runoff data

Watershed total sediment load may directly contribute to intertidal sedimentation on a delta (Fowler, 1957; Poulos *et al.*, 1993). Because basin-derived suspended sediment load, and to a lesser extent bedload, are both related to watershed runoff by simple power laws ($Q_s = a\,Q^b$) without the need for monitoring total suspended sediment (Leopold & Maddock, 1953), streamflow is a very suitable indicator of the role of a basin in seasonal to interannual sedimentation and erosion cycles. Daily streamflow from Winters Run, the primary drainage entering OPC, was obtained from the United States Geological Survey Benson Road gauging station (No. 01581700) near Bel Air, Maryland, which encompasses 60% of the basin. Although it does not measure the entire flow entering OPC, the Benson Road station captures the majority of it and represents the timing of discharge events in the basin. Adjusting flow for basin area would not improve the temporal analyses performed in this study. To test the significance of watershed runoff in redistributing sediment at the biweekly to interannual time scales, runoff was correlated against the envelope of the raw sedimentation data and the F-value and resulting P-value were obtained.

Vegetation survey

Herbaceous vegetation at OPC was surveyed in June 1997 using 1-m^2 quadrats located 1 m from sediment monitoring stations. The methodology was the same as in Pasternack *et al.* (2000). It involved estimating cover by counting presence of each species within each square decimeter of a quadrat (Mueller-Dombois & Ellenberg, 1974). Taxonomy followed Fernald (1970). Once species distributions were determined for each site, the data were used to identify plant associations and marsh habitats at a site according to the OPC vegetation classification scheme of Pasternack *et al.* (2000). The marsh habitat designations in this classification system are aligned along an environmental gradient which is strongly correlated with elevation, but also accounts for a wide range of interdependent biological, hydrological, and geomorphic factors, as expressed in the abundance and distribution of actual tidal freshwater marsh plant species populations.

Two sets of analyses were performed to assess the role of vegetation in the spatio-temporal variability of sediment deposition. The first involved stratifying sedimentation rates and organic content by habitat and assessing within- versus among-habitat dynamics during each of the three distinct seasonal regimes apparent in the raw data using box and whisker plots. For each habitat's box plot, a horizontal line through the box indicates the median value. The box top delineates the upper quartile (point halfway between median and maximum), while the box bottom delineates the lower quartile (point halfway between median and minimum). Whiskers are located at 1·5 times the interquartile distance (distance between upper and lower quartiles) beyond the limits of the upper or lower quartiles. Circles are outliers beyond the whiskers.

The second set of analyses involved averaging data from sites within the same habitat for each two-week sampling period and statistically testing hypotheses about the biweekly variations. To determine which observed variations were nonrandom cycles, the u test of randomness for runs above and below the median was applied to each time series (Freund & Simon, 1991). To test whether data were significantly different among marsh habitats, non-parametric statistics were used. This involved ranking data and then analyzing rankings. These tests were applied in place of statistical tests such as ANOVA because the data did not conform to the null hypothesis which required the standard deviations of each habitat's data to be the same (Till, 1974). Non-parametric statistics require data to be random, but it will be shown that some of the data sets were nonrandom. To solve this and to emphasize the relative roles of plant associations among habitats, only values from the mid-June to mid-November 1997 regime were used in this analysis, thus enabling the data to fit the null hypothesis requiring it to be random in time.

Results

Biweekly monitoring data

Biweekly net sedimentation rates measured at OPC ranged from $-74{\cdot}15$ to $145{\cdot}2\ \mathrm{g\,cm^{-2}\,yr^{-1}}$ [Figure 3(a)]. Negative net sedimentation rate values mean that the site eroded during the sampling period. Fifty-nine percent of measured values fell between 0 and $2\ \mathrm{g\,cm^{-2}\,yr^{-1}}$, with a mean of $1{\cdot}0\ \mathrm{g\,cm^{-2}\,yr^{-1}}$ and a median of $0{\cdot}07\ \mathrm{g\,cm^{-2}\,yr^{-1}}$. These rates correspond to 15·3 g and 1·0 g of material deposited per tile per two weeks, respectively, indicating a net growth for the intertidal zone of the delta over the 60-week study period, assuming all data are from the same statistical population, which is not the case.

