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Accretion of a New England (U.S.A.) Salt Marsh in Response to Inlet Migration, Storms, and Sea-level Rise

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Sediment accumulation rates were determined at several sites throughout Nauset Marsh (Massachusetts, U.S.A.), a back-barrier lagoonal system, using feldspar marker horizons to evaluate short-term rates (1 to 2 year scales) and radiometric techniques to estimate rates over longer time scales (^{137}Cs, ^{210}Pb, ^{14}C). The barrier spit fronting the *Spartina*-dominated study site has a complex geomorphic history of inlet migration and overwash events. This study evaluates sediment accumulation rates in relation to inlet migration, storm events and sea-level rise. The marker horizon technique displayed strong temporal and spatial variability in response to storm events and proximity to the inlet. Sediment accumulation rates of up to 24 mm year^{-1} were recorded in the immediate vicinity of the inlet during a period that included several major coastal storms, while feldspar sites remote from the inlet had substantially lower rates (trace accumulation to 2·2 mm year^{-1}). During storm-free periods, accumulation rates did not exceed 6·7 mm year^{-1}, but remained quite variable among sites. Based on ^{137}Cs (3·8 to 4·5 mm year^{-1}) and ^{210}Pb (2·6 to 4·2 mm year^{-1}) radiometric techniques, integrating sediment accumulation over decadal time scales, the marsh appeared to be keeping pace with the relative rate of sea-level rise from 1921 to 1993 of 2·4 mm year^{-1}. At one site, the ^{210}Pb-based sedimentation rate and rate of relative sea-level rise were nearly similar and peat rhizome analysis revealed that *Distichlis spicata* recently replaced this once *S. patens* site, suggesting that this portion of Nauset Marsh may be getting wetter, thus representing an initial response to wetland submergence. Horizon markers are useful in evaluating the role of short-term events, such as storms or inlet migration, influencing marsh sedimentation processes. However, sampling methods that integrate marsh sedimentation over decadal time scales are preferable when evaluating a systems response to sea-level rise.

Keywords: salt marsh; sedimentation rates; ^{210}Pb; ^{137}Cs; radiocarbon; sea-level rise; storms; Massachusetts (U.S.A.)

Introduction

Evaluation of saltmarsh accretion processes has received much attention over the past decade, largely in response to predictions of accelerated rates of sea-level rise related to global warming (Hoffman *et al.*, 1983; National Research Council, 1983). It is suggested that acceleration of present sea-level rise could cause substantial losses of coastal salt marshes (Orson *et al.*, 1985; Stevenson *et al.*, 1986). In fact, there are extensive areas associated with the Mississippi delta region (e.g. Hatton *et al.*, 1983; Baumann *et al.*, 1984) and some brackish-water marshes of Chesapeake Bay (Stevenson *et al.*, 1985) where relative rates of sea-level rise presently exceed vertical marsh accretion. In the New England region, several studies have focused on relationships between sea-level rise and saltmarsh accretion (Redfield, 1972; Harrison & Bloom, 1977; Orson *et al.*, 1987; Bricker-Urso *et al.*, 1989; Wood *et al.*, 1989; Orson & Howes, 1992) and generally report that rates of accretion currently exceed rates of sea level rise. However, studying a southern New England (Connecticut) salt marsh, Warren and Niering (1993) found dramatic changes in vegetation patterns over the past half century and suggest this change is an initial response to future wetland submergence.

This study estimates sediment accumulation rates of a New England salt marsh employing several techniques, including marker horizons and radiometric dating (^{137}Cs, ^{210}Pb, ^{14}C). Comparison of these estimates to regional tide gauge records of relative sea

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level (1921 to present), coupled with rhizome profiles, sedimentological profiles (e.g bulk density, organic/inorganic content, grain size), the chronology of barrier island inlet migration, sediment supply factors, and storm history, enables a discussion of relationships between processes that influence marsh accretion and associated responses.

Materials and methods

The study site

The 945 ha Nauset Marsh (Orleans and Eastham, Massachusetts, U.S.A.) is a back-barrier estuarine lagoon with direct ocean exchange through a tidal inlet (Figure 1). *Spartina alterniflora* marsh occupies about 35% of the system with tidal channels, intertidal flats and eelgrass meadows (*Zostera marina*) dominating the system (Roman *et al.*, 1990). Tidal range at the ocean side of the Nauset Inlet is about 2 m, with a reduction to 1·5 m on the estuarine side of the inlet and less than 1 m in other parts of the system due to frictional attenuation (Aubrey & Speer, 1985). The barrier spit system fronting Nauset Marsh has a complex geomorphic history associated with inlet migration and overwash events (Aubrey & Speer, 1984; Leatherman & Zaremba, 1986). The history of inlet migration over the past three decades is depicted in Figure 1. Based on an analysis of historical charts (from 1779) and aerial photography (from 1938), Aubrey and Speer (1984) note that the hydraulically preferred location of Nauset Inlet is at the southern end of the system. Most of the system's tidal prism flows through the deep southernmost channels (i.e. 5 m). To the north, shallow channels and intertidal flats dominate. In the late 1930s, Nauset Inlet was located at the extreme southern end of the system. Beginning in the 1950s, perhaps in response to increased storm frequency, the inlet began an active northward migration. During the late 1950s and early 1960s, numerous storms resulted in re-establishment of the inlet to the south. After 1965, the inlet migrated steadily northward at a rate of about 38 m year^{-1}. In the early 1990s, the inlet reached its northernmost location when compared to historical records. Then, in response to a series of major storms (Hurricane Bob, August 1991; 1991 Halloween Eve Storm; December 1992 ' nor'easter '; March 1993 ' Storm of the Century '; see Davis and Dolan, 1993; FitzGerald *et al.*, 1994), another inlet formed further south (nearer the hydraulically preferred location). Since December 1992, multiple inlets were maintained (Figure 1), until May 1996 when the more northern inlet was closed due to natural processes.

