Historical rates of salt marsh accretion on the outer Bay of Fundy

Gail L. Chmura, Laurie L. Helmer, C. Beth Beecher, and Elsie M. Sunderland

Abstract: We examine rates of salt marsh accumulation in three marshes of the outer Bay of Fundy. At each marsh we selected a site in the high marsh with similar vegetation, and thus similar elevation. Accretion rates were estimated by ^{137}Cs, ^{210}Pb, and pollen stratigraphy to estimate rates of change over periods of 30, 100, and -170 years, respectively. These rates are compared with records from the two closest tide gauges (Saint John, New Brunswick, and Eastport, Maine) to assess the balance of recent marsh accretion and sea-level change. Averaged marsh accretion rates have ranged from 1.3 ± 0.4 to 4.4 ± 1.6 mm·year^{-1} over the last two centuries. Recent rates are similar to the rate of sea-level change recorded at Eastport, Maine, suggesting that they are in step with recent sea-level change but very sensitive to short-term variation in relative sea level. Based on the pollen stratigraphy in the marsh sediments, the marsh accretion rate was higher during the late 18th to early 19th century. Higher rates probably were due to local increases in relative sea level as a result of neotectonic activity and may have been enhanced by increased sediment deposition through ice rafting.

Rèsumè : Nous examinons les taux d'accumulation des marais salés pour trois marais externes de la baie de Fundy. À chaque emplacement nous avons choisi un site dans le marais élevé où la végétation, donc l'élévation, était similaire. Les taux d'accrétion ont été estimés par ^{137}Cs, ^{210}Pb et par stratigraphie du pollen afin de déterminer les taux de changement couvrant des périodes respectives de 30, 100 et ~ 170 ans. Ces taux sont comparés aux enregistrements provenant des deux marégraphes les plus proches (Saint John, Nouveau-Brunswick et Eastport, Maine) afin d'évaluer l'équilibre entre la plus récente accrétion de marais et la variation du niveau de la mer. La moyenne des taux d'accrétion varie entre 1,3 ± 0,4 à 4,4 ± 1.6 mm par an pour les deux derniers siècles. Les taux récents sont semblables au taux de variation du niveau de la mer enregistré à Eastport, dans le Maine, suggérant qu'ils concordent avec la récente variation du niveau de la mer, mais qu'ils sont très sensibles à la variation à court terme du niveau relatif de la mer. En se basant sur la stratigraphie du pollen dans les sédiments du marais, le taux d'accrétion était plus élevé à la fin du 18^{e} siècle et au début du 19^{e} siècle. Des taux supérieurs sont probablement dus à des hausses locales du niveau relatif de la mer en raison de l'activité néotectonique; ils peuvent aussi avoir été rehaussés par un plus grand dépôt de sédiments provenant de la dérive des glaces.

[Traduit par la Rédaction]

Introduction

Tidal salt marshes occur on sheltered marine and estuarine coastlines. Over 33 000 ha of salt marshes are found along the coast of eastern Canada (Hanson and Calkins 1996; Létourneau and Jean 1996), despite conversion of considerable areas to agricultural land through dyke construction. Salt marshes are one of the most productive habitats on Earth, with rates of primary productivity comparable with those of agricultural systems (Whittaker 1975). Export of organic matter from salt marshes is considered an important subsidy to coastal fisheries, a process accelerated in northern marshes where ice scours vegetation and transports it to coastal waters (Gordon et al. 1985). The marshes themselves are critical habitat for fish (e.g., Shenker and Dean 1979) and waterfowl (e.g., Reed and Moisan 1971). In Atlantic Canada seven salt marshes have been distinguished as "wetlands of international importance" through the Ramsar Convention.

Salt marshes, which occur over a narrow elevation range spanning mean high water, are assumed to adjust their elevation in step with sea-level changes. However, the rate of increase of salt marsh elevation is limited by plant productivity and sediment supply (Fig. 1). Marsh substrates accumulate through depositional processes often dominated by allochthonous inputs of mineral sediments from tides and redistribution of sediments within the system (essentially a cannibalization of the marsh). Substrates also accumulate through inputs of organic matter from plant litter and in situ contributions from roots and rhizomes (Redfield 1972; McCaffrey and Thomson 1980; DeLaune et al. 1983; Hatton

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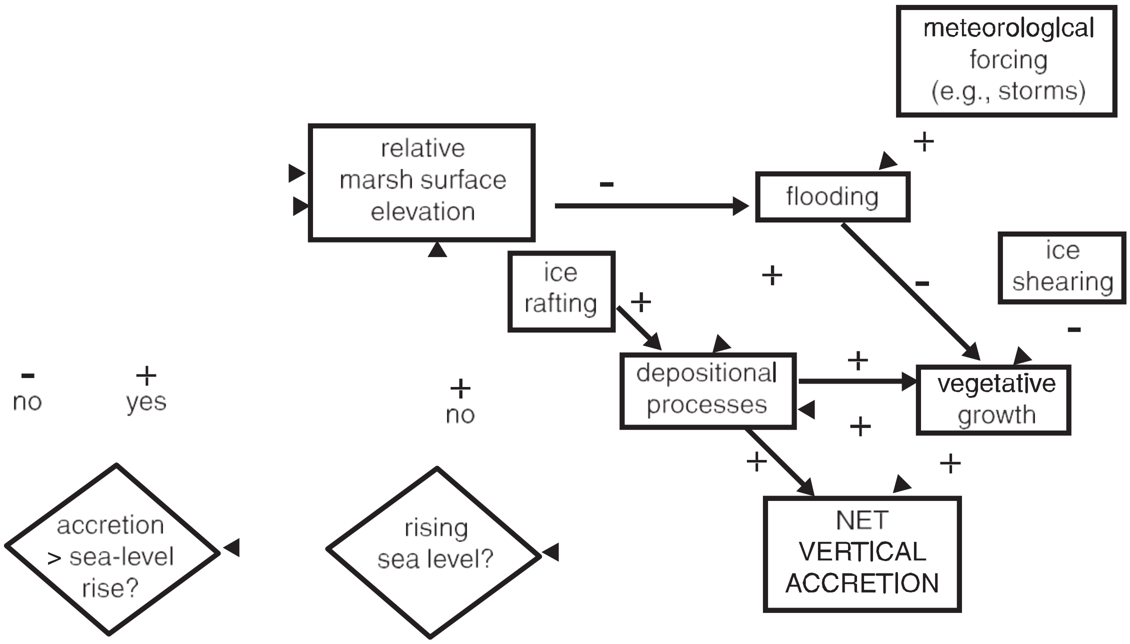
Fig. 1. The interaction of sea-level rise, flooding frequency, and depositional and vegetative processes controlling net vertical sediment (including organic matter) accretion in Bay of Fundy salt marshes (modified from Reed 1990), as described in the text. Plus and minus signs indicate positive and negative feedback, respectively.



et al. 1983; Bricker-Urso et al. 1989). With constant external sediment supply, the rate of marsh elevation change is primarily controlled by redistribution of sediments within the system and organic production. The former may be enhanced by ice rafting (Wood et al. 1989), an important process in northern marshes (Dionne 1989). Organic input is limited by production potential of the salt marsh vegetation, and this production is assumed to decrease with an increase in latitude (Turner 1976). Thus northern marshes may be less able to maintain equilibrium with accelerated sea-level rise predicted as a result of greenhouse warming.

