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Interpreting Sea Level Rise and Rates of Vertical Marsh Accretion in a Southern New England Tidal Salt Marsh

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An investigation of marsh accretion rates on a New England type high marsh (Barn Island Wildlife Management Area, Stonington, Connecticut) reveals that this system is sensitive to changes in sea level and storm activity and the peat can accurately record rates of relative submergence as determined by tide gauge records over intervals of 2–5 decades. The results also suggest that the relationship between the accretion deficit and plant community structure is important when utilizing peat records to reconstruct historic sea-level curves within stable *Spartina patens* high marsh communities. In systems where major vegetation changes are prominent over short periods of time (<50 years), interpretations of sea-level rise should be limited to the system in which they are developed unless careful vertical controls can be maintained on the data and multiple datable horizons can be identified within the substrate. The results of this investigation further show that in a stable *Spartina patens* community within this particular system there is little vertical translocation of ^{137}Cs, making this isotope a powerful tool for assessing rates of vertical marsh development since 1954. © 1998 Academic Press

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Introduction

Estimating sea-level rise from the marsh peat record has received much attention in the literature (Redfield & Rubin, 1962; Bloom & Stuiver 1963; Redfield, 1967; Harrison & Bloom, 1977; McCaffrey & Thomson, 1980; Clark & Patterson, 1984; Bricker-Urso *et al.*, 1989; Brush, 1989; Wood *et al.*, 1989; Orson & Howes, 1992). Although studies have found that long-term accretion rates (50+ years) approximate relative sea-level rise (RSLR) (Redfield, 1967; Harrison & Bloom, 1977; McCaffrey & Thomson, 1980; Bricker-Urso *et al.*, 1989; Orson & Howes, 1992), there is some question as to the resolution with which short-term variations (<10 years) are recorded in the substrate record (Steers, 1960; McCaffrey & Thomson, 1980; Clark & Patterson, 1984). Therefore it is important to understand the sensitivity of these marshes to both long and short-term sea-level variations when attempting to utilize these systems in reconstructing historic sea-level changes.

Estimating rates of accretion or sediment accumulation in a natural marsh system requires collaborating evidence from as many sources as possible. The best results are obtained when a number of dating techniques (i.e. physical or biostratigraphic horizon markers) are employed simultaneously within an individual system. Some of the techniques used to establish rates of vertical marsh development include radioisotope analysis (Redfield & Rubin, 1962; Bloom & Stuiver, 1963; Armentano & Woodwell, 1975; Delaune *et al.*, 1978; Sharma *et al.*, 1987; Van de Plassche *et al.*, 1989), pollen analysis (Brush *et al.*, 1982; Clark & Patterson, 1984; Brush, 1989; Orson *et al.*, 1990), storm lenses (Wolman, 1967; McCaffrey & Thomson, 1980; Orson *et al.*, 1990; Warren & Niering, 1993), pollution (Clark & Patterson, 1984; Allen, 1988; Bricker-Urso *et al.*, 1989), artificial surface markers (Steers, 1960; Harrison & Bloom, 1977; Stumpf, 1983; Stoddart *et al.*, 1989; Cahoon *et al.*, 1995), historic records (Flessa *et al.*, 1977; Orson *et al.*, 1990), foraminifera (Varekamp *et al.*, 1992) and pollen indicators such as ragweed for European settlement (Russell, 1980; Brush *et al.*, 1982) or the decline of chestnut due to blight conditions at the turn of this century (Anderson, 1974). Due to the fact that many of the marsh dating techniques either have a resolution of just a few years (i.e. sediment traps, feldspar markers) or periods greater than 30–50 years (i.e. radioisotope analysis, pollen indicators, the onset of industrial pollution) it is difficult to find identifiable time markers which cover multiple time frames on the

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order of decades or less[1], thus limiting our ability to determine the sensitivity of these marshes to short-term variations in sea level.

Several approaches have been used to relate rates of vertical marsh accretion to RSLR. The most widely used tool for assessing the relationship between RSLR and vertical marsh development is comparing tide gauge records to radioisotope results; ^{210}Pb changes for periods of 50–100 years, and ^{137}Cs accumulations during the last 30–40 years (^{14}C has been used for estimating changes over 100's and 1000's of years, however, these long-term data cannot be directly compared to short-term tide gauge records and will not be discussed further here). These techniques are useful in determining average long-term relationships between RSLR and vertical marsh development, but resolution of finer time-scales has been problematic due to a number of factors including autocompaction of the substrate (Kaye & Barghoorn, 1964; Cahoon *et al.*, 1995), bioturbation and erosion (Sharma *et al.*, 1978), inlet dynamics (Flessa *et al.*, 1977; Clark & Patterson, 1984; Orson & Howes, 1992; Roman *et al.*, 1997) and distance from channel (Stoddart *et al.*, 1989) and ice rafting (Wood *et al.*, 1989). Therefore, the question of how accurately tidal marshes record RSLR and at what level of precision such findings can be interpreted cannot be answered by radioisotopic investigations alone, particularly if one considers the short-term variability in sea-level rise that is apparent in tide gauge records.