Sampling techniques

Feldspar marker horizons. Following Cahoon and Turner (1989), feldspar marker horizon plots were established at five sites throughout Nauset Marsh to evaluate recent sediment accumulation rates. The marsh sites were identified as Inlet 1 (in the vicinity of the inlet when the study was initiated in 1991) and Inlet 2 (in the vicinity of the more southern inlet established in late 1992), Fort Hill Island (a marsh island in the interior of the estuary), and Hemenway Landing and Nauset Bay (marsh areas immediately adjacent to the upland and remote from present or historic inlets; Figure 1). All plots were located at least 10 m from creekbanks to avoid sedimentation processes associated with creekbank levees. Feldspar, crushed to a powder, was shaken into 50 cm × 50 cm plots, through the intact *Spartina*, to establish marker horizons 0·5 cm to 1 cm thick. A total of 12 plots were established at the five sites in June and August 1991 (Inlet 2 was established in August 1993 to document changes after the southern inlet had formed), and then sampled in April 1992, August 1993, and late July 1994. Sediment accumulation above the top of the marker horizon was measured to the nearest mm from a small sediment plug, about 2 cm on a side, cut from the plot with a sharp knife and removed intact.

Marsh cores. Using a stainless steel gouge corer (1 m length, 7 cm diameter), replicate marsh cores ($n=7$ at each site) were collected at three sites (Inlet 1, Fort Hill Island, Nauset Bay) during the period of June 1991 through April 1992. The cores, generally <1·5 m in length, included the entire peat profile from the marsh surface to underlying sand. No visible vertical compaction of peat by the coring process was noted.

Analytical procedures

For each site, two of the seven replicate cores were selected for analysis. To insure that the cores from each site were collected from relatively homogeneous areas and had similar profile characteristics, magnetic susceptibility scans were performed. Whole-core magnetic susceptibility was measured using a Bartington Instruments low frequency (0·47 kHz) susceptibility meter generating an alternating field of 0·1 mT. Magnetic susceptibility, which is proportional to magnetic mineral content of the sample (Thompson & Oldfield, 1986), is the ratio of the magnetization induced in a sample to the intensity of the weak magnetic field to which the sample is subjected. Based on seven magnetic susceptibility profiles from each site, spatial variability appeared to be minimal (Figure 2).