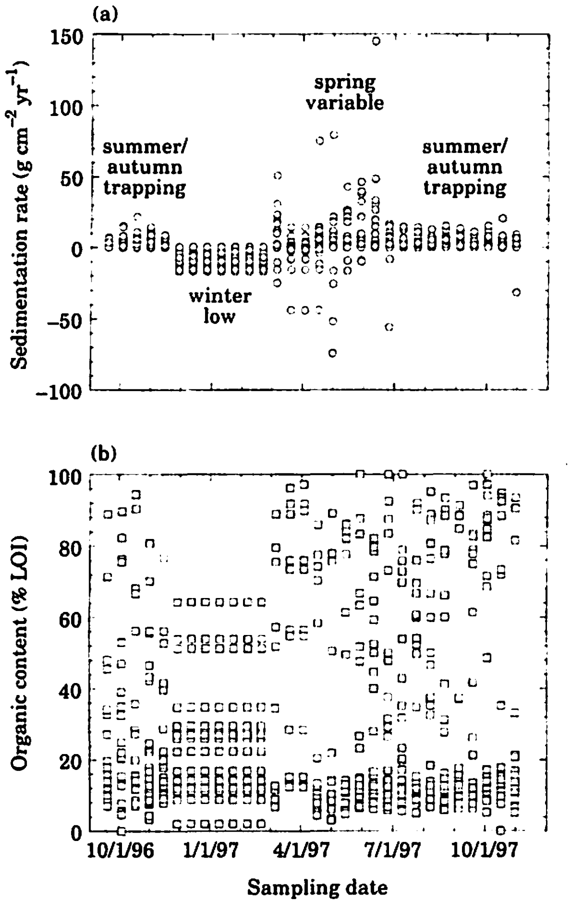

FIGURE 3. Raw biweekly (a) net sedimentation rate and (b) organic content data for a 60-week period at OPC that only show seasonal differences for the former. n=30 for each sampling date.

When the 60-week net sedimentation was calculated, only four sites out of 30 showed net erosion, with two occurring in the low marsh and two in the high marsh. All sites experienced the majority of their erosion in winter when respiration was negligible. In the remaining cases biweekly erosion was both preceded and followed by net sedimentation. This is inconsistent with a compaction-based mechanism that would occur gradually through time. Sites 9-P19 and 9-P22 are frontal sites on one of the delta's middle ground bars (Figure 2). Sediments at these sites had the highest bulk densities and only 5–7% organic content, leaving virtually no potential for compaction by consolidation or respiration. Grain size analyses of the inorganic fraction at these sites (Pasternack, pers. comm.) revealed sand:silt:clay ratios of 67:21:21 and 42:33:25, respectively, thus further confirming the limited opportunity for compaction. Given the frontal location of these sites and their observed exposure to wind and waves, it is most likely that the net elevation change was due to wind-wave scour of the fines. Sites 4-P2 and 3-P16 are high marsh sites with 25–35% organic content and a ~4:48:48 sand:silt:clay ratio. Once again, organic content is too low for compaction to account for such high rates of elevation change. As fine sediments predominate, some consolidation may have occurred, but the high temporal variability of erosion and sedimentation is far more consistent with a physical redistribution mechanism.

Three distinct regimes are evident in OPC sedimentation. Low sedimentation rates or erosion characterized the period from mid-November to March, with little variability among sites. From March to mid-June sedimentation rates showed extreme spatial and temporal variability. From mid-June to mid-November there was spatial variability but little temporal variability.

Biweekly organic content averaged 32% and varied over the full range of 0–100%. Unlike the sedimentation rates, the raw organic content data showed no apparent seasonal variations [Figure 3(b)]. The rate of net organic deposition was obtained by multiplying the sedimentation rate by the organic fraction, and ranged from $-7{\cdot}69$ to $26{\cdot}39\ \mathrm{g\,cm^{-2}\,yr^{-1}}$. Once again, negative net deposition is equivalent to erosion. The mean rate of organic deposition ($0{\cdot}15\ \mathrm{g\,cm^{-2}\,yr^{-1}}$) was more than double the median ($0{\cdot}06\ \mathrm{g\,cm^{-2}\,yr^{-1}}$), indicating a skewed statistical distribution.

Plant associations

Among the 30 locations surveyed, four were in levee/shrub marsh, seven in high marsh, eight were in middle marsh, seven were in low marsh, and four were in floating leaf habitats (Figure 2). Most sites exhibited the same vegetation assemblages observed in those locations since 1991. Two sites on the north side of OPC (2-P15 and 4-P3) were in middle marsh areas affected by animal activity during the study. The only site not completely covered with vegetation was a low marsh site at the tip of the southernmost distributary channel (9-P19). That site had only 35% total cover, and was thus more like a mudflat. Similar to other tidal freshwater marshes around the world, the intertidal portion of the OPC delta comprises floating leaf and low marsh habitats that are virtually monospecific as well as sandy, dry levee and shrub marsh sites with as many as 24 identifiable species in 1 m^2.

