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Vertical Accretion in Microtidal Regularly and Irregularly Flooded Estuarine Marshes

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Vertical accretion rates were measured in microtidal (tidal amplitude less than 0·3 m) regularly (flooded twice daily by the astronomical tides), and irregularly flooded (inundated only during spring and storm tides) estuarine marshes in North Carolina to determine whether these marshes are keeping pace with rising sea-level and to quantify the relative contribution of organic matter and mineral sediment to vertical growth. Accretion rates in streamside and backmarsh locations of each marsh were determined by measuring the Cesium-137 (^{137}Cs) activity in 2 cm soil depth increments. Soil bulk density, organic carbon (C), total nitrogen (N) and particle density also were measured to estimate rates of accumulation of organic matter (OM), mineral sediment and nutrients.

With the exception of the backmarsh location of the regularly flooded marsh, vertical accretion rates in the marshes studied matched or exceeded the recent (1940–80) rate of sea-level rise (1·9 mm year^{-1}) along the North Carolina coast. Accretion rates in the irregularly flooded marsh averaged 3·6 ± 0·5 mm year^{-1} along the streamside and 2·4 ± 0·2 mm year^{-1} in the backmarsh. The regularly flooded marsh had lower accretion rates, averaging 2·7 ± 0·3 mm year^{-1} along the streamside and 0·9 ± 0·2 mm year^{-1} in the backmarsh.

Vertical accretion in the irregularly flooded marsh occurred via *in situ* production and accumulation of organic matter. Rates of soil OM (196–280 g m^{-2} year^{-1}), organic C (106–146 g m^{-2} year^{-1}) and total N (6·9–10·3 g m^{-2} year^{-1}) accumulation were much higher in the irregularly flooded marsh as compared to the regularly flooded marsh (OM = 51–137 g m^{-2} year^{-1}, C = 21–59 g m^{-2} year^{-1}, N = 1·3–4·1 g m^{-2} year^{-1}). In contrast, vertical accretion in the regularly flooded marsh was sustained by allochthonous inputs of mineral sediment. Inorganic sediment deposition contributed 677–1139 g m^{-2} year^{-1} mineral matter to the regularly flooded marsh as compared to only 147–311 g m^{-2} year^{-1} to the irregularly flooded marsh.

The irregularly flooded marsh exhibited an accretionary balance (vertical accretion rate minus local apparent sea-level rise) of 0·5–1·7 mm year^{-1} suggesting that these microtidal marshes would be capable of maintaining their elevation if the rate of sea-level rise increased. In the regularly flooded marsh, the streamside zone had an accretionary balance of 0·8 mm year^{-1} while the backmarsh had a deficit of 1·0 mm year^{-1}. Our results suggest that microtidal regularly flooded

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marshes would be susceptible to submergence by an increase in the rate of sea-level rise unless accompanied by an increase in mineral sediment deposition.

Introduction

Coastal marshes are an important component of estuarine ecosystems. Regularly (inundated twice daily by astronomical tides) and irregularly (inundated only during spring and storm tides) flooded marshes provide habitat and nursery grounds for finfish, shellfish, wildlife and waterfowl (Bellrose & Trudeau, 1988; Odum *et al.*, 1988), support estuarine productivity by contributing detritus to the estuarine foodweb (Marinucci, 1982), serve as sites of nutrient transformations (Nixon, 1980; Jordan *et al.*, 1983) and reservoirs of sediments (Frey & Bason, 1978; Bastian & Benforado, 1988), organic carbon (Armentano & Menges, 1986) and other nutrients (Craft *et al.*, 1988).

Coastal marshes also slow shoreline erosion by buffering storm tides and floodwaters (Rosen, 1980; Knutson, 1988). The root-rhizome mat produced by marsh vegetation increases sediment shear strength, reducing shoreline erosion compared to unvegetated shorelines (Knutson, 1988).

There is increasing concern over the effects of anthropogenic carbon dioxide (CO_2) inputs to the atmosphere on global warming and sea-level rise. It has been estimated that the level of the earth's oceans may rise 30–250 cm by the year 2075 due to melting of polar ice and thermal expansion of ocean surface waters caused by global warming (Revelle, 1983; Titus & Barth, 1984). Since coastal marshes occupy the transition zone between terrestrial and marine ecosystems, these wetlands are extremely susceptible to erosion and submergence by rising sea-level. Maintenance of estuarine wetlands threatened by rising sea-level will depend on landward migration and/or vertical growth.

Many coastal marshes grow upward in response to rising sea-level. For the past century, sea-level has risen 10–20 cm (Gornitz *et al.*, 1982; Barnett, 1983; Revelle, 1983). Estimates of accretion in estuarine marshes of the north-eastern (Redfield, 1972; Armentano & Woodwell, 1975; Bricker-Urso *et al.*, 1989), mid-Atlantic (Kearney & Ward, 1986; Griffin & Rabenhorst, 1989) and south-eastern (Benninger & Chanton, 1985; Sharma *et al.*, 1987) U.S.A. coast suggests these wetlands are keeping pace with sea-level rise. In contrast, many marshes in the Mississippi delta have not kept pace with sea-level rise (DeLaune *et al.*, 1978, 1983; Hatton *et al.*, 1983).

Vertical accretion occurs via sedimentation and accumulation of organic matter derived from net primary production of marsh vegetation (Redfield, 1972; DeLaune *et al.*, 1978; Hatton *et al.*, 1983; Bricker-Urso *et al.*, 1989). In the Mississippi delta, sediment deposition is important, contributing approximately 80% of the mass and 50% of the volume of soil solids (DeLaune & Patrick, 1980; DeLaune *et al.*, 1983). However, many estuarine marshes of the Atlantic coast do not receive large inputs of sediment and must rely on accumulation of organic matter to support their growth (Stevenson *et al.*, 1986; Bricker-Urso *et al.*, 1989).