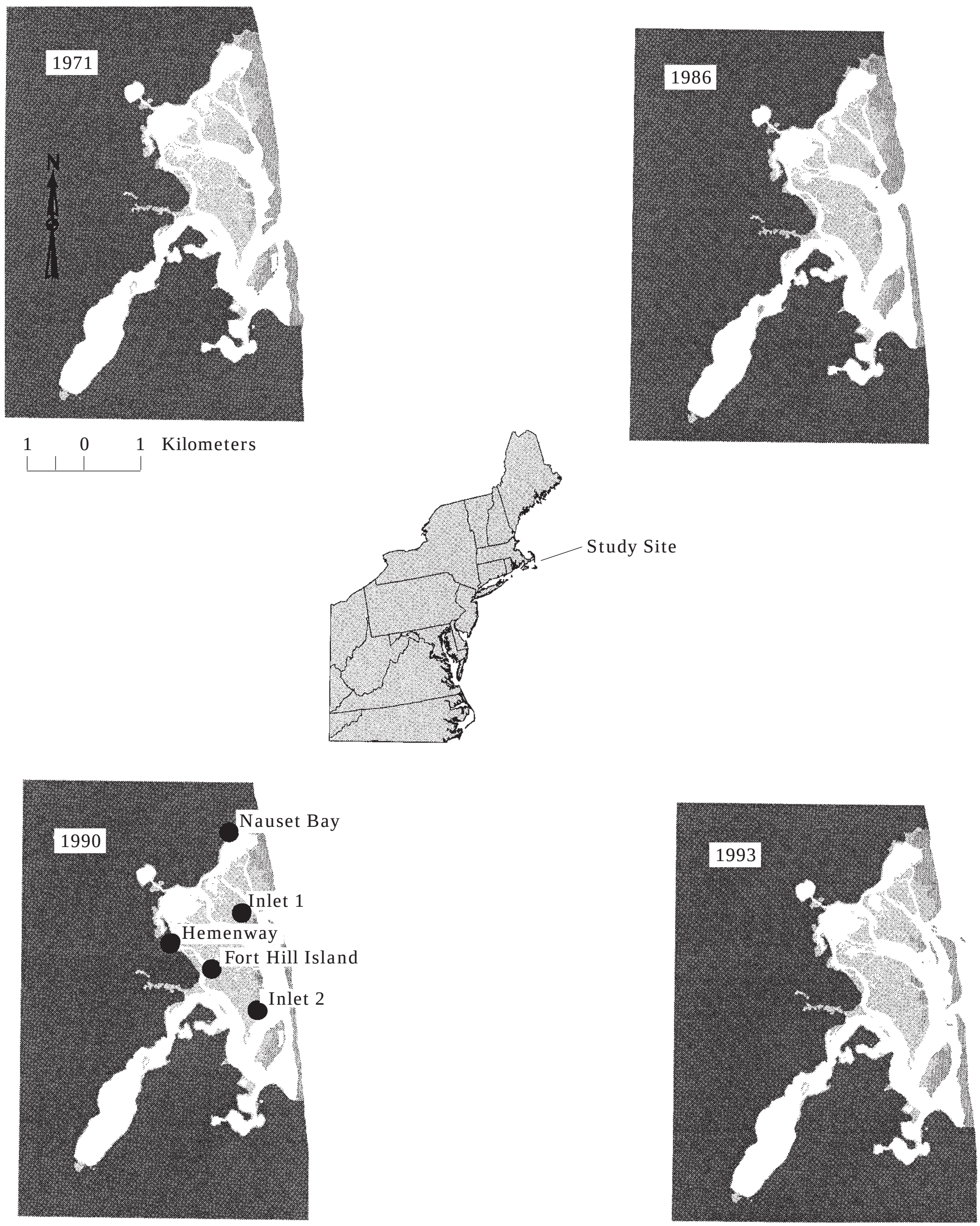

FIGURE 1. The Nauset Marsh back-barrier lagoon in Eastham and Orleans, Massachusetts (USA). The four panels depict dynamics of the inlet/barrier spit shoreline system from an inlet at a southern location in 1971, migrating northward in 1986 and 1990 (northernmost location), and multiple inlets in 1993. Feldspar marker horizon and core sampling stations were established in 1991 when the inlet/barrier configuration was similar to that shown in the 1990 panel. Salt marsh is light grey, barrier spit and sand deposits are medium grey.

One core from each site was visually described for colour (Rock Color Chart, 1970), texture, and grain size characteristics. Rhizomes preserved within the core were identified (after Niering *et al.*, 1977). A bulk sample taken near the basal peat was radiocarbon dated (Beta Analytic, Miami, Florida, U.S.A.) based on a half-life of 5568 years and results reported in years before the 1950 standard.

A second core from each site was frozen and then cut at 0·5 cm intervals from the surface to 10 cm, and then at 1 cm intervals thereafter. These samples were subdivided for loss-on-ignition, grain size and ^{137}Cs/^{210}Pb dating. Using a vernier caliper, a known volume of frozen core sample was obtained and subjected to loss-on-ignition following Dean (1974). Heating to 100 °C for 15 h allowed for dry bulk density calculations followed by heating to 550 °C for 2 h to determine organic and inorganic content of the subsample. The grain size distribution of selected subsamples was determined after removal of $CaCO_3$ by 1 N acetic acid and removal of organics by repeated treatments in 30% H_2O_2. The sample was then wet sieved at 63 µm to determine the percentage of sand. The less than 63 µm size fraction was analysed on an Elzone particle size analyser to obtain the size distribution of silt and clay.

^{210}Pb, ^{226}Ra and ^{137}Cs were measured non-destructively by direct gamma spectrometry using an Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detector fitted with a sodium iodide escape suppression shield (Appleby *et al.*, 1986).

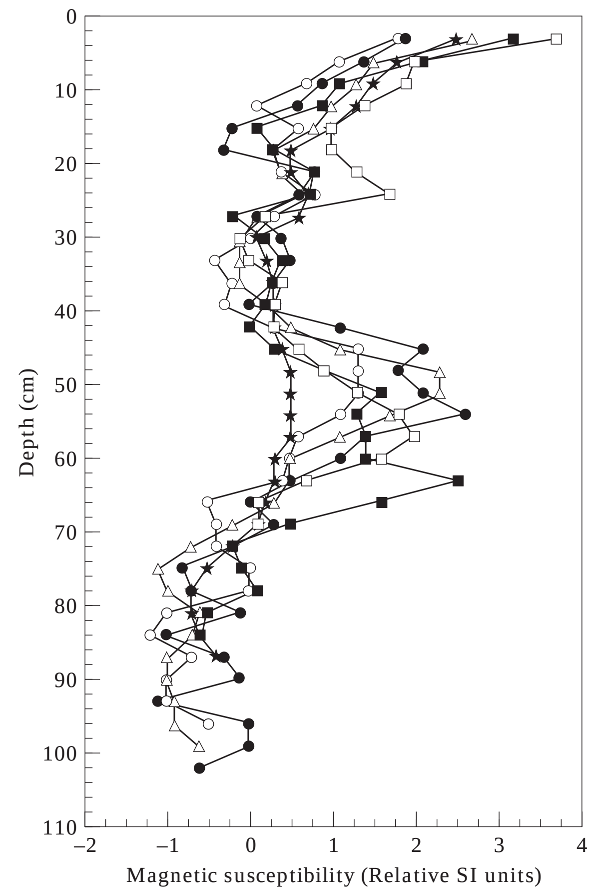

FIGURE 2. Magnetic susceptibility profiles for six cores collected at the Nauset Bay site showing the similarity among cores. ■, core 1; ●, core 2; ○, core 3; ★, core 4; □, core 5; △, core 6.