Delta sedimentation versus precipitation

Precipitation only occurred on 91 of the 420 days of the study (22%). As precipitation on the day of

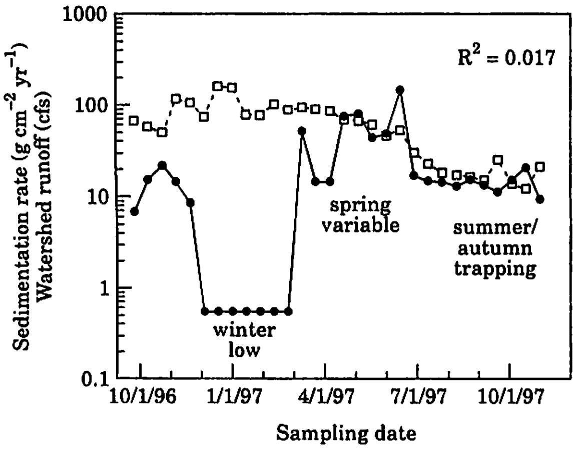

FIGURE 4. Time series of watershed runoff (□) and maximum sedimentation rate (●) showing no relation between the two variables.

sediment sampling only occurred once in 30 days (3%), recent rainfall erosion prior to sampling cannot explain any biweekly variation in observed net sedimentation rates. Of the days when precipitation did occur, peak hourly rates only exceeded 5, 13, and 18 mm hr^{-1} on 39, 8, and 2% of those occasions, respectively, indicating an overall low kinetic energy to drive soil erosion. When either total biweekly precipitation or peak hourly rainfall intensity during each 2-week period were correlated with observed biweekly net sedimentation at each site, no statistically significant relationship was found for any site ($P<0.0001$).

Delta sedimentation versus watershed runoff

When the envelope of the raw sedimentation rate data was plotted together with watershed runoff, no correlation was found (Figure 4). Biweekly sedimentation rates on the delta varied by ~2·5 orders of magnitude as a function of season, whereas runoff showed a gently decreasing trend over time. On some occasions sedimentation increased when runoff increased, but on other occasions the two were inversely related, yielding no significant correlation ($R^2=0.017$, $P<0.0001$).

Role of vegetation in seasonal variations

Spatio-temporal sedimentation regimes. When sites were stratified by habitat type, differences in within-habitat and among-habitat variability were found to depend on the stage of the vegetation growth cycle for the marsh. For the mid-June to mid-November regime, sedimentation rates showed a secular decrease along the environmental gradient [Figure 5(a),(d)]. The floating leaf habitat received the most material, with a mean of 9·29 g cm^{-2} yr^{-1}, whereas the levee/shrub marsh received the least, with a mean of 0·12 g cm^{-2} yr^{-1}. In 1996 there was little significant overlap among habitats, whereas in 1997 middle marsh, high marsh, and levee/shrub marsh sites showed complete overlap.

For the mid-November to March interval, all habitats eroded, with the magnitude of the erosion decreasing along the environmental gradient [Figure 5(b)]. The low marsh eroded the most, with a mean of − 8·74 g cm^{-2} yr^{-1}, whereas the levee/shrub marsh eroded the least, with a mean of − 2·32 g cm^{-2} yr^{-1}. Based on field observations during sediment sampling, erosion in the low marsh is apparently facilitated by the hummocky distribution of the roots of arrow arum (*Peltandra virginica*), the dominant