Accretion in coastal marshes is controlled, to a large extent, by hydrology. Frequency and depth of flooding are important determinants of organic matter accumulation and sediment deposition in marshes (Gosselink & Turner, 1978; Stevenson *et al.*, 1986). Several researchers have observed that accumulation of organic matter in marsh soils is greater in marshes that are irregularly flooded by spring and storm tides as compared to regularly flooded marshes (Gosselink & Turner, 1978; Craft *et al.*, 1988). In contrast, sediment deposition generally is lower in marshes that are irregularly flooded (Gosselink

& Turner, 1978). Depth of flooding also may regulate the rate of marsh accretion. Stevenson *et al.* (1986) observed that accretionary balance (vertical accretion rate minus apparent sea-level rise) was positively correlated with mean tidal range ($r = 0{\cdot}83$). Stevenson *et al.* (1986) observed that coastal marshes in microtidal (tidal amplitude less than 0·5 m) environments exhibited an accretionary deficit and, thus, were susceptible to submergence under the current rate of sea-level rise.

We compared rates of vertical accretion in microtidal regularly and irregularly flooded estuarine marshes in North Carolina to: (1) determine whether these marshes are keeping pace with sea-level rise, and (2) quantify the relative contribution of organic matter and mineral sediment to the accretionary process. The regularly flooded marsh was characterized by twice daily inundation by astronomical tides with a tidal amplitude of 0·3 m. The irregularly flooded marsh was inundated only during spring and storm tides and had a tidal range of less than 10 cm. Recent (25 years) rates of accretion were estimated in streamside and backmarsh locations of each marsh by measuring ^{137}Cs in soil depth increments. Soil bulk density, particle density, organic carbon (C) and total nitrogen (N) also were measured to determine the role of organic and inorganic material in vertical growth and to estimate rates of accumulation of organic C and total N in marsh soils.

Methods

Site description

Soil cores were collected from a regularly and an irregularly flooded estuarine marsh along the North Carolina coast in the autumn of 1988 (Figure 1). The two marshes varied in tidal inundation, salinity and plant species composition. The regularly flooded marsh, Oregon Inlet, was inundated twice daily by the astronomical tides with a tidal amplitude of 0·3 m (Craft *et al.*, 1988). The irregularly flooded marsh, Jacob's Creek, was inundated only during spring and storm tides with a tidal range of less than 10 cm (Craft *et al.*, 1988). Regularly flooded marshes such as Oregon Inlet also are flooded more often (40–50% of the time) and to a greater depth ($\geq$30 cm above the soil surface at high tide) than irregularly flooded marshes which are inundated less than 10% of the time with a flooding depth of less than 10 cm (Jernigan, 1990).

Surface water salinity at the regularly flooded marsh was 20–35 ppt as compared to salinities of 0–15 ppt at the irregularly flooded marsh (Craft *et al.*, 1988). The regularly flooded marsh was vegetated by a monotypic stand of *Spartina alterniflora* Loisel, while the irregularly flooded marsh contained a mosaic of emergent macrophytes dominated by *Juncus roemerianus* Scheele, *Distichlis spicata* (L.) Greene, *S. patens* (Ait.) Muhl. and *S. cynosuroides* (L.) Roth.

Sample collection and analyses

Ten soil cores were collected from each of the two marshes using an 8·5 cm diameter by 30 cm deep stainless steel corer. The samples were stratified by location with five cores collected along the marsh edge (streamside) and five cores taken from the backmarsh, near the upland border. The soil cores were sectioned into 2 cm depth increments and the increments were air-dried, ground, sieved through a 2 mm-mesh diameter screen and weighed.

The depth increments were analysed for ^{137}Cs to estimate rates of vertical accretion over the past 25 years. The ^{137}Cs maximum in the soil profile corresponds to the soil surface in approximately 1964 (the period of maximum deposition of ^{137}Cs from above-ground thermonuclear testing). Cesium-137 has been used successfully to estimate recent rates of

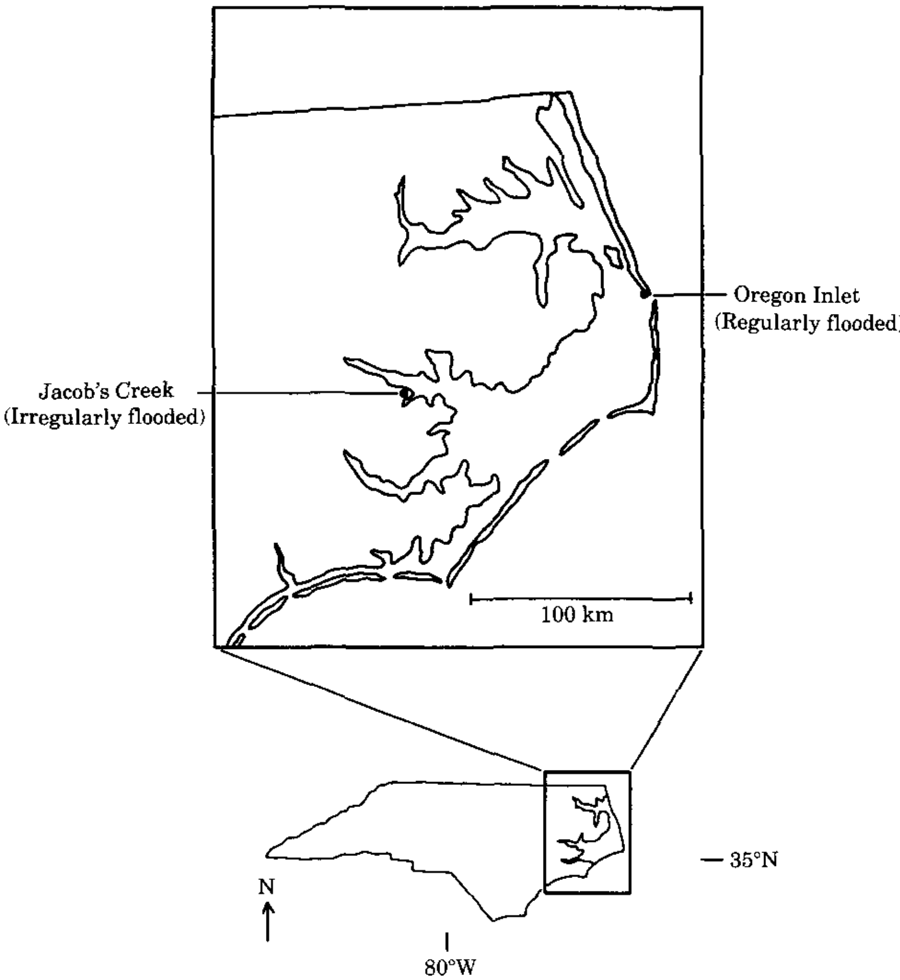

Figure 1. Location of the regularly and irregularly flooded estuarine marshes in North Carolina