Results

Sedimentary characteristics

Spartina alterniflora rhizomes dominated the Inlet 1 and Fort Hill Island cores from the surface to underlying sand deposits, except for a record of sparse *S. patens* near 50 cm in the Inlet 1 core and at the surface of the Fort Hill core (Figure 3). Both cores ranged in colour from dark and very dark greyish-brown at the surface to olive grey and dark grey at the bottom. The Nauset Bay core exhibited greater variation with freshwater or brackish-water peat (*Typha* and sedge) dominating the core profile from 50 to 130 cm, a sedge/*S. alterniflora* transition zone at 40–50 cm, and typical high marsh species (*Distichlis spicata*, *S. patens*) to the surface. The freshwater/brackish-water peat was black while the upper salt marsh peat was a characteristic dark greyish-brown. Well-defined sand deposits were noted in the Fort Hill Island core at approximately 16 cm, and the Nauset Bay core at 50 and 85 cm, essentially bracketing the zone of sedge rhizomes.

Dry bulk density at the Inlet 1, Fort Hill Island and Nauset Bay sites was variable with depth (Figure 3) with means of 0·23, 0·38 and 0·34 g cm^{-3}, respectively. An average organic content of 30% reflects peat accumulation similar to other New England salt marshes (Armentano & Woodwell, 1975; McCaffrey & Thomson, 1980; Bricker-Urso *et al.*, 1989). Percent organic content at the Fort Hill Island site was considerably lower, with a corresponding increase in the sand fraction along the core profile.

Short-term accumulation rates: feldspar horizons

An exceptionally high rate of accumulation, about 24 mm year^{-1}, was recorded at the Inlet 1 site between June 1991 and April 1992 (Table 1). During

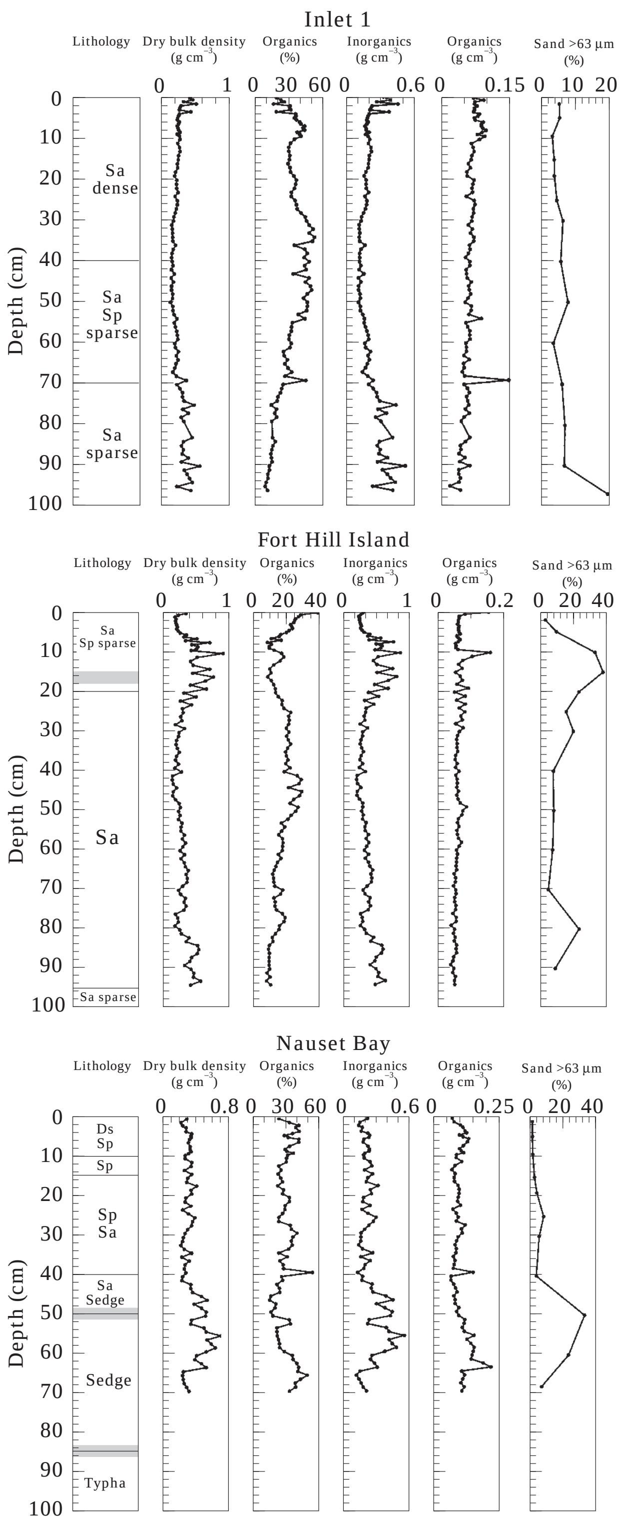

FIGURE 3. Sediment characteristics along core profiles at three sites. Key to rhizomes identified in lithology; Sa *Spartina alterniflora*, Sp *Spartina patens*, Ds *Distichlis spicata*. Stippled pattern in lithology indicates discrete sand layers.

this interval, two major storms, including Hurricane Bob (20 August 1991) and the Halloween Eve Storm of 1991, buffeted New England. The high energy of these storms was evidenced by peat blocks eroded from the marsh and re-distributed on the marsh surface, as well as sand overwash deposits on the marsh, all in the vicinity of the Inlet 1 feldspar plots. From April 1992 to August 1993, an interval containing two major ‘ nor’easters ’ (December 1992, March 1993 ‘ Storm of the Century ’), accretion at the Inlet 1 site remained high (10 mm year^{-1}). The final interval of feldspar monitoring, August 1993 to July 1994, was free of major coastal storms and the accretion rate was lower (<5 mm year^{-1}). Short-term accretion rates at the other sites, more remote from the Inlet, were lower than the Inlet 1 site for the two intervals defined by storms. However, these remote sites revealed a variable response to storm and storm-free periods. For example, accumulation rates at Hemenway were unexpectedly lower during the storm periods. Nauset Bay and Fort Hill Island showed substantially higher rates during the second storm period as opposed to the first.