If the vertical rate of accretion of the marsh is less than the rate of increase of relative sea level, the effective elevation of the surface is decreased and the frequency of tidal flooding is increased (Fig. 1). Although flooded regularly by tidal water, the vegetation dominating salt marshes grows best with aerated soil conditions and will not survive under prolonged flooding. Flooding stress results in decreased plant production (Mendelssohn et al. 1982) and, in turn, decreased input of organic matter to marsh sediments. Submerged salt marsh "peats" found on the inner Scotian Shelf (Shaw and Forbes 1990) provide striking evidence that rapid sea-level rise exceeded the rate of marsh elevation increase during the early Holocene.

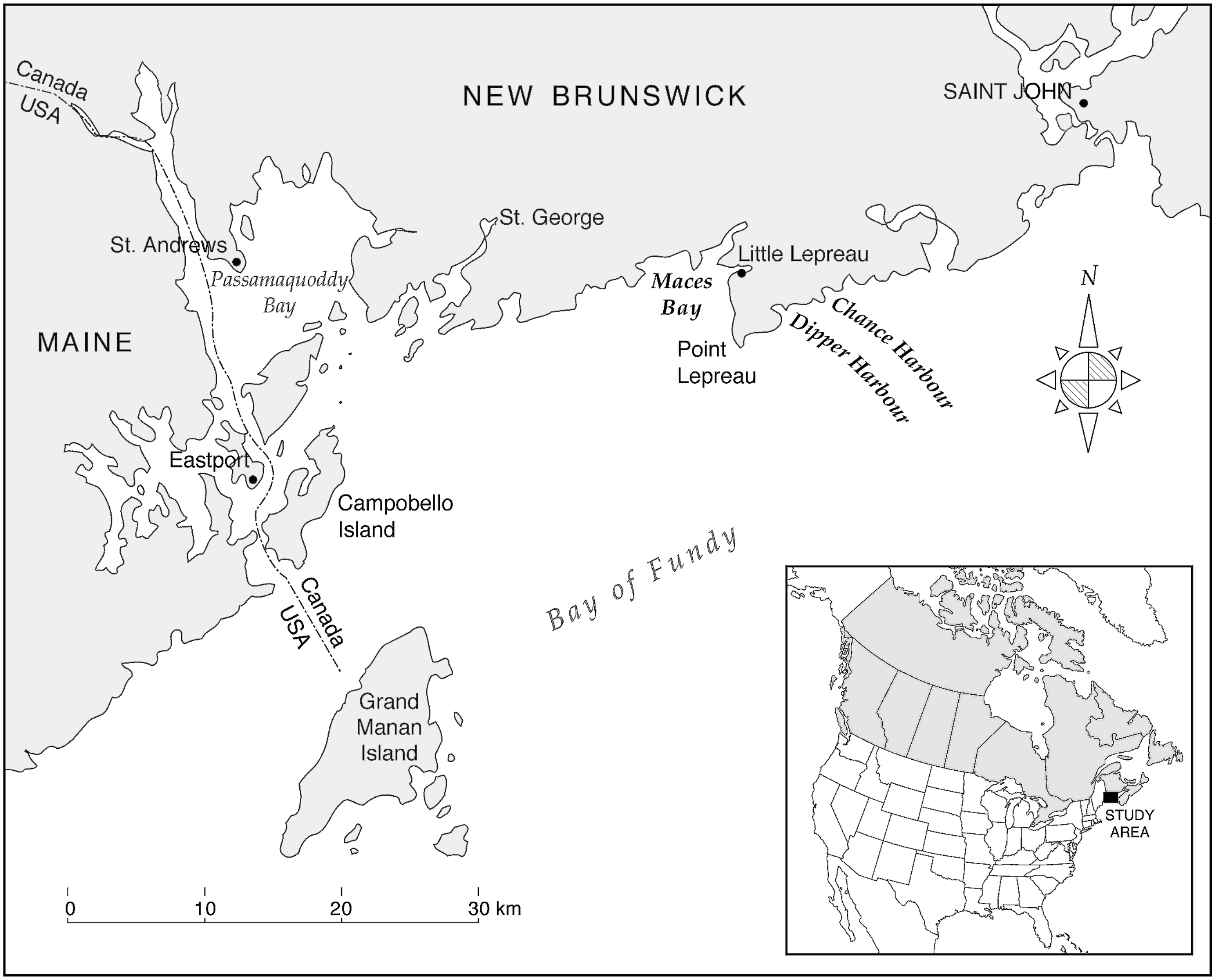
Dating of marsh sediments over the historical period allows us to compare marsh sediment accumulation rates with local tide gauge records and determine whether elevations have been in equilibrium with recent changes in relative sea level. Roman et al. (1997) examined marsh accumulation rates on the Massachusetts coast, over multiple time scales including 30 years (using ^{137}Cs) and 100 years (using ^{210}Pb). Comparison of marsh accretion rates with local tide gauge records indicated that all marshes in the Massachusetts study were keeping pace with sea-level rise over the 30 year period, but not over the 100 year period. In their study of Chesapeake Bay marshes, Kearney and Stevenson (1991) used ^{137}Cs, ^{210}Pb, and pollen analysis to determine sediment accumulation rates on three time scales, namely 30, 100, and 200+ years. Their findings suggested that regional marsh loss over the historical period was due to a deficit in the balance of marsh sediment accumulation and sea-level rise causing submergence of the wetlands. Orson et al. (1998) also used both ^{137}Cs and ^{210}Pb to measure accretion in two marshes on the Connecticut coast. They found the vertical marsh accretion rates averaged about 30% lower than rates of relative sea-level rise during the same period, and deficits were reflected in shifts in marsh plant zones.