The current understanding of the resolution of these peats to record sea-level variations through time are typified by the works of McCaffrey and Thomson (1980) and Clark and Patterson (1984). McCaffrey and Thomson (1980) suggested that rates of accretion in their Connecticut marsh responded to 25–50 year periods while the shorter-term variations appeared to be smoothed over time. In contrast, Clark and Patterson (1984) noted that their Long Island marsh system appeared to record a 10 year lag in sea-level rise in the peat record. To test whether marsh substrates respond to short-term variations in RSLR or long-term variations, the authors will be reporting on the results of an investigation into the relationship between RSLR and rates of vertical marsh accretion during the last 50 years. This study utilizes a unique set of horizon markers including storm deposits, artificial horizon markers and historic plant community structure (the latter to be reported in detail in future articles) that allows specific 10-year intervals to be established within the peat without the need for extrapolation. By applying this unique set of markers to known tide gauge records for the same period, it will be possible to directly compare marsh accretion rates with the variations noted in the tide gauge record and assess the resolution with which these marsh substrates record changes in sea level through time.

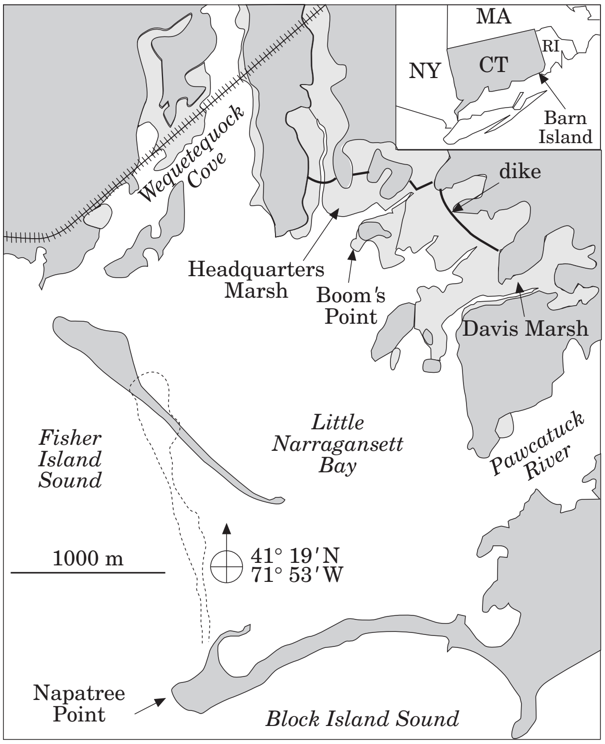

FIGURE 1. Map of study site. Dashed line refers to position of barrier island prior to the 1938 hurricane. Gray tone denotes upland and beaches, marsh pattern denotes both former (areas behind dike) and present tidal marsh area.

Study site

The area chosen for study is the Barn Island Wildlife Management Area, located along the border of Connecticut and Rhode Island in Stonington, Connecticut, U.S.A. The tidal marshes cover about 1·4 km^2 and have formed in the coastal drowned finger valleys of Connecticut's Eastern Upland physiographic region (Bell, 1985). The marsh system is found on Little Narragansett Bay (Figure 1) and is separated from Block Island Sound by a barrier spit (Napatree Point) and a barrier island (Sandy Point). Tides are semi-diurnal with an average range of 0·8 m. Marsh surfaces are flooded irregularly on neap tides and on all spring tides. Salinities average about 25–30 and freshwater sources include seeps, runoff and small stream discharges as well as inputs from the Pawcatuck River and Wequetequock Cove.

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[1] Steers (1960) applied artificial surface markers between 1935 and 1957 to study accretion on an English marsh, however, these markers have been lost over time (Stoddart *et al.*, 1989).

The Barn Island site was originally settled during the 1600s and aside from eighteenth and nineteenth century agricultural use, little development has taken place along the marsh border. Today with the exception of a State owned boat launch, some small roads, a railroad embankment and the Davis Farm (continual operation for the last 350 years), the upper border is surrounded by post-agricultural secondary forests. During the 1930s, a significant portion of the system was ditched for mosquito control purposes. Beginning in the 1940s and continuing into the 1960s, a series of dikes were constructed from west to east across the mouth of a number of valley marshes effectively isolating about a third of the tidal wetland from full tidal flushing. Only the Davis marsh fronting the Davis Farm has never been diked (Figure 1). With the exception of the construction of the dikes and the maintenance of the parking area and boat launch, there have been no major changes in land use within the immediate vicinity of the marshes within the last 50 years (indeed many areas have become reforested during that time).

Until the 1930s, the system was separated from Block Island Sound by a single continuous barrier spit which extended from Rhode Island and accumulated westward. In 1938, the greatest hurricane to hit the southern New England coast this century, passed just west of the site at high tide with a storm surge of over 3·35 m (Pore & Barrientos, 1976). As a result of the extensive flooding and strong winds, a portion of the barrier spit (Sandy Point) separated from the main beach (Napatree Point) and migrated landward (dotted line on Figure 1). This action created the barrier island now present towards the mouth of the system and left Little Narragansett Bay with two major connections to Block Island Sound (Nichols & Marston, 1939). The barrier spit was part of Rhode Island and for it to continue to remain in Rhode Island, state boundaries had to be redrawn. Although storms regularly impact these systems, the greatest concentration of storms to hit the area this century came between 1958 and 1964 (Pore & Barrientos, 1976).

The vegetation of these marshes was initially studied by Miller and Egler (1950) and more recently by Warren and Niering (1993). The marshes throughout the site are typical New England type salt marshes dominated by *Spartina patens* on the high marsh and *Spartina alterniflora* in pannes and in lower elevations. Brackish and freshwater marshes are limited to those areas behind the dikes and thin belts along the upper border where freshwater seeps are evident. Brackish and freshwater areas were not included in this study.