Sediment accumulation rates: radiometric dating

Accumulation rates were estimated using both ^{137}Cs and ^{210}Pb data. In each core, the ^{137}Cs profiles show well-defined peaks in activity, though the magnitude varied among cores (Figure 4). The peak is assumed to record the 1963 maximum fallout of ^{137}Cs from atmospheric testing of nuclear weapons. Annualized mean sediment accumulation rates for the period of 1963–91 determined from the ^{137}Cs peak are given in Table 2.

The overall trends in the unsupported ^{210}Pb profiles for the Inlet 1, Fort Hill Island and Nauset Bay sites (Figure 4) show an exponential decline in activity with depth, suggesting more or less constant rates of sediment accumulation; however, each profile contains irregularities that may be indicative of short-term fluctuations in net deposition. Detailed chronologies were developed by applying the constant rate of ^{210}Pb supply model (Appleby & Oldfield, 1978; Figure 5). This uses an integrated dating parameter that smoothes small scale irregularities. For Inlet 1 and Fort Hill Island, mean accumulation rates for the past 70 years (Table 2) were estimated from the mean slopes of the integrated ^{210}Pb activity *vs* depth profiles (constant rate of supply model). For Nauset Bay, mean accumulation rates were estimated as the average of the constant initial concentration model and the constant rate of supply model (see Appleby & Oldfield, 1978).

TABLE 1. Sedimentation rates measured from the feldspar marker horizons at five sites for three discrete time intervals. Mean rates for the entire 3-year study period (June 1991 to July 1994) are also presented

	Sedimentation rate (mm year^{-1})			
Site	Jun 91–Apr 92 (291 days)	Apr 92–Aug 93 (478 days)	Aug 93–Jul 94 (357 days)	Jun 91–Jul 94 (1126 days)
Inlet 1	23·7 ± 3·2	10·2 ± 2·7	4·8 ± 3·9	11·7 ± 1·1
Inlet 2			Trace	
Fort Hill Island	Trace	3·6 ± 0·7	4·1 ± 0·6	3·0 ± 0·1
Nauset Bay	2·2 ± 0·9	6·0 ± 1·0	− 1·0 ± 1·0	2·8 ± 0·5
Hemenway	2·0 ± 1·2	1·4 ± 0·6	6·7 ± 0·6	3·3 ± 0·2

Means ± SE are presented (n=2,3).

It is noted that for the Inlet 1 and Fort Hill Island cores, there is excellent agreement between the ^{137}Cs and ^{210}Pb dating methodologies (Table 2, Figure 5). At the Nauset Bay site, the ^{137}Cs-determined sediment accumulation rate was similar to the other two sites, but nearly 50% greater than the rate determined by ^{210}Pb. One possible explanation of these results, supported by calculations of the ^{210}Pb inventories, is a loss of surface sediments and associated ^{210}Pb through natural or human-induced erosion sometime prior to the mid-1950s. The Inlet 1 and Fort Hill Island cores both have unsupported ^{210}Pb inventories comparable to that expected by the regional atmospheric ^{210}Pb input (200 Bq m^{-2} year^{-1}; Turekian *et al.*, 1983), as does the post-1963 section of the Nauset Bay core. In contrast, the ^{210}Pb inventory of the pre-1963 section is less than half that consistent with atmospheric flux. In support of this conjecture, it may be noted that the ^{210}Pb profile of Nauset Bay is significantly more irregular below 12·5 cm depth, dated about 1956. Others have found depleted ^{210}Pb in saltmarsh cores relative to atmospheric inputs and have also suggested episodes of erosion as a causative factor (Bricker-Urso *et al.*, 1989). At Nauset Bay, during the period of August 1993 to July 1994, minor erosion of sediment was noted in the feldspar horizon marker plots (Table 1), suggesting that surficial reworking occurred.

Basal radiocarbon dates, obtained on samples from the core profile where rhizomes gave way to underlying sands, were as follows: Inlet 1, 114 cm depth, 610 ± 80 years; Fort Hill Island, 99 cm depth, 290 ± 110 years; Nauset Bay, 120 cm depth, 1210 ± 70 years. Inferred sedimentation rates were quite variable among sites and consistently lower than the short term rates based on ^{137}Cs and ^{210}Pb dating techniques (Table 2). The high sedimentation rate for Fort Hill Island should be viewed with caution because of substantial error in the radiocarbon date.