Shaw and Forbes (1990) analyzed tide gauge records of Atlantic Canada, which show that many locations are experiencing a rise in relative mean sea level. As a consequence of greenhouse gas induced warming, the Intergovernmental Panel on Climate Change (Warrick et al. 1996) projected that eustatic sea level will continue to increase 20–94 cm (1.8–8.5 mm·year^{-1}) over the period 1990–2100. Much of the projected rise is determined by past changes in radiative forcing, which cause thermal expansion. Because of lags in response of the ocean, sea level continues to rise in model simulations, even if concentrations of greenhouse gases are stabilized.

Long-term rates of salt marsh accretion in Atlantic Canada have been published (e.g., Scott and Greenberg 1983; Brookes et al. 1985; Shaw and Ceman 1999), but we have found no studies on historical rates of salt marsh elevation change that allow us to assess whether accretion is in equilibrium with present rates of rise or if accretion might keep up with projected rates of rise. Such research is necessary to determine whether predicted increases in the rate of sea-level rise associated with global warming pose a threat to salt marshes of Atlantic Canada.

We examine rates of salt marsh accumulation in three

Fig. 2. Location of sample sites at Little Lepreau, Dipper Harbour, and Chance Harbour.



marshes on Point Lepreau, New Brunswick, on the outer Bay of Fundy. At each marsh we selected a site in the high marsh with similar vegetation characteristics, thus closely matched in elevation (Chmura et al. 1997). We apply established dating methods for the study of marsh accretion rates, ^{137}Cs, ^{210}Pb, and pollen stratigraphy, to estimate rates of change over periods of 30, 100, and ~170 years, respectively. Accretion rates are compared with records from the two closest tide gauges (Saint John, New Brunswick, and Eastport, Maine) to assess the balance of recent marsh accretion and sea-level change.

Site description

At Point Lepreau, New Brunswick, the tidal range varies from 6 m to an extreme tide of 8 m. Dipper Harbour is located on the east coast of Point Lepreau, 28 km southwest of Saint John (Fig. 2). The marsh and core sites at Dipper Harbour are described by Daoust et al. (1996). Chance Harbour marsh is 7 km northeast of Dipper Harbour, situated behind a gravel barrier; the core site is 300 m upstream from this gravel barrier and downstream of an abandoned dyke. Little Lepreau marsh is on the west coast of the Point Lepreau peninsula at the head of Maces Bay.

The study sites are situated between two tide gauges. The tide gauge record in Saint John, New Brunswick, began in 1894 (Shaw and Forbes 1990). The record from the tide gauge at Eastport, Maine, at the mouth of the Bay of Fundy, began in 1930 (Lyles et al. 1988). Both records show yearly variability, but an overall increase in sea level (Fig. 3).

This area of the New Brunswick coast supports sparse residential development surrounded by second-growth spruce and pine forest. Logging began with the first land grants to settlers in 1786 when 15 parcels were awarded, totaling 2980 acres (1 acre = 0.405 ha; Fig. 4). By 1790, 4070 acres had been granted, comprising 30% of the lands near the marsh study sites. Under contract with Britain, settlers were required to “forfeit all white pine, mines of gold, silver, copper, leads and coals to the Crown” (Provincial Archives of New Brunswick, Fredericton, N.B., RS 663A). This demand, cou-

Fig. 3. Tide gauge records for Saint John, New Brunswick (data from Marine Environmental Data Service, Canadian Hydrographic Service), and Eastport, Maine (data from Lyles et al. 1988 and S.D. Lyles, personal communication, 2000).

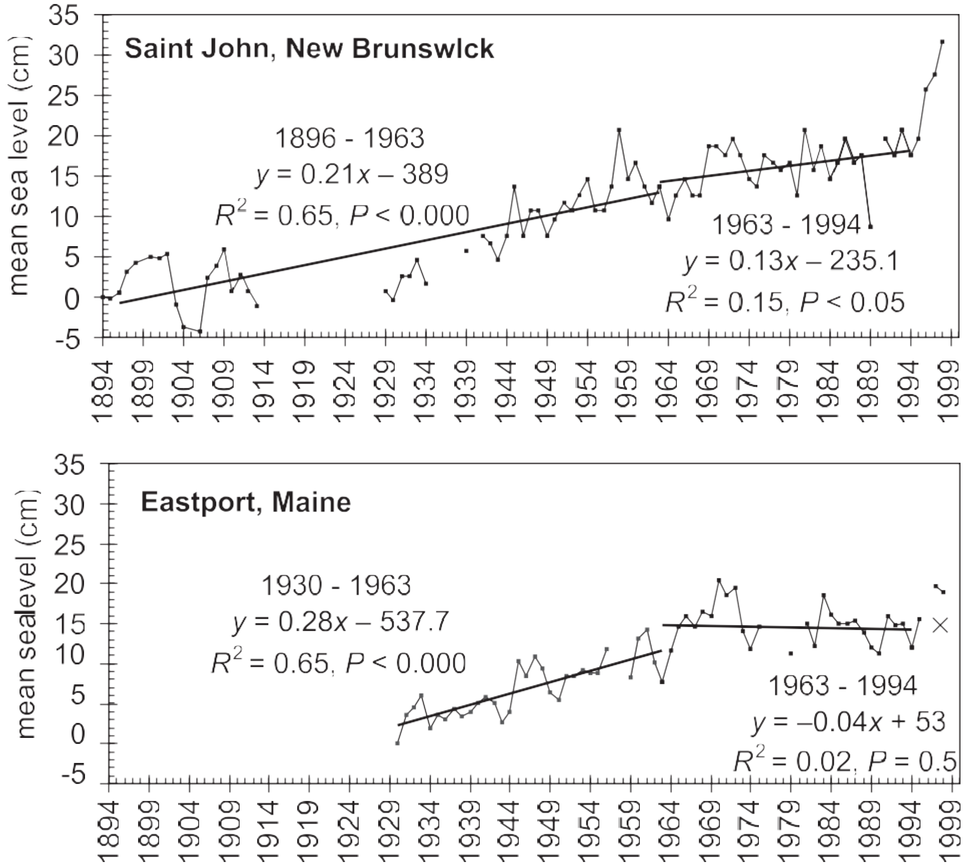
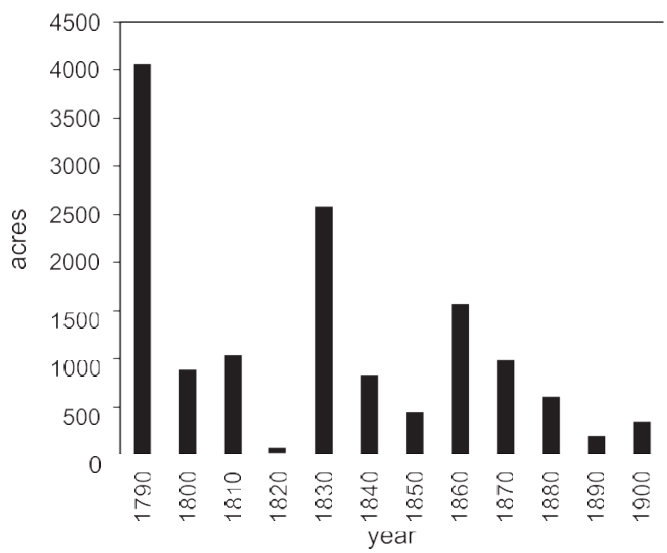