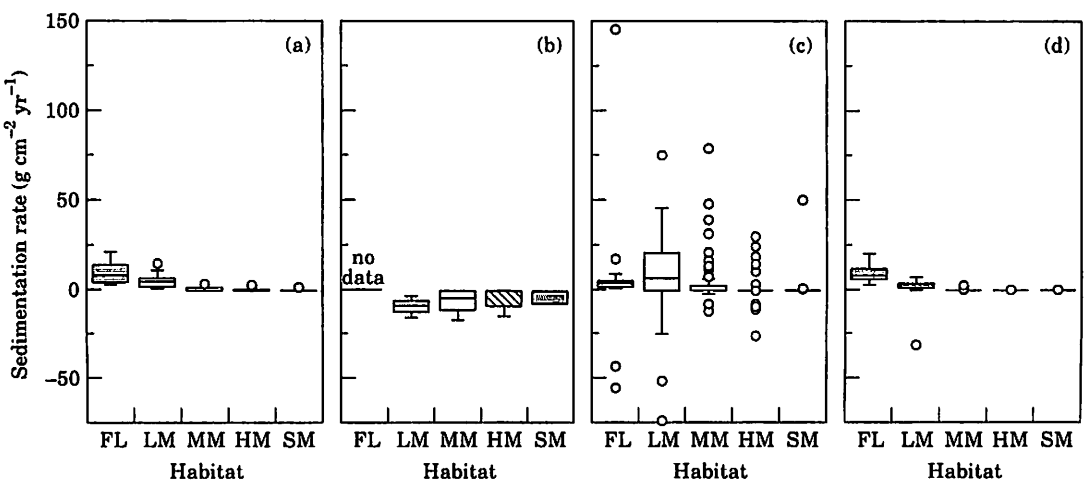

FIGURE 5. Box and whisker plot of habitat-stratified sedimentation rates for (a) September to mid-November 1996, (b) mid-November 1996 to Marsh 1997, (c) March to mid-June 1997, and (d) mid-June to mid-November 1997.

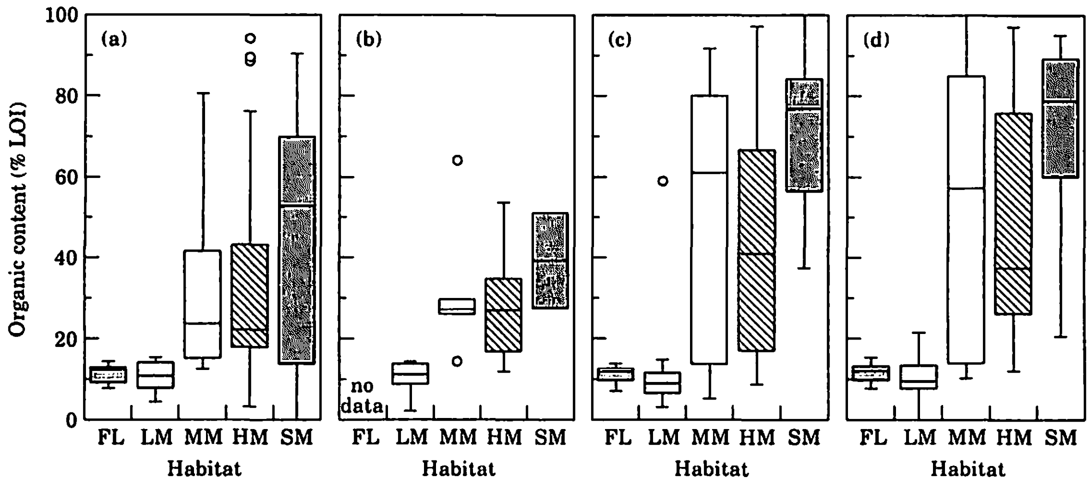

FIGURE 6. Box and whisker plot of habitat-stratified organic contents for (a) September to mid-November 1996, (b) mid-November 1996 to March 1997, (c) March to mid-June 1997, and (d) mid-June to mid-November 1997.

plant in this habitat. Erosion was observed to begin in the unconsolidated mud between hummocks and eventually proceeded to cut into the hummocks themselves.

From March to mid-June sedimentation rates showed extreme variability, as indicated by the large number of outliers [Figure 5(c)]. During this period within-habitat variability exceeded among-habitat variability. The maximum biweekly depositional rate of $145{\cdot}24\ \mathrm{g\ cm^{-2}\ yr^{-1}}$ occurred at site 10-P20 in a floating leaf area completely exposed to the subtidal delta front. The maximum biweekly erosion rate of $-74{\cdot}15\ \mathrm{g\ cm^{-2}\ yr^{-1}}$ occurred at site 1-P10 in a low marsh area adjacent to the northern distributary channel and also completely exposed to the subtidal delta front. These extreme events took place when little to no vegetation was present in those areas, so they are indicative of the scale of changes induced by physical processes when unhindered by biota.