Discussion

Storms appear to be a major factor defining short-term spatial and temporal variability in saltmarsh sedimentation rates (Stumpf, 1983; Cahoon & Reed, 1995). During the sampling period of June 1991 to August 1993 several major storms impacted the northeastern United States (Davis & Dolan, 1994; FitzGerald *et al.*, 1994), resulting in sediment accumulation rates of up to 24 mm year^{-1} in the vicinity of the Nauset Inlet (Table 1). Sedimentation rates were substantially reduced during storm-free periods. Sedimentation rates at the Inlet 1 site are expected to decrease with the recent closure of the northernmost inlet. Episodic pulses of sediment accumulation during storms may represent an important mechanism for salt marshes to keep pace with sea-level rise, especially to compensate for periods of sediment deficit or when rates of accumulation are less than the rate of sea-level rise as evidenced in the short-term horizon marker results (Table 1).

At sites remote from Inlet 1, spatial variability in short-term sedimentation rates during the active storm periods and the storm-free period was considerable (Table 1). Geomorphology in the vicinity of the inlet is undoubtedly a major factor contributing to this variation. A well-developed and dynamic flood-tidal delta landward of Inlet 1 influences channel geometry (e.g. depth, curvature; Aubrey & Speer, 1984), thus affecting tidal prisms, flow patterns and sediment transport, particularly within the shallow northern portion of the Nauset system. Inlet configuration, location and extent of the flood-tidal delta, and intensity and duration of the storm event will all

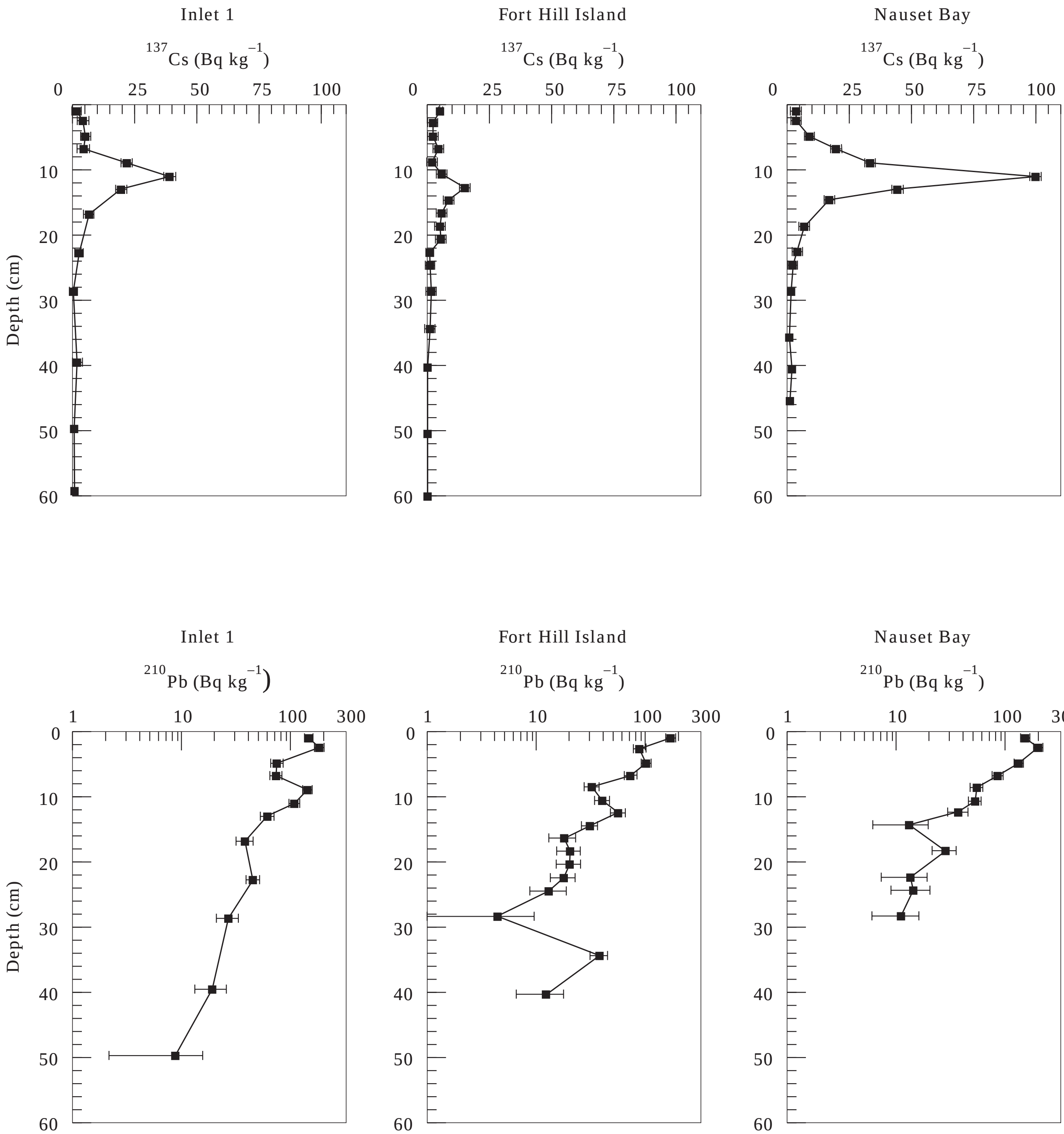

FIGURE 4. ^{137}Cs and unsupported ^{210}Pb profiles at three sites. Means ± 1 SD are presented.

contribute to variation in short-term sedimentation rates throughout the system. Related to channel characteristics, it is suggested that the minimal sedimentation recorded at the Inlet 2 site during the storm-free period is due to a deep channel intercepting sediment from transport to the marsh surface.