Fig. 4. Total area of land granted by "end of decade" on Point Lepreau, New Brunswick. Data compiled from grant plans 163 and 164 and New Brunswick Crown Land Grant Index, New Brunswick Department of Natural Resources and Energy.



pled with subsistence living and ship building in the region, led to large-scale land clearance. Land parcels continued to be awarded, albeit at a slower rate, until the 1820s, when seven parcels were awarded (totaling 2759 acres by 1830), likely resulting in another pulse of land clearance.

Methods

Cores were collected by three methods. At Dipper Harbour, deeper sediments were collected by vibracoring. The core and vibracoring are described by Daoust et al. (1996), who carbon-14 dated basal sediments from 331–334 cm depth. Shallow sediments were collected by gently twisting a thin-walled aluminum tube (16.4 cm diameter) into the marsh. After extrusion from the tube, sediments were sectioned at 1 cm intervals using a special mitre box. At Chance Harbour and Little Lepreau, sediments were cored with a modified Hargis corer (Hargis and Twilley 1994). Our depth of retrieval was 30–40 cm. A core extruder allowed us to subsection the Hargis cores at 0.5 cm. Dipper Harbour was cored in the summer of 1994, and Little Lepreau and Chance Harbour were cored in the fall of 1996. Only at Dipper Harbour was compaction measurable in the shallow core. Depths have been corrected with the assumption that com- paction was uniformly distributed throughout the core.

Radionuclides in sediments of Dipper Harbour and Chance Harbour were measured by C. Milan at Louisiana State University, Baton Rouge. Sediments from Little

Fig. 5. Profiles of ^{137}Cs activity (1 pCi = 37 pBq) in sediments cored from three salt marshes on Point Lepreau, New Brunswick.

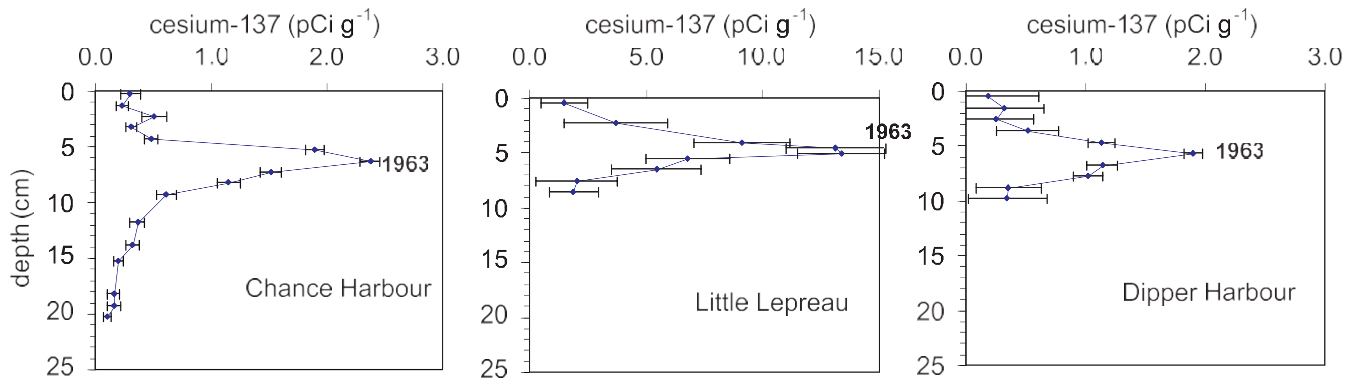
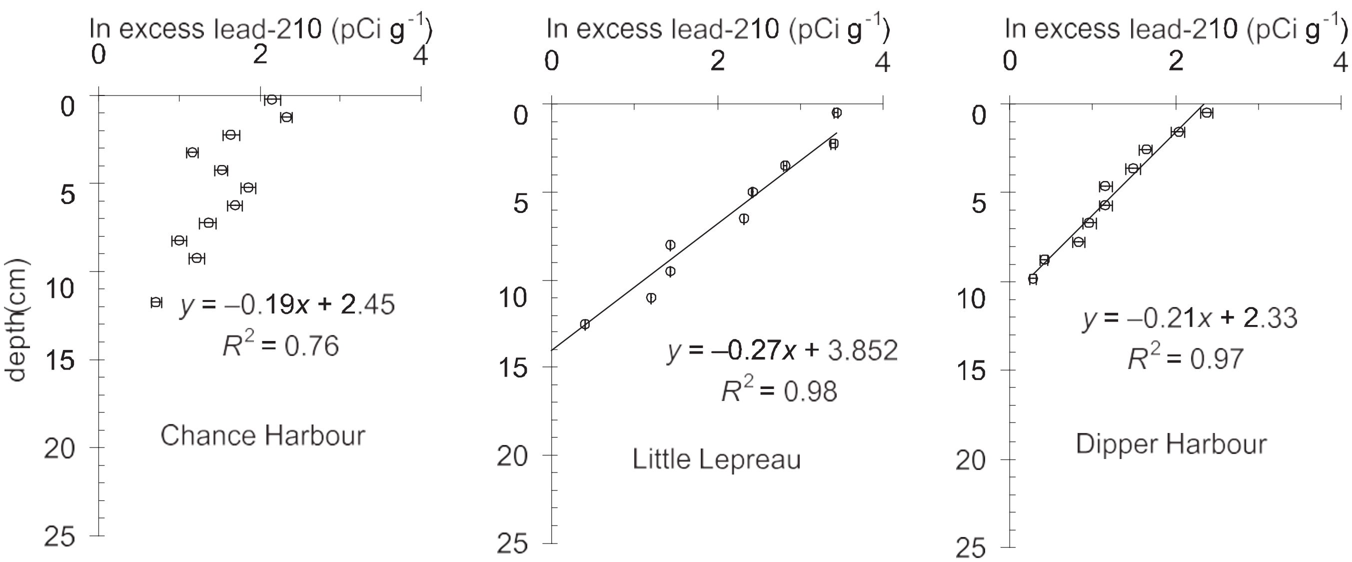


Fig. 6. Profiles of the natural logarithm of ^{210}Pb activity in sediments cored from three salt marshes on Point Lepreau, New Brunswick. Horizontal bars represent ±1 standard deviation.