In terms of organic content, all time intervals showed two distinct spatial patterns despite the five different plant associations represented (Figure 6). The first pattern was one of consistently low organic content that did not change through time or among sites within a habitat type. This pattern occurred in both the floating leaf and low marsh habitats, where inorganic sedimentation was so high and plant decomposition was visibly so rapid that *in situ* biotic processes had no influence on accretion. The second pattern was one of high organic content condition with highly variable within-habitat values. This pattern occurred in the middle, high, and levee/shrub marsh habitats. Despite the significant differences in plant species and abundances among these habitats, the overall low sedimentation rates in these habitats enabled the large array of local factors to generally outweigh habitat-controlled factors. As a result, there was large within-habitat variability. For all periods, the levee/shrub marsh had the highest organic contents, but the range of values in the middle and high marsh always matched that of the levee/shrub marsh. Examination of the organic material in the middle marsh showed that it primarily comprised dead stalks of cattails (*Typha angustifolia*) from adjacent plants. *Typha angustifolia* was one of the species whose dead stalks remained upright through most of the winter. Given the large areal extent of cattail-dominated middle marsh at OPC (Figure 2), it is surmised that this species significantly contributes to long-term accretion. As a result, the amount of organic deposition in the middle marsh exceeded that in the less widespread high marsh throughout all three depositional regimes.

Habitat-stratified sedimentation cycles

When sedimentation rates for sites of the same habitat were averaged for each two-week sampling period, significant temporal variations were evident for all habitats (Figures 7–9). Summary statistics for the habitat-stratified time series show that each habitat had a distinct average condition with a large standard deviation indicative of temporal variability (Table 1). The floating leaf habitat received the most material, whereas the high marsh actually eroded on average over the 60-week study. During early spring, the floating leaf habitat experienced six weeks (6 March–17 April 1997) of extreme erosion peaking at $-43{\cdot}77\ \mathrm{g\ cm^{-2}\ yr^{-1}}$ in mid-March (Figure 7).

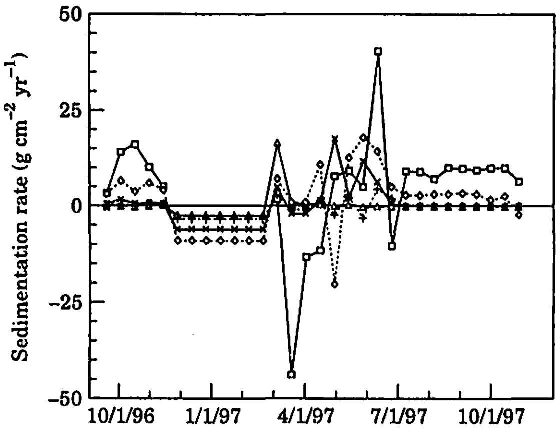

FIGURE 7. Habitat-averaged net sedimentation showed distinct temporal variations for each habitat. Winter values are averaged over a longer sampling period due to extreme field conditions. Floating leaf (—⊟—), low marsh (- -◇- -), middlemarsh (—×—), high marsh (- - + - -), levee (—△—).

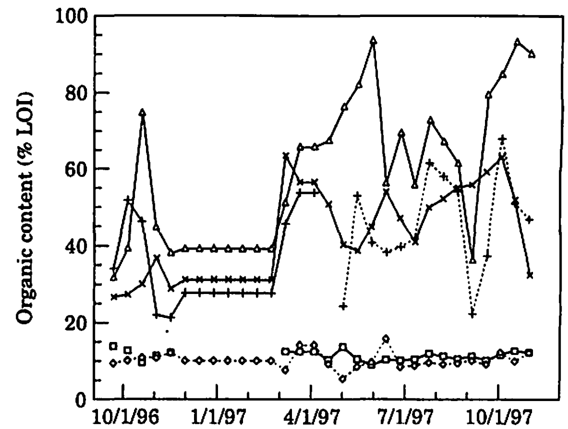

FIGURE 9. Habitat-averaged organic contents at OPC exhibit significant variations in the middle, high, and levee/shrub marsh habitats where biotic processes control sedimentation. Floating leaf (—⊟—), low marsh (- -◇- -), middlemarsh (—×—), high marsh (- - + - -), levee (—△—).

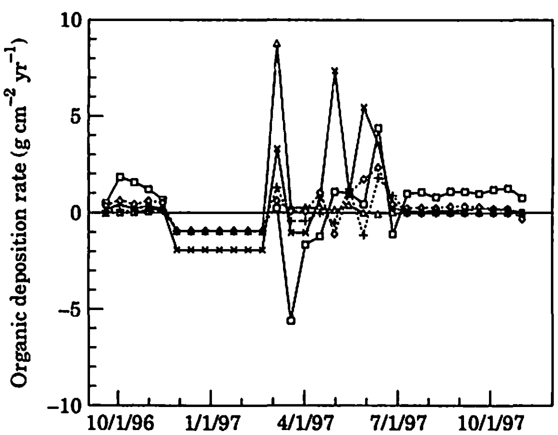

FIGURE 8. Habitat-averaged organic deposition was highest in the floating leaf habitat and lowest in the high marsh. Floating leaf (—⊟—), low marsh (- -◇- -), middlemarsh (—×—), high marsh (- - + - -), levee (—△—).