The influence of storms and spatial variability is also noted when interpreting the core profiles (Figure 3). A sand lens in the Fort Hill Island core at 16 cm is clear in the core lithology and grain size data, with no evidence of such a sand deposit at the other sites. Based on the core chronology and associated error (Figure 5), this sand horizon corresponds to the early

TABLE 2. Mean sediment accumulation rates based on radiometric dating

Site	Dating method (mm year^{-1})		
	^{137}Cs	^{210}Pb	^{14}C
Inlet 1	3·8 ± 0·4	4·0 ± 0·5	1·9
Fort Hill Island	4·5 ± 0·4	4·2 ± 0·6	3·4
Nauset Bay	3·8 ± 0·4	2·6 ± 0·4	1·0

1950s, a time characterized by intense storm activity (Hayden & Smith, 1982; Aubrey & Speer, 1985). Although the Inlet 1 and Nauset Bay core sites were somewhat remote from the southern location of Nauset Inlet in the 1950s, there is no evidence of a sand or mineral deposit at these other sites. Discrete mineral layers in peat profiles have been attributed to the 1938 Hurricane in other southern New England saltmarsh sites (Orson *et al.*, 1987; Warren & Niering, 1993).

The reasons for spatial variability observed at Nauset Marsh require further study, including a greater density of core and marker horizon sites. However, similar to other research sites, it is reasonable to conclude that the factors associated with this variability are related to a combination of tidal creek hydrodynamics, marsh topography, and frequency and duration of marsh surface flooding (Stoddart *et al.*, 1989; Kearney *et al.*, 1994; Cahoon & Reed 1995). All these factors are dramatically influenced by the migrating Nauset Inlet and associated effects on tidal flows, hydrodynamics, and sediment transport (Aubrey & Speer, 1984; 1985).

When Nauset Marsh sedimentation rates are estimated over decadal time scales by ^{137}Cs and ^{210}Pb techniques, both spatial and temporal variability become less apparent (Table 2). ^{137}Cs and ^{210}Pb are, respectively, integrating sediment accumulation rates over 28 and 70 year time scales. At the Inlet 1 and Fort Hill Island sites the rates, when compared between sites and between radiometric methods, are similar. The ^{210}Pb-based sediment accumulation estimate at the Nauset Bay site is lower than the ^{137}Cs-based estimate as previously noted.

The ^{14}C-based sediment accumulation rates are substantially lower than the other radiometric-based techniques (Table 2) because the ^{14}C method integrates over centennial (Inlet 1, Fort Hill Island) and millennial (Nauset Bay) time scales. Factors such as peat compaction and organic decomposition may be particularly relevant at the older and more organic Inlet 1 and Nauset Bay sites. Orson & Howes (1992), also studying a Massachusetts salt marsh, found ^{210}Pb-based sedimentation rates to be almost three times those of radiocarbon-based rates.

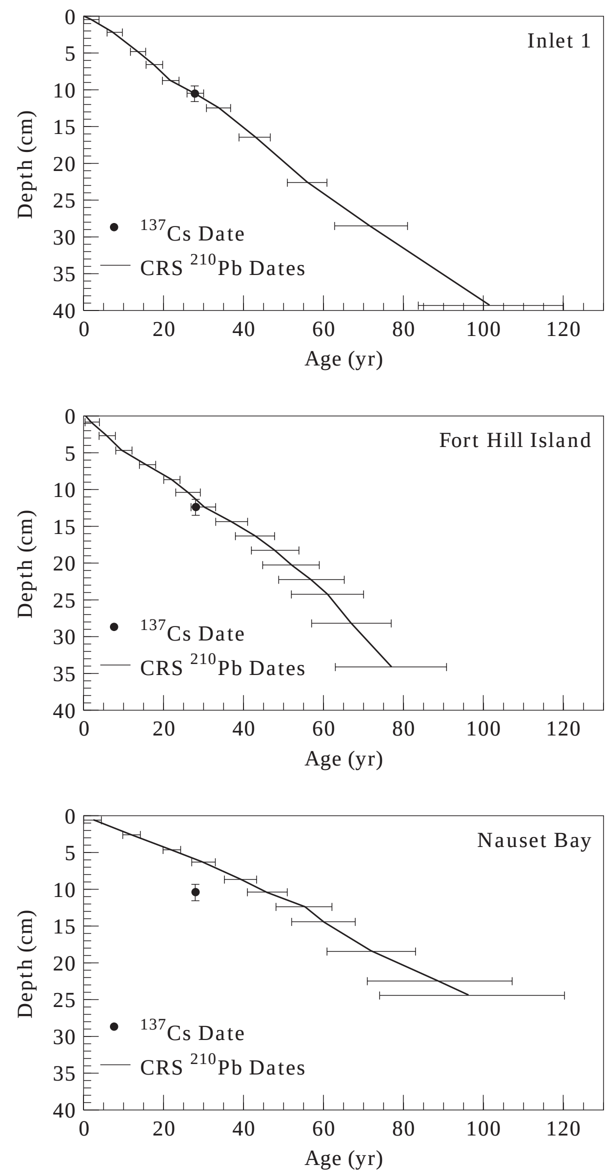

FIGURE 5. Chronologies of the three sites based on the constant rate of ^{210}Pb supply model (CRS). The ^{137}Cs-based date is presented for comparison. Means ± 1 SD are presented. ●, ^{137}Cs date; ——, CRS ^{210}Pb date.