Beginning in the early 1960s and continuing through to the present, glitter markers of different colours were placed on the marsh surface at about 10 year intervals at a location on Bloom's Point (1962, 1964, 1973, 1983 by Dr A. Bloom of Cornell University and in 1994 as part of this investigation). These glitter markers were surveyed during the mid 1970s (Harrison & Bloom, 1977), the mid 1980s (Young, 1985) and again for this investigation.

Methods

Sampling to determine rates of accretion was conducted in three primary locations (Figure 1). The Bloom's Point samples were taken in a *S. patens* high marsh zone approximately 15 m from the edge of a large bay front channel. Because the channel edge is an erosionary feature, there is no *S. alterniflora* low marsh border to intercept sediments between the sampling location and the bay. The Headquarters samples were also taken in a high marsh zone approximately 25 m from the bay front border. Here too, low marsh is limited along the channel edge and sediments can be deposited directly onto the high marsh surface. The Davis samples were taken in a stunted to intermediate *S. alterniflora* zone about 25 m from the channel edge. Here the marsh grades directly into the bay and there is a 2 m low marsh border (tall *S. alterniflora*) fronting the main channel.

Substrate characteristics

Over 100 peat cores have been collected and analysed from the Barn Island system using a side chambered sectional coring device (Russian Peat Sampler). Based on the analysis of these cores, sites were chosen within two of the subsystems (Headquarters Marsh and Davis Marsh) for additional substrate sampling based on depth of peat and stability of the plant community through time. Sampling at Bloom's Point was further decided based on earlier sampling by Dr Art Bloom of Cornell University between the 1960s and 1980s. In each subsystem, five additional cores were collected and removed for substrate dating and analysis. Of the 15 cores collected for this portion of the investigation, 11 were used for analyses and the remaining cores were stored as backup material. In two of the locations (Bloom's Point and Headquarters) sampling was conducted within a relatively stable *S. patens* dominated plant community while sampling in the third location (Davis marsh) was conducted in a stable stunted *S. alterniflora* dominated community on the marsh.

Immediately upon removal of each core, changes in colour (using a Munsell Colour chart) and texture were recorded in the field. Cores were then wrapped in plastic and transported to the laboratory where they were stored at 4 °C.

In the laboratory one core was carefully dissected. The relative abundance of dominant plant taxa (Niering *et al.*, 1977; Orson *et al.*, 1987) and major sedimentological characteristics including stickiness, plasticity, grain size and texture (Soil Survey Staff, 1975) were determined.

To determine bulk densities, organic and water content of the substrate, one core from each subsystem was cut into 2 cm thick slices. Each 2 cm thick slice was then dried at 100 °C for 24 h, weighed on an analytical balance and ashed at 375 °C for 4 h before being weighed again. Bulk densities were reported in grams per cubic centimetre of dry weight and combustible organics in percent loss on ignition and water content as percent loss.

Radioisotope analysis

A total of four cores were analysed for radioisotopes, one from each subsystem (Davis, Headquarters, Bloom's Point) was tested for ^{137}Cs and ^{210}Pb activity and an additional core from Bloom's Point was used for ^{137}Cs analysis outside of the glitter plot. In the laboratory ^{137}Cs and ^{210}Pb samples were prepared for analysis by sectioning the core into 0·5 cm intervals over the top 20 cm of substrate and transferring the material to plastic storage bags. Since cesium analysis is a non-destructive technique, a single sample was used for both ^{137}Cs and ^{210}Pb analyses. All ^{210}Pb (measured as a function of ^{210}Po activity) and ^{137}Cs samples were analysed under the direction of Dr H. Jeter, Teledyne-Brown Engineering, Westwood, New Jersey, U.S.A. ^{137}Cs was analysed using a high resolution gamma ray spectroscope [Ge(Li) detector] coupled to a nuclear data acquisition and reduction system and the results were recorded in picoCuries per gram dry weight of sediment. ^{210}Pb activity was determined radiochemically by assaying the beta activity of its bismuth-210 daughter series standardized to a ^{208}Po tracer. To determine unsupported levels of activity, the activity from two to three deep samples was averaged for each core and subtracted from the laboratory results. A straight line regression analysis was performed on the unsupported activity and age was determined according to Faure (1986). Assumptions of this technique include a steady input of atmospheric lead and a constant rate of decay.

At Bloom's Point, sampling locations were further divided between those within a glitter marker bed established by Dr Arthur Bloom during the 1960s (Bloom's Point—In) and a second sampling location 10 m away (Bloom's Point—Out). Twenty ^{137}Cs samples were taken from each core from within and out of the Bloom's Point marker bed plot. An additional 10 samples were analysed for a core from the Davis Marsh. Twelve ^{210}Pb samples were analysed from the individual cores used for ^{137}Cs analysis taken within each subsystem. An additional 10 ^{210}Pb samples were analysed in the core taken from within the glitter plot at Bloom's Point to increase the resolution and help define mixing in the lower layers. Differences among samples were compared using χ^2 analysis and *t*-tests.

Glitter marker beds

Beginning in 1962, coloured glitter was applied to 1 m^2 plot on the marsh surface at Bloom's Point. These applications were repeated with different colours in 1964, 1974, 1983 and most recently in 1994 (this study), to continue the database into the future. One core from Bloom's Point—In was dissected and the glitter horizons were identified by counting individual glitter grains over depth.

Tide gauge records

Tide gauge records were obtained from the New London Tide Gauge (Station no. 8461490) located in New London, Connecticut, U.S.A., approximately 10 km west of the site. This gauge has been in continuous operation since 1938 (Lyles *et al.* 1988) and, due to the stability of the coast, can be applied directly to the Barn Island marshes (Harrison & Bloom, 1977).