accretion in estuarine wetlands (DeLaune *et al.*, 1978; Smith *et al.*, 1983; Sharma *et al.*, 1987). Cesium-137 activity was measured for 8–24 h using a high purity germanium gamma detector (EG&G Ortec, Oak Ridge, Tennessee). Counting efficiency (2·08%) was determined by counting a ^{137}Cs standard of the same geometry. Depth increments also were analysed for bulk density, organic C and total N. Soils were analysed for organic C and total N using a Perkin-Elmer CHN analyser. Analysis ($n=40$) of bituminous coal (NBS standard no. 1632b; 78·11% C, 1·56% N) yielded values of $77{\cdot}59 \pm 0{\cdot}23$ %C and $1{\cdot}55 \pm 0{\cdot}01$ %N. Previous analysis of soils from these locations indicated no measurable carbonates in the samples (Craft *et al.*, 1991). For this reason, it was assumed that all of the C in the samples was organic. Soil organic matter was calculated using the organic C content as described by Craft *et al.* (1991).

After analysis for ^{137}Cs, bulk density, organic C and total N, increments in the 0–10 cm depth of each core were combined for determination of particle density. Particle density was measured by the pycnometer method (Blake & Hartge, 1986). The particle density

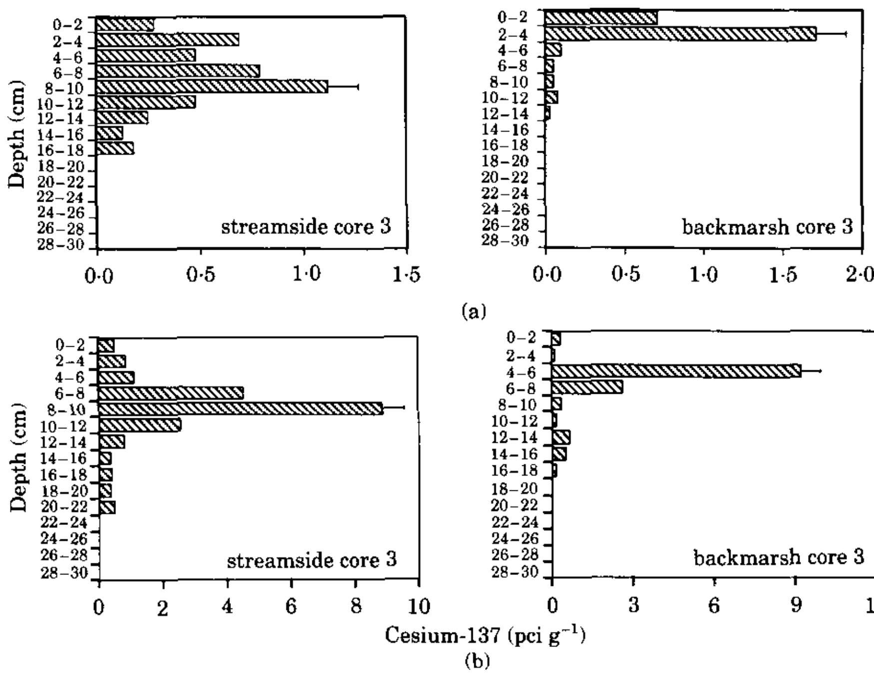

Figure 2. Depth distribution of ^{137}Cs in representative soil cores collected from (a) regularly and (b) irregularly flooded estuarine marshes. The ^{137}Cs data for all 20 cores are presented in Tables 1 and 2.

data was used to estimate the relative contribution of organic and mineral material to vertical accretion. All analyses were expressed on a dry weight basis by drying 1·0 g subsamples overnight at 105 °C.

Results and discussion

Accretion rates

There were well-defined ^{137}Cs maxima in the soils of both regularly and irregularly flooded marshes (Figure 2), corresponding to the period of maximum deposition of ^{137}Cs (approx. 1964). The depth of the ^{137}Cs peak occurred at a shallower depth in the regularly flooded marsh (0–10 cm) as compared to the irregularly flooded marsh (5–13 cm) (Tables 1 and 2). Using the ^{137}Cs maxima in the soil profile as a marker of the marsh surface in 1964, we calculated vertical accretion rates of 0·4–3·7 mm year^{-1} in the regularly flooded marsh and 2·1–5·4 mm year^{-1} in the irregularly flooded marsh.

Vertical accretion rates were significantly higher in the irregularly flooded marsh as compared to the regularly flooded marsh (Student's t-test, $P=0·05$; Figure 3). The average rate of accretion in the irregularly flooded marsh was 3·00 mm year^{-1} while the regularly flooded marsh grew at a rate of 1·81 mm year^{-1}. The higher accretion rates in the irregularly flooded marsh were attributed to reduced tidal flushing in this low energy, brackish-water marsh. Irregularly flooded marshes in North Carolina are inundated only during spring and storm tides and during extended periods when north-easterly winds push water into the Albemarle and Pamlico Sounds. As a result, only a small amount of the net primary production (NPP) of these marshes is removed by the tides as most of the plant material remains on the marsh (Craft *et al.*, 1988). In contrast, a larger proportion of

TABLE 1. Cesium-137 activity (pci g^{-1}) in soil cores collected from a regularly flooded estuarine marsh