Thereafter, erosion gave way to deposition which peaked at 40·55 g cm^{-2} yr^{-1} in mid-June. Because of the magnitude of spring and early summer biweekly variability, the u test of randomness for runs above and below the median showed that the biweekly variations in the floating leaf habitat could not be statistically distinguished from random noise [Table 2(a)]. This means that the physical processes controlling sedimentation and erosion in this habitat were equally likely to be stochastic as they were to be deterministic.

In contrast to the floating leaf habitat, the low, middle, and levee/shrub marshes did show non-random annual sedimentation cycles (Figure 7). The average deposition rate in the low marsh slowly varied through time. In the last period of April there was significant erosion at all low marsh sites. By contrast, rates in the middle and levee/shrub marshes were close to zero most of the time. In spring, a large early flood from a small tributary to the delta deposited sediment and plant debris at site 6-P11 causing a spike in the habitat-averaged deposition rate for that period. Later in spring, beaver activity caused significant local sediment redistribution at site 2-P15, generating 2 spikes in the middle marsh habitat-averaged sedimentation rate. Even with significant winter erosion of the frontal high marsh, the variability in sedimentation experienced in that habitat was indistinguishable from random noise [Table 2(a)]. This means that efforts to further quantify causal mechanisms in that habitat based on this type of data would be statistically fruitless.

Because the range of biweekly sedimentation far exceeds the range of organic content, variations in organic deposition rates mimicked those for total sedimentation (Figure 8), whereas organic content cycles showed different fluctuations (Figure 9). The floating leaf habitat received the most organic material and the high marsh the least (Table 1). The low marsh had the lowest organic content, whereas the levee/shrub marsh had the highest. Peak organic contents for all habitats occurred in either autumn or early spring. Autumn peaks coincided with the decay of *in situ* marsh plants and the influx of leaves and woody debris from adjacent forests. The early spring peak

TABLE 1. Statistical summary of habitat-stratified data from field monitoring on the Otter Point Creek delta

Habitat	Total deposition[a]			Organic deposition[a]			Organic content[b]		
	Mean	Standard Deviation	N[c]	Mean	Standard Deviation	N[c]	Mean	Standard Deviation	N[c]
Floating leaf	5·23	14·95	23	0·58	1·77	23	11·67	1·27	23
Low marsh	1·26	8·36	30	0·17	0·83	30	10·38	2·02	30
Middle marsh	0·31	5·29	30	0·32	2·14	30	42·96	12·11	30
High marsh	−0·38	2·08	30	−0·07	0·71	30	40·25	13·51	29
Levee/shrub marsh	0·15	3·36	30	0·16	1·69	30	59·50	19·62	30

[a]Units are g cm^{-2} yr^{-1}.
[b]Units are weight %.
[c]N=number of bi-weekly, habitat-averaged values.

TABLE 2. Test for non-random behaviour in habitat-stratified (a) 60-week time series and (b) summer series only

Habitat	P-value[a] Total sediment rate	Organic rate	Organic percent
(a)			
Floating leaf	0·33	0·42	0·19
Low marsh	0·01	0·01	0·25
Middle marsh	0·01	0·001	2·18E-05
High marsh	0·13	0·03	0·01
Levee/shrub marsh	0·01	0·001	0·01
(b)			
Floating leaf	0·02	0·25	0·50
Low marsh	0·09	0·09	0·09
Middle marsh	0·09	0·09	0·02
High marsh	0·25	0·02	0·25
Levee/shrub marsh	0·25	0·02	0·09

[a]Shaded P-values indicate random behaviour.

resulted from the redistribution of plant material trapped in ice over the winter as well as from watershed inputs during floods. The u test of randomness for runs above and below the median shows that the middle, high and levee/shrub marshes and nonrandom cycles in organic content. The floating leaf and low marsh habitats did not have enough variability to generate a statistically significant trend in organic content [Table 2(a)]. Based on the analysis of organic matter input pathways by Knight and Pasternack (2000), it may be speculated that organics accumulating in these two habitats stemmed primarily from particulate organic matter transported by tides from a single source, most likely comprising well-homogenized mud from the intertidal mudflat.