Results

Substrate characteristics

General substrate characteristics for the top 20 cm of all cores showed little variation with depth. Peats were dominated by a dense mat of *S. patens* roots and rhizomes and the substrate was brown in colour (10YR 5/3–4/3). Inorganic sediments within the peat accounted for about 20% of the volume and were comprised of silts and clays except where sand lenses were evident. Bulk densities from Bloom's Point (Figure 2) averaged $0·362 \pm 0·018$ g cm^{-3} with combustible organic material averaging *c.* 25% and water *c.* 60%. At Headquarters, bulk densities averaged $0·373 \pm 0·020$ g cm^{-3} and at Davis $0·398 \pm 0·031$ g cm^{-3}.

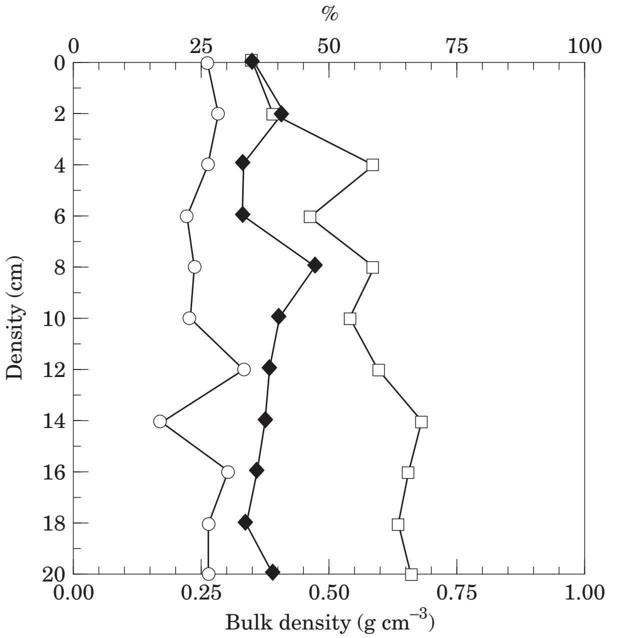

FIGURE 2. Representative substrate characteristics for the top 20 cm at Bloom's Point. —□—, % water; —○—, % ash free dry wt.; —◆—, bulk density.

Radioisotope analysis

The results of ^{210}Pb and ^{137}Cs analyses are shown on Figures 3 and 4, respectively. Figure 3 shows the unsupported ^{210}Pb results obtained from two *S. patens* zones (Headquarters and Bloom's Point—In) and one *S. alterniflora* zone (Davis). Supported ^{210}Pb averaged 0·14 pCi gm^{-1} dry wt. at Bloom's Point; 0·21 pCi gm^{-1} wt. at Headquarters; and 0·04 pCi gm^{-1} dry wt. at Davis. Based on the combined results from all sites, five samples between 14 and 18 cm at Bloom's Point were rejected as outliers (noted by open circles). The average long-term accretion rates noted for each sample location are based on the slope of the regression. (Note: financial constraints limited our ability to increase the resolution of ^{210}Pb sample taken at Headquarters and Davis Marsh. Therefore, utilizing ^{210}Pb for analysing 10-year intervals will be limited to the results obtained for the Bloom's Point core). The average rate of vertical marsh growth at Bloom's Point was 0·202 cm year^{-1} (r^2=0·961) (Table 1); at Headquarters, 0·180 cm year^{-1} (r^2=0·885); and at Davis, 0·330 cm year^{-1} (r^2=0·880). The accretion rate at Davis is statistically different (P<0·05) from the other two sites, reflecting the differences in plant community structure.

Rates of accretion interpreted from ^{137}Cs are shown in Figure 4. Two samples were taken at Bloom's Point: one within the plot (Bloom's Point—In) and a second 10 m away (Bloom's Point—Out) and a third sample was obtained from the Davis Marsh. The ^{137}Cs results from Bloom's Point—In also include the results of the glitter counts (Table 1). At Bloom's Point the inferred rate based on the 1954 ^{137}Cs horizon is 0·225 cm year^{-1} within the glitter plot and 0·231 cm year^{-1} outside of the plot. The accretion rates at these sample locations obtained from the 1963/1964 horizon show that accretion in the system has averaged 0·170 cm year^{-1} during the last 30 years for both samples. At Davis the 1954 horizon yields a rate of 0·29 cm year^{-1} and the extrapolated 1964