Depth (cm)	Streamside core					Backmarsh core				
	1	2	3	4	5	1	2	3	4	5
0–2	0·08	0·43	0·28	0·38	0·28	1·04	0·20	0·71	0·46	0·15
2–4	0·13	0·56	0·69	0·43	0·69	0·66	0·51	1·71	0·31	0·59
4–6	0·36	0·48	0·48	0·74	0·69	0·23	0·28	0·10	0·13	0·41
6–8	0·66	0·79	0·79	0·69	0·56	0·13	0·08	0·05	0·08	0·13
8–10	0·56	0·74	1·12	0·48	0·56	0·05	0·05	0·05	0·08	0·08
10–12	0·20	0·69	0·48	0·51	0·15	0·08	0·08	0·08	0·10	0·03
12–14	0·08	0·25	0·25	0·13	0·13	0·08	0·03	0·03	0·05	0·00
14–16	0·05	0·13	0·13	0·13	0·10	0·03	—[a]	—[a]	—[a]	—[a]
16–18	0·03	0·15	0·18	0·03	0·08	0·03	—	—	—	—
18–20	0·15	—[a]	—[a]	—[a]	—[a]	0·03	—	—	—	—
20–22	0·08	—	—	—	—	0·03	—	—	—	—
22–24	0·00	—	—	—	—	0·00	—	—	—	—
24–26	0·00	—	—	—	—	0·00	—	—	—	—
26–28	0·00	—	—	—	—	0·05	—	—	—	—
28–30	0·00	—	—	—	—	0·03	—	—	—	—
Counting error[b]	0·14	0·13	0·15	0·19	0·15	0·11	0·08	0·19	0·10	0·06

The ^{137}Cs maximum in each core is underlined.
[a] ^{137}Cs was not measured below this depth, [b] counting error of the ^{137}Cs maximum.

TABLE 2. Cesium-137 activity (pci g^{-1}) in soil cores collected from an irrregularly flooded estuarine marsh

Depth (cm)	Streamside core					Backmarsh core				
	1	2	3	4	5	1	2	3	4	5
0–2	0·48	0·53	0·51	0·71	0·56	0·48	0·63	0·33	0·48	0·59
2–4	0·89	0·97	0·86	1·04	0·89	0·92	1·02	1·35	0·99	0·61
4–6	1·40	1·73	1·12	1·98	1·58	4·91	5·73	9·24	4·40	0·66
6–8	1·55	6·59	4·52	6·01	5·85	4·78	1·96	2·65	4·61	3·66
8–10	2·16	4·78	8·88	1·25	5·06	0·28	0·33	0·36	0·56	0·87
10–12	4·73	1·17	2·54	0·38	1·04	0·36	0·18	0·15	0·20	0·28
12–14	5·22	0·38	0·79	0·15	0·71	0·51	0·18	0·66	0·25	0·10
14–16	3·69	0·13	0·36	0·31	0·38	0·31	0·48	0·51	0·31	0·41
16–18	2·19	0·23	0·41	—[a]	—[a]	—[a]	—[a]	0·15	—[a]	0·25
18–20	1·55	0·23	0·38	—	—	—	—	—[a]	—	0·36
20–22	1·25	0·23	0·48	—	—	—	—	—	—	0·18
22–24	1·22	0·08	—[a]	—	—	—	—	—	—	0·28
24–26	0·71	—[a]	—	—	—	—	—	—	—	0·31
26–28	0·56	—	—	—	—	—	—	—	—	0·28
28–30	0·00	—	—	—	—	—	—	—	—	0·25
Counting error[b]	0·47	0·40	0·71	0·36	0·41	0·00	0·46	0·74	0·46	0·37

The ^{137}Cs maximum in each core is underlined.
[a] ^{137}Cs was not measured below this depth, [b] counting error of the ^{137}Cs maximum.

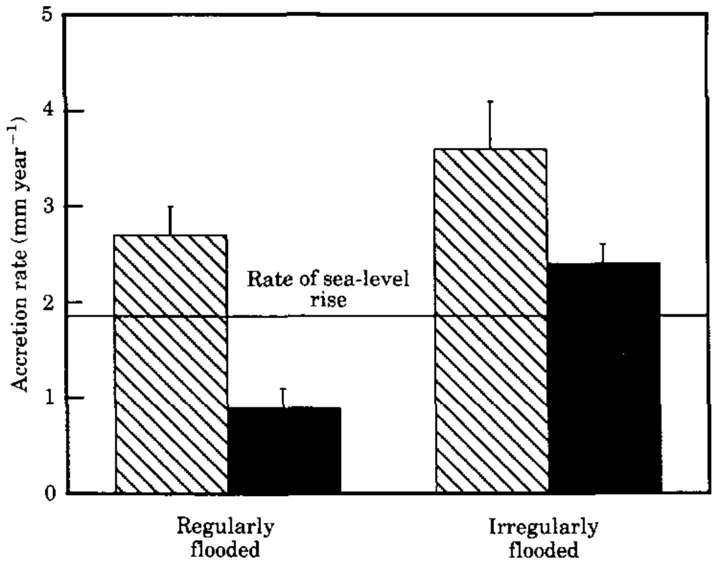

Figure 3. Mean vertical accretion rates in regularly and irregularly flooded marsh soils. Each value represents the mean (± 1 SE) of five cores. ■, backmarsh; ▨, streamside.

the NPP in regularly flooded marshes is removed by the astronomical tides so that less organic matter is available to contribute to vertical accretion. Craft *et al.* (1988) observed that 20% of the NPP accumulated in the soil of an irregularly flooded estuarine marsh annually as compared to 11–12% in regularly flooded marshes.

At both locations, accretion rates were higher in the streamside marsh than in the backmarsh (Figure 3). Accretion rates in the irregularly flooded marsh averaged 3·6 mm year^{-1} along the streamside and 2·4 mm year^{-1} in the backmarsh while the mean accretion rate in the streamside and backmarsh of the regularly flooded marsh was 2·7 and 0·9 mm year^{-1}, respectively. Several researchers (DeLaune *et al.*, 1978; Richard, 1978; DeLaune & Patrick, 1980; Hatton *et al.*, 1983) also observed higher rates of accretion in streamside marshes and attributed it to increased inputs of sediment from the water column. Sediment deposition may also enhance plant growth by adding particulate nutrients to the marsh (DeLaune *et al.*, 1981; Bricker-Urso *et al.*, 1989). DeLaune and Patrick (1980) estimated that sedimentation processes contributed 23·1, 2·31 and 99·1 g m^{-2} year^{-1} of N, phosphorus (P) and potassium (K) respectively to a Louisiana saltmarsh. The addition of particulate nutrients to the marsh may act as a positive-feedback to vertical accretion by stimulating plant growth and organic matter accumulation (Bricker-Urso *et al.*, 1989).