Nonparametric tests used to determine whether deposition differed among marsh habitats included the Kruskal-Wallis test and the rank-sum U test for large samples. These tests were applied to data from the mid-June to mid-November 1997 habitat-averaged data which were found to come from random populations [Table 2(b)]. For the Kruskal-Wallis test, resulting P-values were all negligible, demonstrating that at least some of the mean values must be different from each other.

The results of the rank-sum U tests for large samples demonstrate that virtually all of the habitat-stratified time series represented unique statistical populations. For total sedimentation and organic deposition [Table 3(a),(b)], the means of habitat-stratified data differed above the 99% confidence level, except for high marsh versus levee/shrub marsh which were indistinguishable using this test. For organic content [Table 3(c)], all habitats were statistically distinguishable with a high confidence, except the middle marsh versus high marsh.

Total loading in the vegetated intertidal zone

All analyses of monitoring data from OPC showed significant differences among habitats. Consequently, estimates of loadings in the vegetated intertidal zone of the delta were carried out on a habitat by habitat basis. Time-averaged inorganic, organic, and total sediment loadings (Table 1) were combined with the known area of each habitat within OPC to obtain an estimate of total annual flux for the vegetated intertidal zone of the delta. Overall, the vegetated intertidal zone showed rapid growth (Table 4), and inorganic sedimentation in the floating leaf habitat accounts for the vast majority of that growth. Middle marsh, high marsh, and levee/shrub marsh sites all showed net inorganic losses, but in two of those habitats inorganic losses were offset by large amounts of organic

TABLE 3. Rank-sum U test for large samples that compares the means of habitat-averaged (a) total sedimentation, (b) organic sedimentation, and (c) organic percentage. Low P-values demonstrate that samples from the two habitats come from different statistical populations

Habitat	P-value[a]				
	Floating leaf	Low marsh	Middle marsh	High marsh	Levee/shrub
Floating leaf	X	0·0025	0·0025	0·0025	0·0025
Low marsh	X	X	0·0025	0·0032	0·0025
Middle marsh	X	X	X	0·0041	0·0002
High marsh	X	X	X	X	0·36
Levee/shrub	X	X	X	X	X
(b)					
Floating leaf	X	0·0025	0·0025	0·0041	0·0025
Low marsh	X	X	0·0041	0·0191	0·0025
Middle marsh	X	X	X	0·0041	0·0015
High marsh	X	X	X	X	0·65
Levee/shrub	X	X	X	X	X
(c)					
Floating leaf	X	0·0126	0·0002	0·0002	0·0002
Low marsh	X	X	0·0002	0·0002	0·0002
Middle marsh	X	X	X	0·60	0·0041
High marsh	X	X	X	X	0·0065
Levee/shrub	X	X	X	X	X

[a]Shaded P-values indicate random behaviour.

TABLE 4. Annual fluxes of inorganic and organic sediment to the vegetated intertidal zone of OPC, expressed in metric tonnes per year to three significant figures

Habitat	Area (ha)	Inorganic	Organic	Total
Floating leaf	12·2	5670	702	6370
Low marsh	9·0	978	156	1130
Middle marsh	19·7	− 22·5	629	607
High marsh	16·4	− 501	− 123	− 624
Levee/shrub marsh	4·0	− 3·41	72·7	69·3
Vegetated intertidal zone total	61·3	6121	1436	7552

deposition. Notably, no estimate was possible for the intertidal mudflats which were not studied due to their inaccessibility at low tide (Figure 2). Also, lack of estimates of suspended load and bedload inputs from Winters Run and HaHa Branch precluded determination of net import or export from the system.

Discussion

The large tidal freshwater marsh zone of the OPC delta experienced significant spatio-temporal variations in sedimentation and erosion. Three different sedimentation regimes have been identified in the raw data and in habitat-averaged time series analyses. The majority of sediment deposition occurred during summer. Some erosion occurred during winter, but ice in and overlying the saturated substrate sequestered sediment through this period. When ice melted in the spring, waves and tidal action redistributed the sediment from the vegetated zone to the pioneer mudflat and subtidal delta front. The amount of eroded material exported to Chesapeake Bay is unknown, but the continued long term growth of the delta front suggested that only a small fraction of the total storage leaves the delta. Because plant associations, wind spectra, and tidal pumping are fairly constant from year to year (Pasternack, pers. comm.) and sediment supply in the system is not limiting due to the presence of a vast mudflat, interannual total summer deposition should be relatively constant. Furthermore, none of the hurricanes which affected

Chesapeake Bay during 1995–1997 had a significant influence on delta sedimentation, although there was no direct hit such as occurred during Hurricane Agnes in 1972. These observations suggest that the ultimate control on net accretion in the intertidal zone must be the timing and extent of ice formation and thaw which varied between the very cold winter of 1995 and the record-setting warm conditions in 1996. Since the extent of ice is directly controlled by winter temperatures, it may be speculated that this system, and others like it, are directly affected by climate variability and climate change, and not just indirectly by sea-level rise.