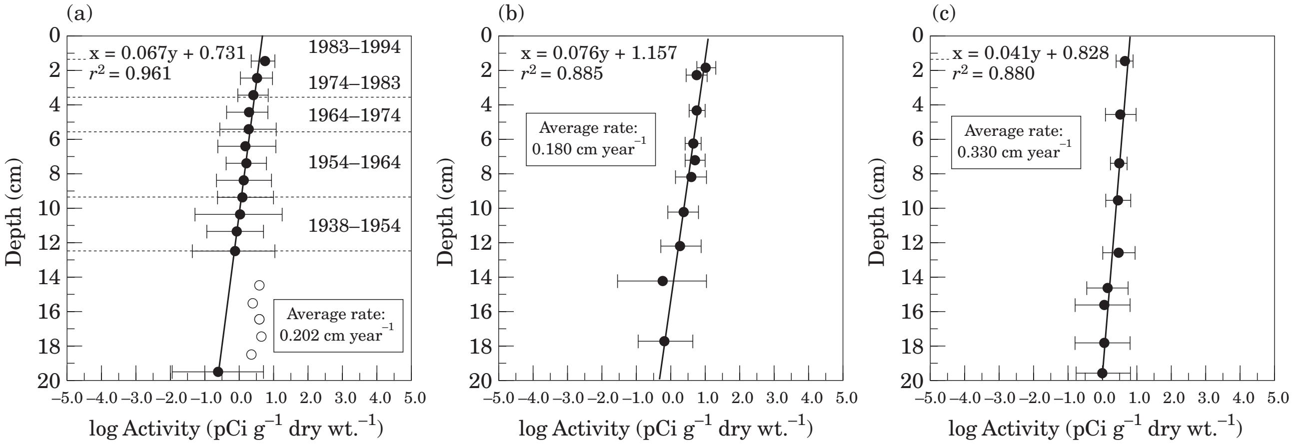

FIGURE 3. Unsupported ^{210}Pb profiles for the three sample areas* (a) Bloom's Point (In); (b) Headquarters; (c) Davis Marsh. Average rate of accumulation is based on the slope of the regression through all points. Activity is expressed as a function of picoCuries per gram of dry wt. of sediment plotted against depth on a semi-log scale. Open circles denote outliers (see text for explanation). Dashed lines denote periods of time determined by storm and glitter markers except 1954 which was extrapolated from ^{137}Cs results.

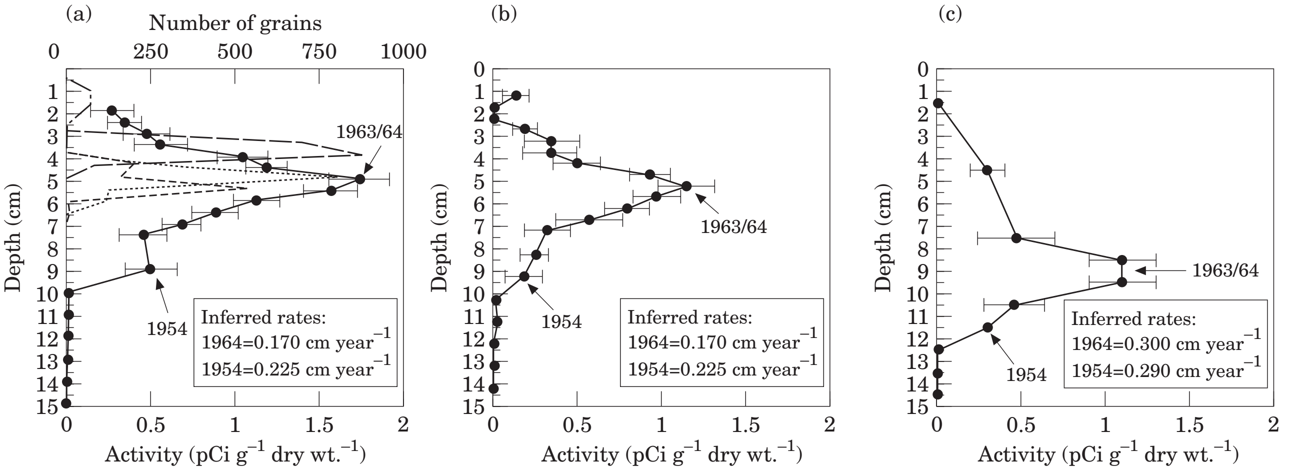

FIGURE 4. ^{137}Cs results for (a) Bloom's Point In (b) Bloom's Point Out and (c) Davis Marsh. Bloom's Point—In also includes the results of glitter counts for that site. Inferred rates of accretion are extrapolated from atmospheric inputs of cesium due to the testing of thermonuclear devices during the early 1950s (1954) which peaked in 1963/1964 just prior to the introduction of the Test Ban Treaty of 1964. Due to fewer sampling points from Davis, the 1963/1964 peak was extrapolated based on known patterns of accumulation. —·—, 1983; – – –, 1973; · · · ·, 1964; - - - -, 1962.

TABLE 1. Rates of Vertical marsh accretion at Bloom's Point—In as determined by the various methods of analysis

	From New London Tide			RSLR as determined			
Interval Years	Δ RSL (cm)	Mean RSLR (cm year^{-1})	Regression RSLR (cm year^{-1})	210Pb (cm year^{-1})	137Cs (cm year^{-1})	Glitter (cm year^{-1})	Sand line (cm year^{-1})
1938–1954 (I)	6·5	0·406	0·400	0·120			
1954–1964 (II)	− 2·5	− 0·250	− 0·125[a]	0·356	0·400		
1964–1974 (III)	6·0	0·600	0·750	0·095	↑	0·200[d]	
1974–1983 (IV)	5·0	0·555	0·230	↑	0·170	0·170[e]	
				0·091			
1983–1994 (V)	− 3·0	− 0·272	0·081[a]	↓	↓	0·180	
1938–1994	12·0	0·21	0·22	0·20	0·22[b]	0·18[c]	0·22

^{210}Pb rates were subdivided into smaller groups based on the number of samples located between the horizons marked by the different glitter markers and storm deposits. ^{210}Pb rates for sections I–V (Figure 5) are extrapolated based on the slope of the regression for points represented by those years (I, 4 points; II, 3 points; III, 2 points; IV, 3 points; V, no samples above 1·5 cm). Other storm bands were noted, however only the 1938 sand band could be independently identified as to year of storm. RSLR, relative sea-level rise.