With the exception of the backmarsh location at the regularly flooded marsh, accretion rates equalled or exceeded the rate of sea-level rise (Figure 3). The rate of sea-level rise along the North Carolina coast (1940–80) has been estimated at 1·9 mm year^{-1} (Stevenson *et al.*, 1986) which indicates that the vertical growth of these marshes generally, is keeping pace with the current rate of sea-level rise.

Stevenson *et al.* (1986) postulated that the amount of tidal energy (expressed as mean tidal range) is a major factor controlling marsh accretion under conditions of both low and high sediment inputs. These researchers found a positive correlation ($r = 0{\cdot}83$) between accretionary balance (vertical accretion rate minus local apparent sea-level rise) and mean tidal range. According to Stevenson *et al.* (1986), marshes of microtidal environments

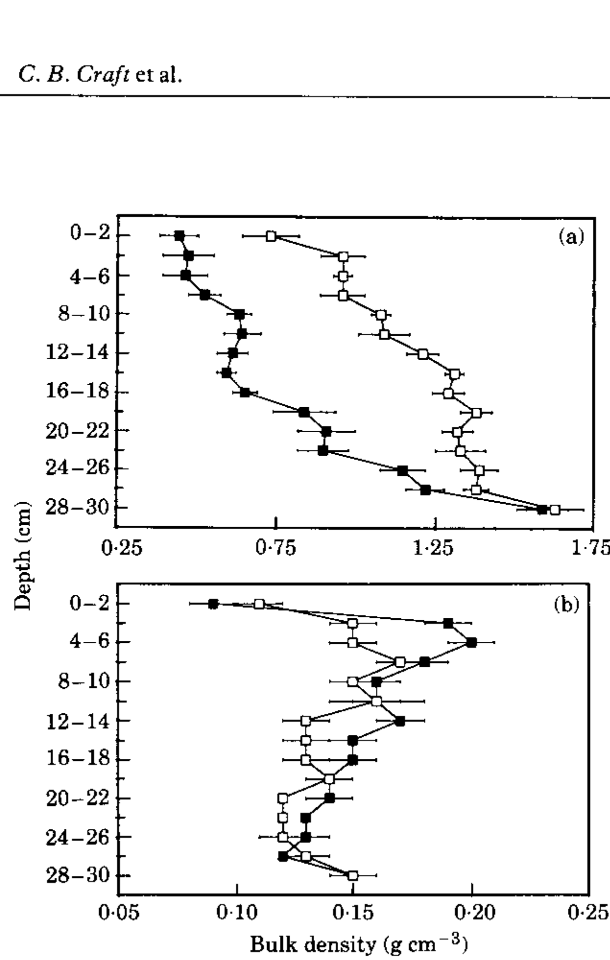

Figure 4. Mean bulk density by depth in (a) regularly and (b) irregularly flooded estuarine marsh soils. Each data point represents the mean ($\pm$1 SE) of five cores. —□—, backmarsh; —■—, streamside.

(mean tidal amplitude of 0·5 m or less) have a negative accretionary balance and are not keeping pace with sea-level rise. However, both our regularly and irregularly flooded marshes are keeping pace with sea-level rise in spite of low tidal amplitude. The irregularly flooded marsh, Jacob's Creek (tidal range less than 10 cm), has an accretionary balance of 0·5–1·7 mm year^{-1}. The regularly flooded marsh, Oregon Inlet (tidal range of 0·3 m), exhibited a positive accretionary balance in the streamside zone (0·8 mm year^{-1}) but the backmarsh zone had a deficit of 1·0 mm year^{-1}. Our results suggest that regularly and irregularly flooded microtidal marshes in North Carolina are able to maintain elevation in response to the current rate of sea-level rise. However, the mechanisms controlling vertical accretion differ between the two marsh types with *in situ* organic matter accumulation being the primary mechanism in irregularly flooded marshes and mineral sediment deposition as the dominant mechanism in the regularly flooded marsh (see section on *Accumulation rates of organic matter and mineral sediment*).

Soil bulk density, organic carbon and total nitrogen

Soil bulk density varied inversely with the organic matter content of the soil. Bulk density was much higher in the low organic matter regularly flooded marsh (0·44–1·63 g cm^{-3}) as compared to the organic soils of the irregularly flooded marsh (0·09–0·20 g cm^{-3}) [Figure 4(a,b)]. In the regularly flooded marsh soil, bulk density was lowest at the surface and increased with depth [Figure 4(a)]. Soil bulk density was lower at the streamside location than the backmarsh [Figure 4(a)] as a result of the higher organic C content [see Figure

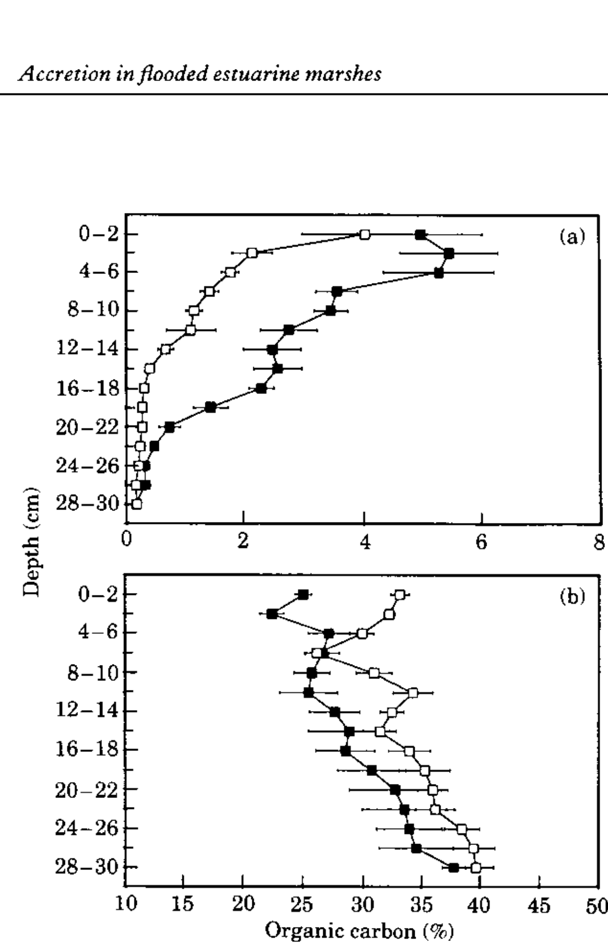

Figure 5. Mean organic carbon content by depth in (a) regularly and (b) irregularly flooded estuarine marsh soils. Each data point represents the mean ($\pm$1 SE) of five cores. —□—, backmarsh; —■—, streamside.