Similar to other sites in the northeast with ^{210}Pb dating (there are no reported ^{137}Cs-based estimates of marsh sedimentation rates in the northeast), Nauset Marsh appears to be keeping pace with relative rates of sea-level rise (Table 3). The average rate of relative sea-level rise from 1921–93 (NOAA, National Ocean Service; Boston gauge) was 2·4 mm year^{-1} (Figure 6). Corresponding to the period represented by the

TABLE 3. Comparison of sedimentation rates for *Spartina* marshes of the northeastern United States estimated by the ^{210}Pb dating technique

Location (source)	Sedimentation rate (mm year^{-1})
Flax Pond, Long Island, New York (Armentano & Woodwell, 1975)	4·6–6·3
Fresh Pond, Long Island, New York (Clark & Patterson, 1984)	1·8–4·3
Narragansett Bay, Rhode Island (Bricker-Urso *et al.*, 1989)	2·4–6·0
Waquoit Bay, Massachusetts (Orson & Howes, 1992)	2·7–3·7
Nauset Marsh, Massachusetts (This Study)	2·6–4·2

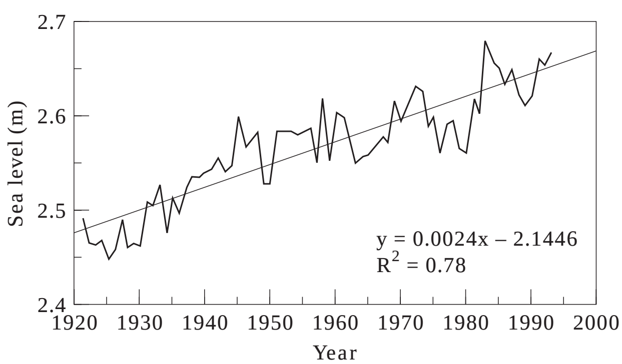

FIGURE 6. Annual mean sea level from National Oceanic and Atmospheric Administration, Boston, Massachusetts tide station number 8443970. Data from Lyles *et al.*, 1988 and personal communication, NOAA, National Ocean Service, Tidal Datums Branch.

^{137}Cs dating (1963–91), the rate of relative sea-level rise was somewhat greater (2·8 mm year^{-1}). Based on ^{210}Pb and ^{137}Cs techniques, sediment accumulation exceeded the relative rate of sea-level rise at all three Nauset Marsh sites, although at the Nauset Bay site the rates (i.e. ^{210}Pb and sea level) were nearly similar. Rhizome analysis (Figure 3) at Nauset Bay shows that over the past 40 years *Distichlis spicata* has become established at this once *Spartina patens* dominated site. The recent introduction of *D. spicata*, a marsh plant with wide ecological tolerance (Miller & Egler, 1950; Bertness & Ellison, 1987), may suggest that the Nauset Bay site is getting wetter. Warren and Niering (1993), studying a Long Island Sound marsh, suggest that conversion of a *S. patens* marsh to a wetter short *S. alterniflora*, *D. spicata*, and forbs community may be an indication that marsh accretion is not keeping up with sea-level rise. Further, they (Niering & Warren, 1980) suggest that colonization of marsh upland border communities with *D. spicata* may be attributed to rising sea level.

The observed vegetation changes at the Nauset Bay site and assumption that the site is tending toward wetter conditions may also be related to the underlying freshwater/brackish-water peat substrate (Figure 3), rather than a sediment supply deficit. Freshwater/brackish-water peat, because of greater organic content, lower mineral content and lower bulk density, may tend to collapse or compact at a greater rate than the overlying saltmarsh peat (see Nyman *et al.*, 1990). The present marsh surface could be accreting at rates similar to other portions of the marsh, as suggested by the ^{137}Cs-based sedimentation rates and ^{210}Pb inventories, but the marsh surface elevations at the Nauset Bay site, relative to the other sites, could be lower due to greater internal compaction. These processes appear to be localized to the Nauset Bay site and not occurring system-wide, as sediment cores from throughout the system (this study and others; e.g. Zaremba & Leatherman, 1984) reveal no other areas with freshwater/brackish-water peat deposits.

Marsh accretion rates throughout the Nauset Marsh ecosystem are variable, both spatially and temporally. Factors such as proximity to major tidal channels and inlets, as well as the character of peat substrate, are important to defining spatial variation. Storms are clearly important in delivering pulses of sediment to the marsh surface and these vary in time and space. A higher density of core and horizon marker sites would be required at Nauset Marsh, similar to studies at other marshes (Cahoon & Turner, 1989; Stoddart *et al.*, 1989; Cahoon & Reed, 1995), to elucidate a more comprehensive assessment of short and long-term processes associated with marsh development. Horizon marker studies provide valuable insight as to the role of storms, marsh topography, creek hydrodynamics and other factors that define both spatial and temporal variability. However, when evaluating the response of a salt marsh to sea-level rise, sampling methods such as ^{210}Pb and ^{137}Cs that integrate marsh accretion over decadal time scales are preferable to the highly variable short-term horizon marker techniques or to radiocarbon dating that infers sedimentation rates over centennial or millennial time scales.

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