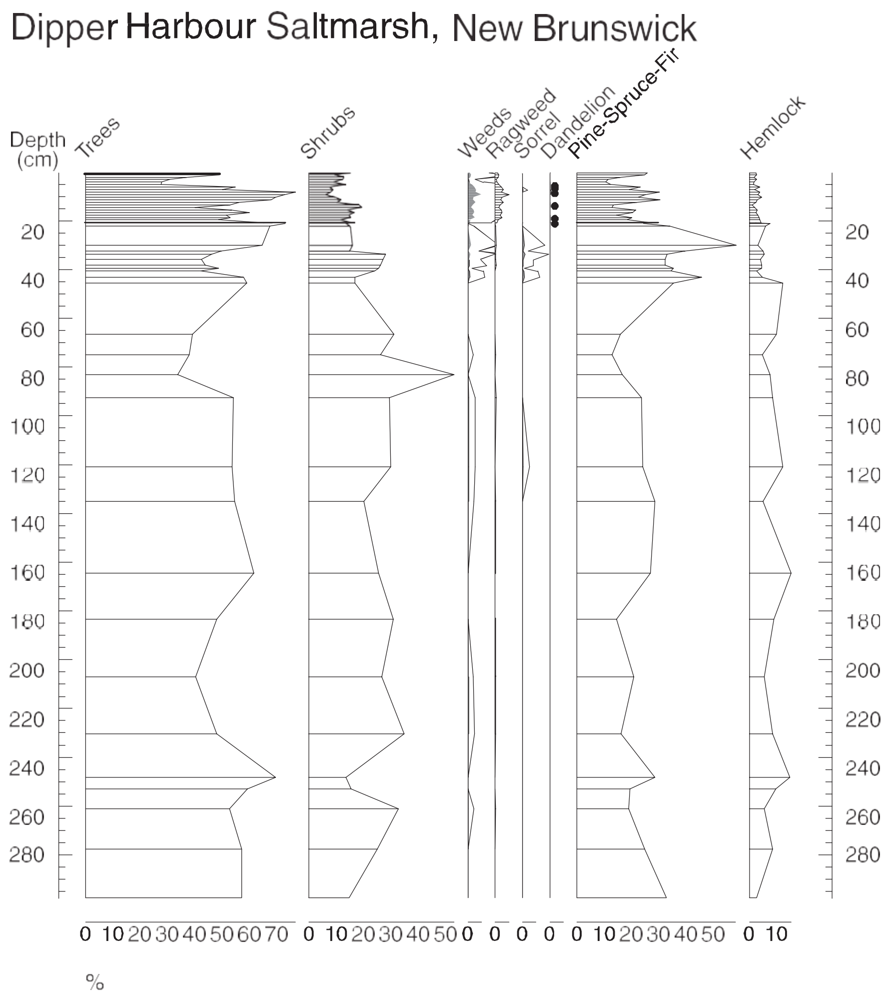
Lepreau were analyzed by Flett Research Ltd., Winnipeg, Manitoba. Concentrations of ^{137}Cs were measured on dried and ground samples by using standard gamma radiation techniques (Merriwether et al. 1988). Accretion rates were based on the depth of the sample for which greatest activity was measured. The midpoint of the depth interval that corresponds to peak activity is divided by the years elapsed since deposition. It is assumed that peak activity corresponds to 1963, the year of the peak in aboveground nuclear testing, as ^{137}Cs is an artificial element formed as a by-product of fission reactions (Pennington et al. 1973; DeLaune et al. 1978).

Lead-210 activity in sediments from Dipper Harbour and Chance Harbour sediments was measured nondestructively by direct counting of ^{210}Pb activity as described by He and Walling (1996). Measurements on Little Lepreau sediments were made by counting the activity of ^{210}Po, a daughter nuclide of ^{210}Pb. The two are assumed to be in equilibrium. Supported ^{210}Pb was determined by the visual inspection of constant ^{210}Pb activity in the deeper sections of the core. Methods are described by Flynn (1968) and Nitrouer et al. (1979). Calculation of accretion rates from excess ^{210}Pb data assumes that there is negligible migration of the radionuclide and that atmospheric deposition of ^{210}Pb has been constant through time. Lynch et al. (1989) describe the equations used to calculate accretion rates.

Immediately upon sectioning, subsamples were removed for pollen analysis. Pollen was concentrated using conventional techniques (Moore et al. 1991) and identified following Kapp (1969), McAndrews et al. (1973), and Moore et al. (1991) or by comparison to the reference collection maintained in the Department of Geography at McGill University. The minimum number of pollen grains identified in a sample was 510 in the Little Lepreau core, 621 in Chance Harbour sediments, and 376 in Dipper Harbour sediments. Counts averaged 1956, 813, and 485, respectively. Pollen percentages are calculated based on a sum of all identified pollen.

We use pollen stratigraphy to date the periods associated with clearance of forests in this region applying an interpretation similar to that of Brugham (1978), who used landscape changes associated with European settlement to detect “settlement horizons” in the pollen stratigraphy of sediments

Fig. 7. Pollen stratigraphy (% total sum) from entire core of salt marsh sediments at Dipper Harbour, New Brunswick. A patterned area under the curves represents percentages of weeds and sorrel, and an open area under the curves a 10× exaggeration. e, presence of pollen type.



from a Connecticut lake. We searched for indicators of deforestation and replacement by weed species and introduced species.