5(a)]. In contrast to the regularly flooded marsh, bulk density in the irregularly flooded marsh soils exhibited no clear differences with regard to location or depth [Figure 4(b)].

The regularly flooded marsh soils contained much lower concentrations of organic C ($<6\%$) than the soils of the irregularly flooded marsh (22–40%) [Figure 5(a,b)]. In the regularly flooded marsh, soil organic C decreased with depth in both the streamside and backmarsh locations [Figure 5(a)] while organic C increased with depth in the irregularly flooded marsh [Figure 5(b)].

The difference in concentration and distribution of soil organic C in the regularly and irregularly flooded marshes reflects the age difference of the two marshes. The regularly flooded marsh is located on the sound side of the North Carolina barrier islands. During the past 5000 years, as sea-level has risen, the barrier islands have migrated landward with the rising sea (Pilkey *et al.*, 1982). As a result, these barrier island marshes are an ephemeral part of the landscape as the barrier islands 'roll over' in their landward migration (Leatherman, 1982). In contrast, the irregularly flooded marsh is located on the Pamlico terrace; a much older (approx. 50 000 years) landform (Daniels *et al.*, 1984). The thickness of the organic layer (2–3 m) and uniform depth distribution of organic C suggests that this marsh has existed for several thousand years. In fact, ^{14}C dating from the basal peat of a nearby marsh yielded a date of 2600 years BP (before present) (Bellis & Gaither, 1985).

Soil organic C was much lower at the backmarsh location of the regularly flooded marsh as compared to the streamside marsh [Figure 5(a)]. Again, the difference in soil organic C

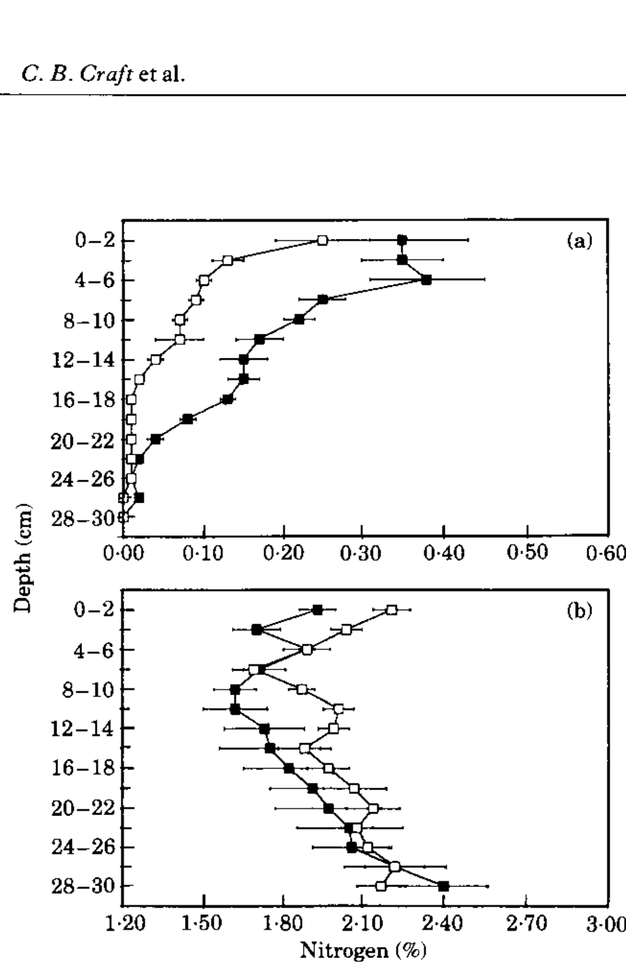

Figure 6. Mean total nitrogen content by depth in (a) regularly and (b) irregularly flooded estuarine marsh soils. Each data point represents the mean (±1 SE) of five cores. —□—, backmarsh; —■—, streamside.

between the streamside and backmarsh is due to the difference in age. As the sea-level rose, the streamside marsh was initially inundated and colonized by emergent vegetation. During this time the backmarsh area probably was dominated by maritime shrub vegetation such as red cedar (*Juniperus*), wax myrtle (*Myrica*) and marsh elder (*Iva*) (Leatherman, 1982). Only recently, as the sea-level continued to rise, has this area been flooded and colonized by *S. alterniflora*.

In contrast to the regularly flooded marsh, soil organic C was lower along the streamside of the irregularly flooded marsh [Figure 5(b)]. The lower organic C content of the streamside marsh soil probably reflects higher sedimentation rates adjacent to the stream than in the interior of the marsh.

The distribution of total N in the marshes was similar to that of organic C. Soil N was much higher in the organic soils of the irregularly flooded marsh (1·62–2·40%) than in the sandy soils of the regularly flooded marsh [0–0·38%; Figure 6(a,b)]. Total N decreased with depth in soils of the regularly flooded marsh [Figure 6(a)] and increased with depth in the irregularly flooded marsh [Figure 6(b)]. Like organic C, soil N was higher in the streamside of the regularly flooded marsh and in the backmarsh of the irregularly flooded marsh [Figure 6(a,b)].

Accumulation rates of organic carbon and total nitrogen

Rates of organic C and total N accumulation were much higher in the irregularly flooded marsh as compared to the regularly flooded marsh (Table 3) and were attributed mostly to

TABLE 3. Mean accumulation rates of organic carbon and total nitrogen in regularly and irregularly flooded estuarine marsh soils

Marsh type	Location	Organic carbon ($g\ m^{-2}\ year^{-1}$)	Total nitrogen ($g\ m^{-2}\ year^{-1}$)
Regularly flooded	Streamside	$58{\cdot}9 \pm 7{\cdot}3$	$4{\cdot}11 \pm 0{\cdot}56$
(Oregon Inlet)	Backmarsh	$21{\cdot}3 \pm 4{\cdot}7$	$1{\cdot}32 \pm 0{\cdot}28$
Irregularly flooded	Streamside	$145{\cdot}5 \pm 19{\cdot}4$	$10{\cdot}28 \pm 1{\cdot}40$
(Jacob's Creek)	Backmarsh	$106{\cdot}5 \pm 6{\cdot}8$	$6{\cdot}89 \pm 0{\cdot}57$

Each value represents the mean (± 1 SE) of five cores.

much higher concentrations of organic C and total N (Figures 5 and 6) and, to a lesser extent, to higher accretion rates (Figure 3). Rates of organic C and total N accumulation in our marshes were much lower than reported for coastal marshes in Louisiana (DeLaune *et al.*, 1981; Hatton *et al.*, 1982; Smith *et al.*, 1983). The difference was attributed to much higher accretion rates (5·2–14·0 mm $year^{-1}$) in the Louisana marshes (DeLaune *et al.*, 1981; Hatton *et al.*, 1982; Smith *et al.*, 1983).