[a] Slope not significant.
[b] (1954–1994).
[c] (1964–1994).
[d] Harrison and Bloom, 1977.
[e] Young, 1985.

horizon shows a rate of 0·300 cm year^{-1}. At both locations there was no statistical difference between the long-term ^{210}Pb and ^{137}Cs results (since 1954) within each site. However, there was a statistical difference ($P<0{\cdot}05$) between the long-term ^{210}Pb rates and the ^{137}Cs rates since 1963–1964.

If the average rate of accretion is considered based on the 1954 horizon at Bloom's Point, the 40 year rate is comparable to the long-term RSLR rate as established through 50 years of tide gauge data (0·225 cm year^{-1} *vs* 0·221 cm year^{-1}). However, based on an analysis of the 1963–1964 ^{137}Cs peak in activity, there has been a decline in the average annual rate to 0·170 cm year^{-1} during the last 30 years or so. Adjusting for the differences between 1954 and the present (0·225 cm year^{-1}) and 1963 and the present (0·170 cm year^{-1}), accretion rates between 1954 and 1963/1964 averaged 0·400 ± 0·00 cm year^{-1} both in

(9·0–5·0 cm in 10 years) and out (9·25–5·25 cm in 10 years) of the glitter plot at Bloom's Point.

Glitter and other horizon markers

The results of the glitter analysis are shown in Figure 4 (Bloom's Point—In). According to these markers, the marsh has been accumulating at an average rate of 0·183 cm year^{-1} since 1962. Based on this and other investigations, rates of accretion at this site can be further divided into *c.* decade intervals. Between 1962 and 1974 Harrison and Bloom (1977) report a rate of 0·200 cm year^{-1}, between 1974 and 1983 Young (1985) found a rate of 0·170 cm year^{-1} and between 1983 and 1994 (this study) the rate was 0·180 cm year^{-1} (Table 1).

Using storm deposited marker horizons to calculate accretion rates is often difficult due to a number of factors including preservation of deposits and the degree with which a single event can be separated from other events within the peat record. Although a number of storm bands were found at various depths through a number of cores, the sand bands for the 1938 hurricane are the most conspicuous. Since this storm was the greatest on record for this region and there is direct evidence of a large movement of sand within this system, the sand layers noted at an average depth of 12·2 cm in 29 different cores can be assigned to the 1938 hurricane with a fair degree of certainty. Based on this analysis, the rate of accretion since 1938 has averaged 0·223 cm year^{-1}.

Tide gauge records

Although the annual rates of RSLR have varied substantially over the last 50 years (Figure 5), the long-term rate of RSLR has averaged 0·221 cm year^{-1} during the last half century [adjusted by Emory & Aubrey (1991) for crustal warping and rebound]. Based on radioisotope results and glitter marker analysis, tide gauge records have been divided into approximately 10-year intervals (designated by Roman numerals in Figure 5 and Table 1). Within each interval, tide gauge records were regressed for those years and a relative rate of sea-level rise was established for each period (Table 1 and thin lines in Figure 5). These interval rates varied significantly and ranged from a low of $-0·125$ cm year^{-1} (not statistically different from zero) between 1954 and 1964 to a high of $+0·750$ cm year^{-1} between 1964 and 1974. Figure 6 shows the relationship between RSLR and vertical marsh accretion as determined by storm and glitter markers and ^{137}Cs results.

Discussion

Bloom's point

Rates of vertical accumulation will depend on sediment inputs, flooding regime, microtopography of the site, plant community structure and autocompaction of the peat. At Bloom's Point, the surface exhibits little variation (0·27 cm) in elevation (both micro and macrorelief) between sampling locations. The site is in close proximity (15 m) to the edge of a large channel where there is no low marsh border of tall *S. alterniflora* to interfere with the movement of sediments from the channel onto the marsh surface. The substrate and vegetation have remained generally unchanged for the last 50 years and bulk densities and organic content changed little during the last 100 years (top 20 cm). Further, since the peats at Bloom's Point are comprised of a tightly woven mat of *Spartina patens* roots and rhizomes a metre or less in depth which overlie a sandy/rock substrate, significant autocompaction is extremely unlikely. Due to these site characteristics (minimal compaction, direct exchange between tidal waters and surface sediments, a stable plant community, fairly smooth marsh surface), this sampling location is ideal for assessing the record of sea-level rise as preserved and recorded in the marsh peat.

In general, the agreement between the rates of accretion established by the various techniques employed during this study increases as the interval of time increases. Comparisons between 10-year intervals of tide gauge records and rates of accretion established through horizon markers show no correlation (i.e. 1964–1974: 0·750 cm year^{-1} *vs* 0·200 cm year^{-1}) (Table 1, Figure 5). The 30 year rate of accretion established through glitter analysis (0·183 cm year^{-1}) is comparable ($P<0·1$) to the 1963/1964–1994 rate as established through ^{137}Cs (0·170 cm year^{-1}) and tide gauge records (0·181 cm year^{-1}), but not ^{210}Pb (0·123 cm year^{-1}). While at 50 years there is no statistical difference ($P<0·1$) between the 1938 to 1994 rate of 0·202 cm year as established through ^{210}Pb analysis, the 0·221 cm year^{-1} rate determined from tide gauge records and the 0·223 cm year^{-1} calculated by the 1938 storm band analysis.