Results

Radionuclide analyses

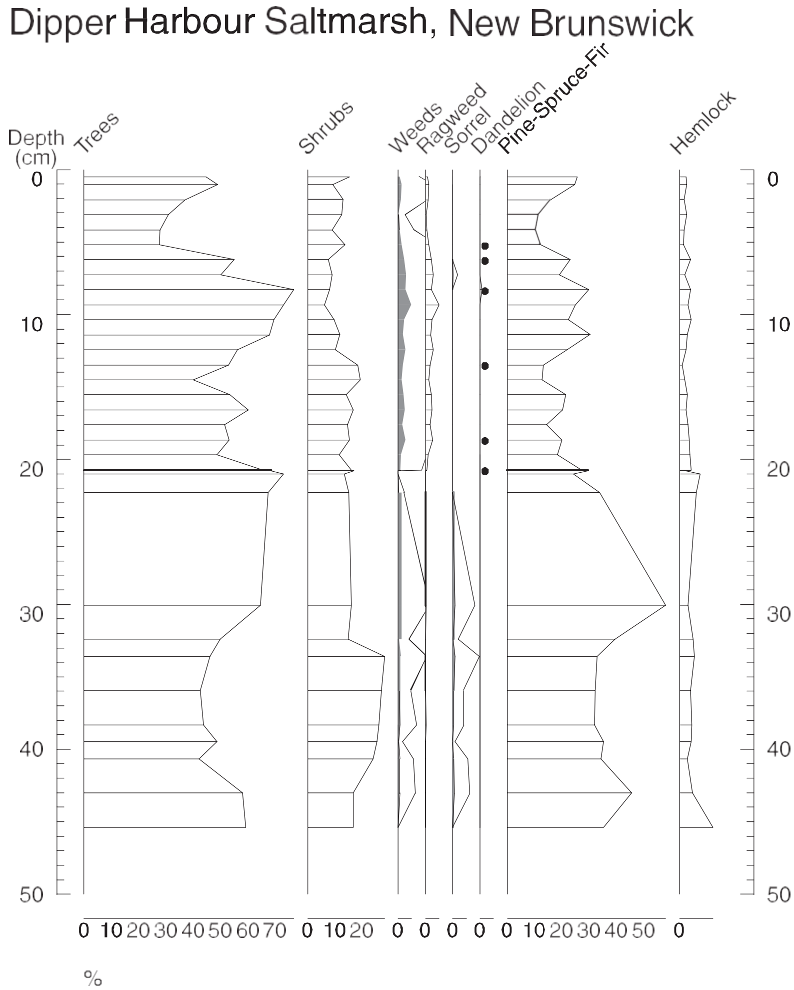
Cesium concentrations show distinct peaks in all three cores (Fig. 5). At Little Lepreau, ^{137}Cs activity is essentially the same from 4.3 to 5.3 cm depth, thus we calculate the accretion rate from the mid-depth of these two sections, i.e., 4.8 cm. As this depth represents -33 years of deposition (1996–1963), the accretion rate is 1.5 mm·year^{-1}. At Chance Harbour the ^{137}Cs activity peaks at 6.3 cm depth. This core was collected in the same field season as the Little Lepreau core, thus the period of deposition is the same, providing an accretion rate of 1.9 mm·year^{-1}. At Dipper Harbour, ^{137}Cs activity peaks at 5.7 cm depth, but the period of deposition is slightly shorter (1994–1963), yielding an accretion rate of 1.8 mm·year^{-1}.

All three cores show an exponential decline in unsupported ^{210}Pb with depth, and plots of the natural logarithm of ^{210}Pb are fairly linear (Fig. 6). This suggests relatively constant rates of deposition, thus our chronology applies the constant rate of supply model (Appleby and Oldfield 1978). Calculated rates of sediment accretion are similar for the three sites: 1.5 mm·year^{-1} at both Little Lepreau and Dipper Harbour, and 1.7 mm·year^{-1} at Chance Harbour. However, irregularities in the plot of the natural logarithm of ^{210}Pb at Chance Harbour suggest there could have been a short-term fluctuation in net deposition.

Pollen stratigraphy

The deep core at Dipper Harbour shows multiple cycles of tree pollen minima paired with peaks in shrub pollen over the last 2664 years (670 ± 160 CalBC (calibrated years B.C.) from 2560 ± 60 years BP determined at 331–334 cm,

Fig. 8. Pollen stratigraphy (% total sum) from the top 50 cm of salt marsh sediments at Dipper Harbour, New Brunswick. A patterned area under the curves represents percentages of weeds and sorrel, and an open area under the curves a 10× exaggeration. e, presence of pollen type.



laboratory number AA11014; Fig. 7). These cycles likely represent forest fires that removed trees from the landscape, as Wein and Moore (1977) suggest that fires in New Brunswick's red spruce – hemlock – pine forests occurred at a frequency of 230 years. After fire, forest openings were rapidly infilled with shrubs as terrestrial succession proceeded.

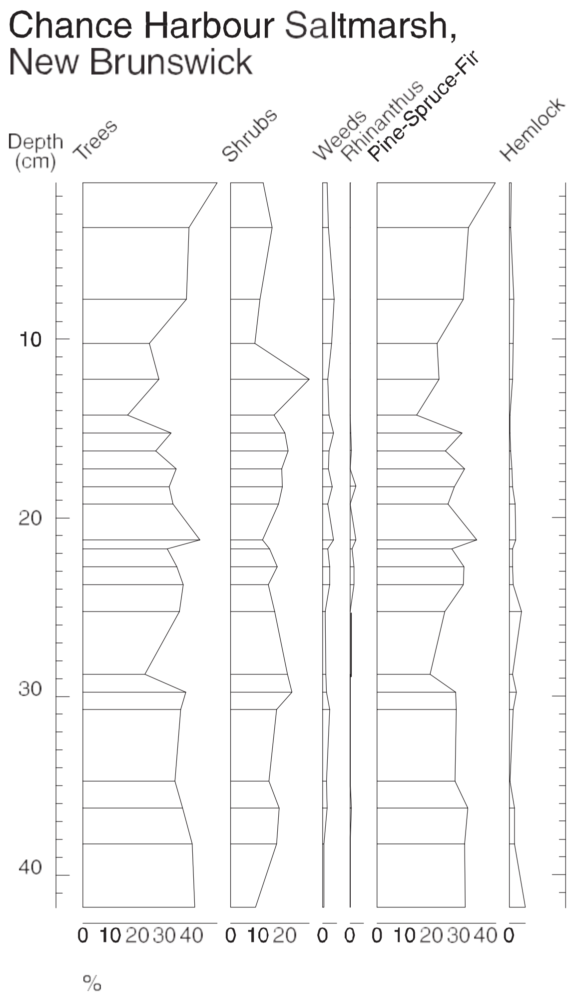
However, not until the 43 cm depth is the decrease in tree pollen associated with weed pollen (Fig. 8). The two most abundant types of weed pollen are from ragweed (*Ambrosia*) and sorrel (*Rumex*). Both rapidly exploit sunny, open areas and can survive only in lands kept open, free of shade. The proportion of tree pollen continues to decrease to 36 cm depth, where it increases, suggesting forest recovery has begun. A second decline in tree pollen begins at 21 cm depth, also accompanied by an increase in weed pollen. Only above 21 cm is there pollen of dandelions (Asteraceae–Liguliflorae-type pollen), another plant that does not grow in shade. Dandelion flowers are insect-pollinated and produce relatively small amounts of pollen that is not readily dispersed by wind. Occurrence of dandelion pollen in sediments is rare and indicates local presence or tidal transport from local sources of these weeds.