The higher rates of C and N accumulation in the irregularly flooded marsh may be attributed to: (1) reduced rates of decomposition caused by waterlogging, (2) higher net primary production (and organic matter deposition), (3) emergent vegetation (e.g. *Juncus*) which is inherently more resistant to decomposition or (4) reduced tidal flushing and export of detritus. The weak and irregular inundation in marshes such as Jacob's Creek may result in waterlogging of the sediments, slowing decomposition and enhancing organic matter accumulation as compared to coastal wetlands that are vigorously flooded by astronomical tides (Stevenson *et al.*, 1986). However, Jernigan (1990) surveyed 12 marshes in North Carolina and found that the sediments underlying irregularly flooded *Juncus* marshes were less reduced (55 mV) than sediments underlying *S. alterniflora* (−112 mV). Differences in net primary productivity or decomposition rates of emergent vegetation also cannot account for the higher rates of C and N accumulation in the irregularly flooded marsh. Net primary productivity of emergent vegetation was similar in the regularly (1046 g C m^{-2} $year^{-1}$) and irregularly flooded (900 g C m^{-2} $year^{-1}$) marshes (S. W. Broome, unpubl. data). Decomposition rates of *Juncus* and *Spartina* also appear to be similar. Hackney and Cruz (1980) observed that, after 1 year, litter bags containing *Juncus* and *Spartina* roots lost 17 and 20% of their mass, respectively. Likewise, McKee and Seneca (1982) found that litter bags containing above-ground *Spartina* and *Juncus* tissue exhibited similar decomposition rates (approximately 80% weight loss after 13 months).

It is likely that rates of organic matter and nutrient accumulation are often higher in irregularly flooded marshes because less of the NPP is removed from the marsh surface by tidal action (Hackney & Cruz, 1982; Craft *et al.*, 1988). The percentage of NPP buried annually was nearly four times higher in the irregularly flooded marsh (14%, 126 g C m^{-2} $year^{-1}$) as compared to the regularly flooded marsh (3·4%, 40 g C m^{-2} $year^{-1}$). Craft *et al.* (1988) also observed that only 11–12% of the NPP in a regularly flooded transplanted marsh accumulated in the sediments annually as compared to 20% in an irregularly flooded transplanted marsh.

TABLE 4. Mean accumulation rates of organic matter and mineral sediment in regularly and irregularly flooded estuarine marshes

Marsh type	Location	Organic matter ($g\ m^{-2}\ year^{-1}$)	Inorganic sediment ($g\ m^{-2}\ year^{-1}$)
Regularly flooded	Streamside	137 ± 17 (11%)	1139 ± 210
(Oregon Inlet)	Backmarsh	51 ± 11 (7%)	677 ± 197
Irregularly flooded	Streamside	280 ± 39 (47%)	311 ± 63
(Jacob's Creek)	Backmarsh	196 ± 13 (57%)	147 ± 14

Each value represents the mean (± 1 SE) of five cores. Numbers in parentheses represent the mass contribution of organic matter to the vertical accretion rate

Accumulation rates of organic matter and mineral sediment

Like organic C, rates of organic matter accumulation were much higher in the irregularly flooded marsh (196–280 $g\ m^{-2}\ year^{-1}$) than in the regularly flooded marsh (51–137 $g\ m^{-2}\ year^{-1}$). At both sites, accumulation of organic matter was greater in the streamside marsh as compared to the backmarsh (Table 4). In contrast to organic matter, deposition of inorganic sediment was much higher in the regularly flooded marsh (677–1139 $g\ m^{-2}\ year^{-1}$) as compared to the irregularly flooded marsh (147–311 $g\ m^{-2}\ year^{-1}$). On a mass basis, organic matter accounted for 47–57% of the accretion of solids in the irregularly flooded and only 7–11% in the regularly flooded marsh (Table 4).

Accumulation rates of organic matter and mineral sediment were two to three times greater along the streamside as compared to the backmarsh of the regularly flooded marsh (Table 4). As a result, the streamside location is able to maintain its elevation (2·7 $mm\ year^{-1}$) against rising sea-level (1·9 $mm\ year^{-1}$). In contrast, accretion rates in the backmarsh location (0·9 $mm\ year^{-1}$) indicate that there is insufficient organic matter and mineral sediment accumulation to sustain vertical growth in the face of rising sea-level. It is likely that the accretionary deficit in the backmarsh location at Oregon Inlet is due to reduced mineral sediment inputs (Table 4) caused by a reduction in tidal inundation (as compared to the streamside location). There also appears to be little if any contribution by overwash at this site.

Soil bulk density and particle density (upper 10 cm) was much lower in the organic soils (>50% organic matter) of the irregularly flooded marsh than in the sandy soils (7–11% organic matter) of the regularly flooded marsh (Table 5). Particle density of the regularly flooded marsh soil was somewhat less (2·40–2·50 $g\ cm^{-3}$) than the particle density reported for mineral soils (2·60–2·75 $g\ cm^{-3}$; Brady, 1984). Assuming a particle density of 2·65 $g\ cm^{-3}$ for inorganic sediment, we calculated that the particle density of organic matter in the irregularly flooded marsh was 1·24–1·34 $g\ cm^{-3}$. Our values are within the range (1·10–1·40 $g\ cm^{-3}$) given by Brady (1984) for organic matter.