One of the most important considerations in studies of this kind is the vertical stability of materials once deposited. This is particularly true of radioisotope investigations where vertical translocations of an isotope can render the results inconclusive (Church *et al.*, 1981). One of the more interesting aspects of this investigation was the precision with which specific

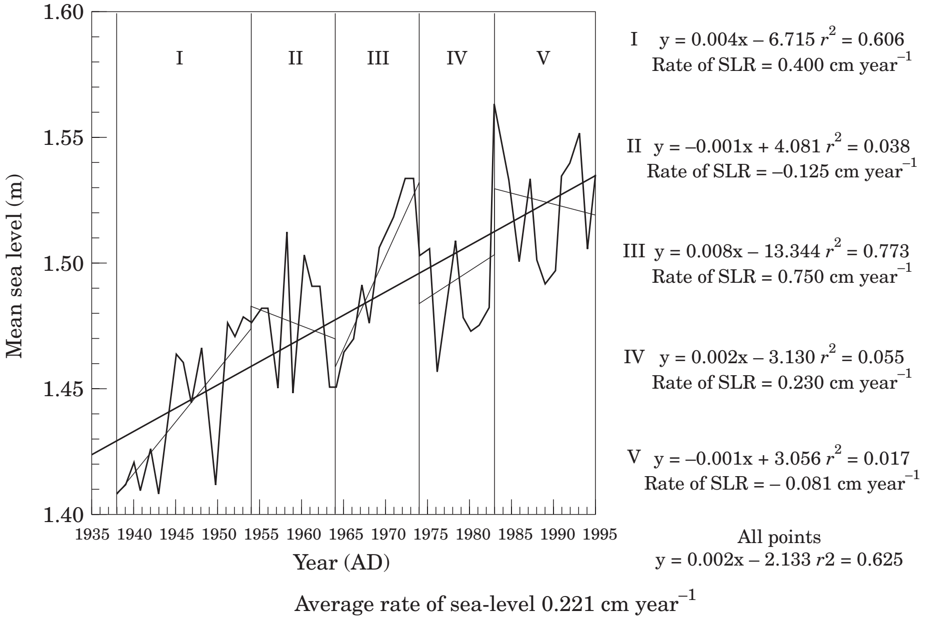

FIGURE 5. Records of the New London Tide Gauge (Station no. 8461490) since 1938. Roman numerals refer to divisions in the data based on time lines established through radioisotope analysis and physical horizon markers in the peat. Thinner lines denote regression of data within the individual time intervals. Slope of each regression and its corresponding fit are listed to the right of the figure. Long-term average rate of sea-level rise (SLR) is adjusted for crustal warping according to Emery and Aubrey (1991).

years could be identified within the peat. Having glitter horizons which bracket the 1963/1964 ^{137}Cs peak is invaluable when attempting to understand the movement of this isotope in these substrates after deposition. Based on the authors' findings (Figure 4), ^{137}Cs is very stable once deposited in this substrate and exhibits virtually no vertical translocation within these peats. Thus, ^{137}Cs in this stable *S. patens* community accurately identifies the 1963/1964 horizon in these sediments and permits its use as a tool for dating this type of substrate. Although glitter markers do not extend back to 1954, it is reasonable to assume that interpreting ^{137}Cs for this period is accurate as well, particularly since the vegetation has not changed at this location during this period.

There is evidence that the tight relationship between RSLR and ^{137}Cs deposition in this high marsh community may not hold for other vegetation zones or mixed communities (Bricker-Urso *et al.*, 1989; Orson & Howes, 1992), a topic presently under investigation. Some caution must be exercised when attempting to extrapolate these results to other systems.

Based on the data presented in Figure 6, the decade between the early 1950s and the mid-1960s was particularly important to the overall development of the Bloom's Point marsh during the last 50 years. During this period, the combined total of 0·525 cm year^{-1} (between 1954 and 1964 RSL decreased 0·125 cm year^{-1} while concurrently marsh accretion increased by an average of 0·400 cm year^{-1} for a combined net change in relative submergence at Bloom's Point of 0·525 cm year^{-1}) has helped compensate for accretion deficits during other portions of the last half century. One reason for the high rate of accretion between 1954 and 1964 may be the presence of increased storm activity during the same time [between 1954 and 1964, more major storms hit the coast than any other 10-year period this century (Pore & Barrientos, 1976]. Since coastal storms are a common occurrence for all coastal systems, it is postulated here that repeated periods of increased storm activity allow the marsh surface to compensate for accretion deficits in following decades by maintaining marsh surface elevations in relation to RSLR while providing some degree of stability to the plant community (Orson & Howes, 1992).

Barn island marsh

Over the last 30 years, vertical marsh accretion rates in both Headquarters and Bloom's Point have averaged about 30% lower than rates of relative sea-level rise during the same period (0·183 cm year^{-1} *vs* 0·299 cm year^{-1}). This supports the contention by Warren and Niering (1993) that the loss of *Juncus gerardii* from the high marsh upper border and the conversion of

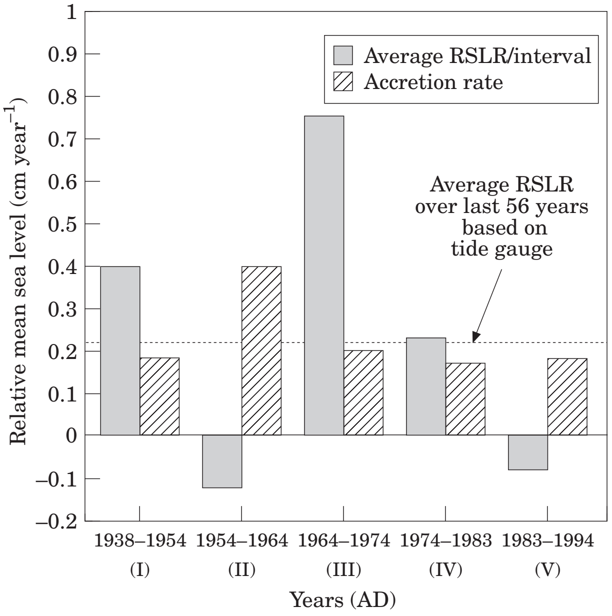

FIGURE 6. Comparisons between relative sea-level rise (RSLR) based on tide gauge records and marsh accretion rates (based on 1938 hurricane, glitter horizons and ^{137}Cs results) for the same periods at Bloom's point. The accretion rate between 1938 and 1954 was extrapolated using the 1938 hurricane marker and the 1954 ^{137}Cs peak. Other rates taken from Table 1. See text for additional detail on how rates were calculated.