A comparison of monitoring data between non-frozen periods when vegetation was present and when it was absent demonstrates that vegetation had a dominant control on sedimentation. Before vegetation grew in the early summer, sedimentation rates showed widespread spatial and temporal variability within and among habitats [Figure 5(c)]. Once vegetation became fully established, a predictable trend in sedimentation set in along the environmental gradient from floating leaf to levee/shrub marsh [Figure 5(a),(d)]. Each habitat had a unique summer-average sedimentation rate and governing statistical population distribution as shown by the nonparametric test. Ecological factors observed to affect the among-habitat trend included plant-rooting strategy (e.g., hummocky versus evenly distributed) and timing/extent of plant decomposition. More fine-scale mechanisms remain to be investigated, but the conclusion is that spatial patterns in vegetation affect geomorphic evolution through their control on sedimentation rates and patterns.

In contrast, sediment compaction, rainfall-induced erosion, and watershed runoff were not able to account for the observed variations in delta sedimentation and erosion at the biweekly time scale. Sediments were too low in organic content at sites experiencing erosion to generate measurable compaction in 2 weeks between sampling visits. The lack of any correlation between precipitation and sedimentation variables shows that rain impact does not generate measurable amounts of sediment erosion and can be neglected in the future. Whereas Pasternack *et al.* (in press) reported that runoff delivers sediment to the delta over long time scales, the lack of relationship between watershed runoff and net sedimentation found in this study shows that runoff does not redistribute sediment throughout the system on biweekly to interannual time scales. Instead, the presence of vast stores of sediment in the subtidal front and pioneer mudflat zones of the delta, including easily-mobilized fluidized mud, suggests that tides coupled with wind-induced sediment entrainment are most likely responsible for sediment transport. Detailed wind-wave modelling, grain size analyses, and event-based monitoring by Pasternack (pers. comm.) have corroborated this hypothesis.

Much more research on sedimentation in tidal freshwater marshes remains to be done, but some preliminary comparisons with tidal salt marshes are warranted. In terms of similarities, both systems have tidal channels whose hydraulic geometry is primarily controlled by the tidal prism (Myrick & Leopold, 1963; Garofalo, 1980; Haltiner *et al.*, 1997). Both show decreasing sedimentation rates and increasing organic content with increasing elevation and distance from channels (Letzsch & Frey, 1980; Stoddart *et al.*, 1989; Leonard, 1997; Pasternack & Brush, 1998; Pasternack *et al.*, 2000). At seasonal to interannual time scales, the morphodynamics of both environments show similarities in the interplay among hydroperiod, vegetation, and geomorphology (Letzsch & Frey, 1980; Leonard, 1997; Pasternack *et al.*, 2000). Rather than simply evolving from ' youth ' to ' maturity ', both systems exhibit strong evidence for dynamic equilibrium between process and morphology.

Despite these similarities, there are key differences that should motivate further and expanded research to tidal freshwater marshes. First, whereas coastal salt marshes are often limited by sediment supply, deltaic tidal freshwater marshes are not supply-limited over time scales of seasons to years, except when affected by historic upstream river management (Pasternack *et al.*, in press). Instead, the growth of deltaic tidal freshwater marshes is transport limited, as winds and tides can only generate relatively low momentum and turbulence for sediment transport. As illustrated in this study and previously demonstrated by Serodes and Troude (1984) and Pasternack and Brush (1998), a constant availability of sediment leads to overall higher sedimentation rates in tidal freshwater marshes. Second, in high latitude salt marshes the tidal range is large and the climate cold, as a result of which ice acts as a strong erosional agent (Wood *et al.*, 1989). In tidal freshwater marshes, the research at OPC shows that ice serves to sequester sediment and buffer the erosional impact of devegetation in late autumn. Third, the greater spatial variation in plant associations in a tidal freshwater marsh allows for a finer control of spatial patterns in sedimentation and erosion than is possible in tidal salt marshes. Finally, the landscape position of tidal freshwater marshes places them near riparian forests that can supply large amounts of organic material and thereby promote accretion. It is hoped that this study will motivate more wetland scientists to initiate research efforts in tidal freshwater marshes, as there is still a great need for more data sets to provide a comprehensive conceptual model of geomorphic evolution in these systems.

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