At both marshes, most of the volume in the upper 10 cm of the soil was occupied by pores (Table 5). Voids accounted for 65–80% of the volume in the regularly flooded marsh soil and 91–93% in the irregularly flooded marsh soil. Organic matter accounted for 4–5% of the total volume in the regularly flooded marsh compared to 16–30% for inorganic sediment (Table 5). In the irregularly flooded marsh, organic matter and inorganic sediment contributed 5–6 and 2–3% of the volume, respectively (Table 5). If the data are expressed as the percentage contribution to the solid phase, then soil organic matter

TABLE 5. Soil physical properties (bulk density, particle density, organic matter content and porosity) in the upper 10 cm and percentage contribution of organic matter and inorganic sediment to volume accretion

	Regularly flooded (Oregon Inlet)		Irregularly flooded (Jacob's Creek)	
	Streamside	Backmarsh	Streamside	Backmarsh
Bulk density (g dry weight cm^{-3})	$0{\cdot}48 \pm 0{\cdot}01$	$0{\cdot}85 \pm 0{\cdot}09$	$0{\cdot}16 \pm 0{\cdot}02$	$0{\cdot}13 \pm 0{\cdot}01$
Particle density (g dry weight cm^{-3})	$2{\cdot}40 \pm 0{\cdot}07$	$2{\cdot}50 \pm 0{\cdot}07$	$1{\cdot}95 \pm 0{\cdot}06$	$1{\cdot}87 \pm 0{\cdot}07$
Organic matter (% dry weight)	11 ± 1	7 ± 2	53 ± 2	55 ± 2
Particle density of organic matter (g cm^{-3})[a]	—	—	$1{\cdot}34 \pm 0{\cdot}08$	$1{\cdot}24 \pm 0{\cdot}11$
Porosity (%)[b]	80 ± 1	65 ± 3	91 ± 1	93 ± 1
% contribution of organic matter[c]	4 (20)	5 (14)	6 (67)	5 (71)
% contribution of inorganic sediment[c]	16 (80)	30 (86)	3 (33)	2 (29)

Each number represents the mean (± 1 SE) of the averaged depth integrated (0–10 cm) values of the five cores.

[a] $$D_p\,(OM) = \frac{D_p\,(soil) - (\%\,IS/100)\,(D_p(IS))}{(\%\,OM/100)}$$

[b] Porosity $= 1 - (D_b/D_p)$.

[c] Volume (OM or IS) = Mass (OM or IS)/D_p (OM or IS). Calculated using the mean D_p for each location and the D_p (OM) and D_p (IS) of 1·29 and 2·65 g cm^{-3}, respectively. Numbers in parentheses represent the percentage contribution of organic matter or mineral sediment to accretion of solids.

D_b, bulk density; D_p, particle density; IS, inorganic sediment; OM, organic matter.

accounts for 14–20 and 67–71% of the volume of solids in the regularly (7–11% organic matter by weight) and irregularly (53–55% organic matter by weight) flooded marshes, respectively.

Other studies also have documented the importance of soil organic matter in vertical accretion. DeLaune *et al.* (1983) observed that coastal marshes in Louisiana containing 20–30% soil organic matter by weight contributed approximately 50% of the volume of soil solids. In Rhode Island saltmarshes (30–60% organic matter), organic matter accounted for 50 and 73% of the volume of soil solids in the low and high marsh, respectively (Bricker-Urso *et al.*, 1989). Our results and those of other researchers demonstrate the importance of organic matter to vertical accretion in both organic and mineral marshes by enhancing soil volume. Other studies also have documented the importance of soil organic matter to vertical accretion by providing structural support and pore space (DeLaune & Patrick, 1980; DeLaune *et al.*, 1983; Hatton *et al.*, 1983; Bricker-Urso *et al.*, 1989).

Although both regularly and irregularly flooded microtidal marshes are able to grow vertically in response to the current rate of sea-level rise, the mechanisms controlling accretion differ between the two marsh types. Irregularly flooded marshes grow vertically through accumulation of organic matter from emergent vegetation (Tables 4 and 5). The weak and irregular inundation of marshes such as Jacob's Creek results in limited export of detritus so that most of the NPP accumulates on the marsh surface. Likewise, the low tidal energy associated with irregularly flooded marshes limits allochthonous inputs of mineral sediment, reinforcing the importance of organic matter to vertical growth in these marshes. In contrast, much of the NPP in regularly flooded marshes such as Oregon Inlet is exported by the astronomical tides. However, the increased tidal energy associated with regularly flooded marshes contributes substantial amounts of inorganic sediment to the surface of these marshes. As a result, the vertical growth of these microtidal regularly flooded marshes is sustained primarily by allochthonous inputs of mineral material (Tables 4 and 5).

Conclusions

Vertical accretion rates in an irregularly flooded estuarine marsh (2·4–3·6 mm $year^{-1}$) indicate that this coastal wetland is keeping pace with sea-level rise (1·9 mm $year^{-1}$). Accretion rates in a regularly flooded marsh suggest that the streamside marsh (2·7 mm $year^{-1}$) is maintaining its elevation relative to sea-level rise but the backmarsh (0·9 mm $year^{-1}$) is not keeping pace with rising sea-level. At both marshes, vertical accretion was greater in streamside than backmarsh locations as a result of greater deposition of organic matter and inorganic sediment.

The mechanisms controlling vertical accretion are different in the two marshes. In the irregularly flooded marsh, accretion occurs via *in situ* production and accumulation of organic matter. However, allochthonous inputs of mineral sediment are responsible for the vertical growth of the regularly flooded marsh. The irregularly flooded marsh exhibited a positive accretionary balance (vertical accretion rate minus local apparent sea-level rise) of 0·5–1·7 mm $year^{-1}$, suggesting that this marsh is capable of maintaining itself in response to an increase in the rate of sea-level rise. In the regularly flooded marsh, the streamside zone had a positive accretionary balance (0·8 mm $year^{-1}$) but the backmarsh exhibited an accretionary deficit of 1·0 mm $year^{-1}$. Our results suggest that regularly flooded microtidal (tidal amplitude less than 0·5 m) marshes would be susceptible to submergence if exposed to increased rates of sea-level rise. Vertical growth of these marshes in response to rising sea-level will be dependent on a concomitant increase in allochthonous mineral sediment inputs.

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