Because there were two pulses of land clearance during settlement of Point Lepreau, we associate the lower clearance horizon (43 cm) with 1790 A.D. and the upper clearance horizon (21 cm) with 1830 A.D. Thus, we calculate accretion rates of 2.1 mm·year^{-1} for the past 200 years and 1.3 mm·year^{-1} for the past 160 years. If 21 cm corresponds to 1830 A.D., the accretion rate is 1.3 mm·year^{-1}, close to that calculated through ^{210}Pb dating of this core (Table 1).

At Chance Harbour we interpret two phases of forest clearance from pollen above -38 cm (Fig. 9). Weed pollen, particularly ragweed, increases above this depth as tree pollen decreases, particularly pine (*Pinus*) and hemlock (*Tsuga*). By 30 cm depth weed pollen disappears and tree pollen increases (with a reciprocal decrease in shrub pollen). A second increase in weed pollen occurs above 25 cm depth. Weed pollen percentages exceed those of the earlier episode and include yellow rattle (*Rhinanthus*), a weed introduced from Europe (Roland and Smith 1969). We interpret these clearance phases to correspond to 1790 and 1830 A.D., which indicate accretion rates of 1.9 and 1.5 mm·year^{-1}, respectively.

Palynological preparations from tidal salt marsh sediments also contain the inner linings of the calcium carbonate shells

Fig. 9. Pollen stratigraphy (% total sum) from salt marsh sediments at Chance Harbour, New Brunswick.



of foraminifera (Mathison and Chmura 1995) and dinoflagellate cysts (referred to as hystrichospheres by Clark 1986). These palynomorphs occur in Dipper Harbour above 310 cm and throughout Chance Harbour sediments. At Little Lepreau they are absent from sediments below 25 cm, indicating that the salt marsh here is of more recent origin (Fig. 10). Above 26 cm there is a dramatic decrease in tree pollen including spruce (*Picea*) and hemlock. Pine pollen decreases just above this level. As tree pollen decreases, ragweed, sorrel, and dandelion pollen appear, indicating forest clearance. As tree pollen declines to 14 cm depth where the ^{210}Pb record begins, we assume that the pollen changes above 26 cm correspond to the second phase of clearance. A date of 1830 A.D. for the 26 cm depth provides an accretion rate of 1.6 mm·year^{-1}.

Comparison with tide gauge records

Yearly records of relative sea-level change typically display variability, such as is demonstrated by the tide gauge records at Saint John, New Brunswick, and Eastport, Maine (Fig. 3). The Saint John gauge has recorded a 20.7 cm overall increase in relative sea level since its installation in 1894, but the rate of increase has slowed since 1969. Although the record in earlier years is incomplete, sea level appears to have been steady from 1894 to 1929. This stability in the early years of the gauge's operation parallels some European gauges (Woodworth 1990). The Eastport gauge record, which begins in 1929, is like that of the Saint John gauge but shows more stable sea levels since 1969.

The surface elevation of these Point Lepreau marshes has increased an average of 1.7 ± 0.2 mm·year^{-1} over the last 30 years and 1.6 ± 0.1 mm·year^{-1} over the last 100 years, or 16–17 cm·century^{-1} (Table 1). A comparison with the Saint John gauge suggests that Point Lepreau marshes have an accretion deficit. In recent years, however, readings from this gauge are likely overestimates as a result of increases in tidal range (Scott and Greenberg 1983) and problems inherent in the gauge location, which prevent it from recording some extreme low tides (C. O'Reilly, personal communication, 1999). Comparison to the Eastport gauge indicates that the marsh accretion rate over the last 30 years is considerably higher than the *average* rate of sea-level rise (derived from the regression equation), which is nearly stable (–0.2 mm·year^{-1}). Marsh accretion rates are only slightly higher than the rate (1.4 mm·year^{-1}) calculated from the simple difference between 1994 and 1963 Eastport gauge levels (43.9 mm). Assuming that the Eastport record is the more accurate record for comparison, our results suggest that regional marsh accretion is highly sensitive to and rapidly reaches equilibrium with sea-level change.

Rates based on the ^{210}Pb record integrate over a time period that begins -1896 A.D., 35 years before the Eastport gauge record, but the Saint John gauge covers this time period. The Eastport gauge records an overall rate (based on simple differences) of sea-level rise of 2.3 mm·year^{-1} from 1930 to 1963, and the Saint John gauge an overall rate of 2.0 mm·year^{-1} from 1896 to 1963. Averaged rates based on regression equations are similar, i.e., 2.8 and 2.0 mm·year^{-1}, respectively. Marsh sediment accretion rates are lower for this period (Table 2). Interpolating between the depths corresponding to 1896 by ^{210}Pb dating and the ^{137}Cs depth that corresponds to the year 1963, the average marsh accretion rate is 1.5 ± 0.1 mm·year^{-1}. This difference could easily be explained by compaction of sediment through processes such as collapse of dead root channels.

If compaction at lower depths causes those accretion rates calculated from lower depths to be underestimated, then the period from 1790 to 1830 was likely one of rapid relative sea-level rise at Point Lepreau (Table 2). Interpolating between the two settlement horizons determined through pollen stratigraphy, we calculate an average rate of 4.4 ± 1.6 mm·year^{-1}, the highest rate over the period of record. Curiously, European records show a eustatic regression starting in 1740 and culminating in 1800–1840, corresponding to a cold period, as indicated by the ™^{18}O record of the Camp Century ice core (Mörner 1973). As our pollen stratigraphies are based on the timing of clearance, the error is difficult to calculate and likely higher than that associated with our radionuclide dating, but accretion rates are more than twice that indicated in the last -160 years.

We pose two explanations for rapid accretion rates in the late 18th century. This period may have been colder in New Brunswick and associated with more intensive ice rafting, thus increasing inputs of mineral sediment to the high

Fig. 10. Pollen stratigraphy (% total sum) from salt marsh sediments at Little Lepreau, New Brunswick. A patterned area under the curves represents percentages of ragweed and dinoflagellate cysts, and an open area under the curves a 10× exaggeration. e, presence of pollen type.