S. patens dominated high marsh to a stunted *S. alterniflora*/forbs/*S. patens* complex within the last 30 years may be due to disparities between accelerated sea-level rise and vertical marsh accretion rates. *Juncus* has been shown to be declining in nearby systems as well, and if this relationship holds, *Juncus* may prove to be a good indicator species for assessing the relative impacts of accelerated submergence and storm activity on New England type tidal marshes. In the stunted *S. alterniflora* dominated Davis site, rates of accretion have been comparable to the 30 year rate of RSLR and no vegetation changes have been noted. Thus, although RSLR has accelerated recently, its impacts likely will vary depending on the plant community and location within the system.

Southern New England/Long Island Sound

Rates of accretion at Barn Island are comparable to other investigations conducted on southern New England marshes. The long-term rate of 0·22 cm year^{-1} from Bloom's Point in this study is comparable to the rate of 0·24–0·25 cm year^{-1} for a Rhode Island high marsh (Bricker-Urso *et al.*, 1989), and 0·27–0·29 cm year^{-1} for a Cape Cod, Massachusetts high marsh (Orson & Howes, 1992). At all sites, these high marsh long-term accretion rates were in close agreement with the 60+ year RSLR rate was established through tide gauge measurements (New York, 0·31 cm year^{-1}, New London, Connecticut, 0·22 cm year^{-1}; Newport, RI 0·26 cm year^{-1}; Woods Hole, MA, 0·27 cm year^{-1}). The higher rate of accretion of 0·33 cm year^{-1} obtained in the *S. alterniflora* marsh at Davis is about 1·5 times the rate of RSLR and is in agreement with rates established in *S. alterniflora* communities in Rhode Island (Bricker-Urso *et al.*, 1989; 1·5–1·7 times RSLR) and Massachusetts (Orson & Howes, 1992; 1·3–1·5 times RSLR), suggesting that surface adjustments in this community are responding to processes other than just RSLR. Although Stoddart *et al.* (1989) noted that differences in sedimentation rates may be attributed to distance from channel, other factors such as density of culms and rhizome mats (Christiansen & Miller, 1983) and autocompaction of the peat (Kaye & Barghoorn, 1964), and shallow subsidence (Cahoon *et al.*, 1995) may also play a role. It is a subject requiring further investigation.

Clark and Patterson (1984) suggested that the New England type salt marsh is capable of tracking sea-level rise with a resolution of about 10 years. The results of this investigation did not find support for a decadel lag response of salt marsh accretion to sea-level variations. Instead, the authors have found that the Barn Island marshes require 25–50 years to track and record RSLR with this correlation increasing dramatically as the time frame approaches 50 years. These findings are in agreement with McCaffrey and Thomson (1980) who suggested that short-term variations in sea level are probably smoothed over periods of decades in marsh accretion processes.

Conclusions

The tidal salt marshes of southern New England are sensitive to changes in sea levels and can accurately record rates of vertical marsh accumulation over intervals of 2–5 decades. Paleostratigraphic investigations using marsh sediments to reconstruct historic sea-level changes will have to account for this resolution when determining past rates of sea-level rise. Short-term differences between changes in sea level and marsh accretion are probably due to a number of factors, including the time the plant communities require to assimilate to a new flooding regime associated with higher or lower rates of submergence (Niering & Warren, 1980) as well as storm frequencies and other hydrodynamic processes influencing the marsh system (i.e. inlet *vs* open embayments; Orson & Howes, 1992; Roman *et al.*, 1997). Although RSL changes over 10 years may be enough time to be recorded in the peat record, reliable long-term records probably require at least 2–3 decades, with accuracy increasing as one gets to 50 year intervals. This is particularly true when considering the relationship of storm activity on vertical marsh accretion processes.

Comparisons between this and other studies in southern New England (Orson *et al.*, 1987; Bricker-Urso *et al.*, 1989l Orson & Howes, 1992; and unpubl. data) suggest that different plant communities may be accreting at different rates. The authors are postulating that sampling in areas where the vegetation differs, is mixed or fluctuates rapidly through time may lead to results which are difficult to interpret and may also help explain some of the variability noted in the literature for sediment accumulation rates between and within systems.

The results of this investigation show that in a mature, stable, *S. patens* dominated New England type high marsh, there is little vertical translocation of ^{137}Cs, making this isotope a powerful tool for assessing rates of vertical marsh development since 1954 in this marsh setting. Future work will help to determine how differences between plant communities influence our ability to interpret the history of a marsh system and accurately reconstruct the history of sea-level preserved in the long-term peat record. For now it is important to realize that when assessing paleostratigraphic records in tidal salt marsh systems such as these, controls be maintained between and within plant communities. In systems where major vegetation changes are prominent over short periods of time, it may be necessary to limit the interpretations to the system in which they are developed and not be used to assess historic sea-level changes unless careful vertical controls can be maintained on the data and multiple datable horizons can be identified within the substrate.

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