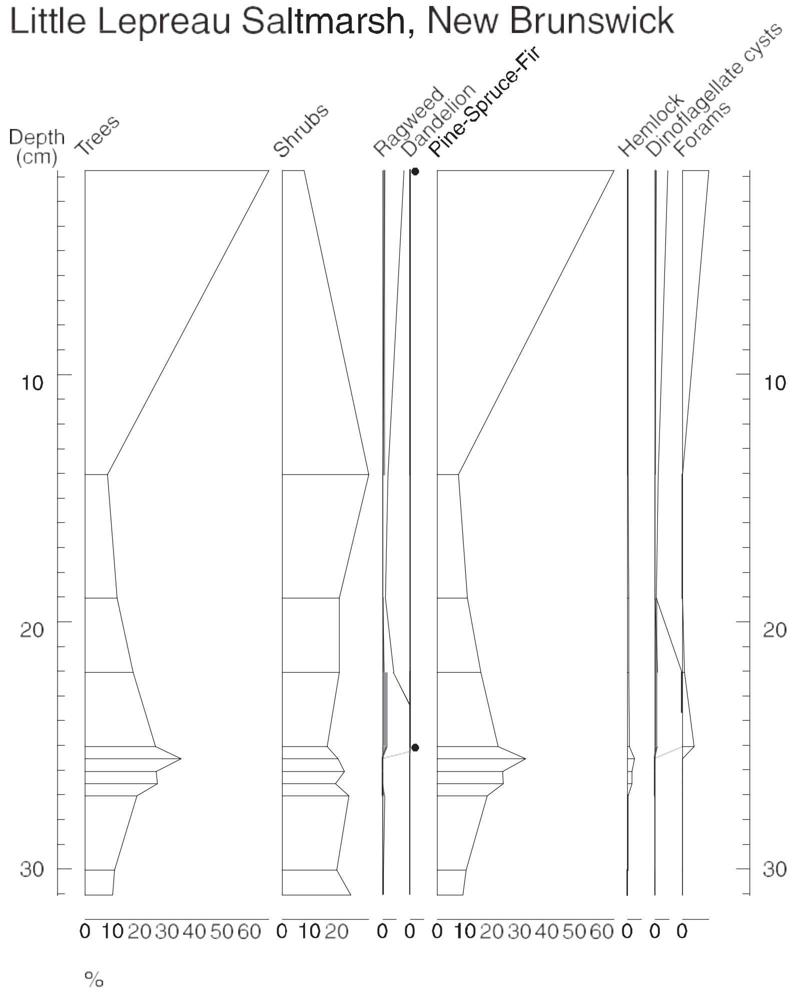


Table 1. Salt marsh sediment accretion rates based on radionuclide dating and pollen stratigraphy in sediment cores from three salt marshes on the New Brunswick coast, Bay of Fundy.

			Pollen stratigraphy	
	^{137}Cs	^{210}Pb	1830 A.D.	1790 A.D.
Chance Harbour	1.9	1.7	1.5	1.9
Dipper Harbour	1.8	1.5	1.3	2.1
Little Lepreau	1.5	1.5	1.6	
Average	1.7	1.6	1.5	2.0
Standard deviation	0.2	0.1	0.2	0.1

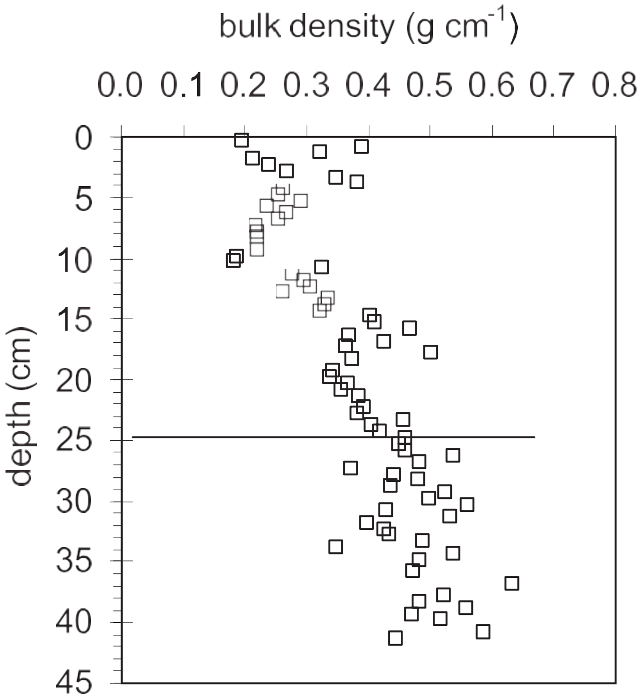
marsh. Increased mineral input should increase bulk density of sediments, and at Chance Harbour the bulk density of sediments (Fig. 11) from this period (below 25 cm) averages 0.48 ± 0.06 g·cm^{-3}, considerably higher than the average bulk density of sediments above 25 cm depth, i.e., 0.33 ± 0.08 g·cm^{-3}. Only at these lower depths do we find stones, which further supports a conclusion of more intensive ice rafting, as ice has been observed to lift stones from creek channel bottoms. (Similar data are not available from the Dipper Harbour core.) In addition, accretion rates in the period following 1830 A.D. (1830–1896) are the lowest observed at Chance Harbour and Dipper Harbour (Table 2). These lower rates could be the consequence of the relatively high marsh surface elevations established in the preceding period (Fig. 1).

An explanation of enhanced sediment deposition due to intensified ice rafting does not exclude a second explanation based on neotectonic activity. Marsh sediment accumulation over structures built in the early 19th century provides evidence of rapid relative sea-level rise on the coast of Maine

Table 2. Salt marsh sediment accretion rates interpolated between radionuclide-dated and pollen-dated horizons.

	Period			
	1930–1963	1896–1963	1830–1896	1790–1830
Chance Harbour	1.6	1.6	1.2	3.3
Dipper Harbour	1.4	1.4	0.9	5.5
Little Lepreau	1.6	1.5	1.7	
Average	1.5	1.5	1.3	4.4
Standard deviation	0.1	0.1	0.4	1.6

Fig. 11. Dry bulk density of sediments cored at Chance Harbour.



(as much as 3.6 mm·year^{-1}), which Smith et al. (1989*a*) attribute to neotectonic activity in coastal Maine. A review of historical records reveals that over 17 earthquakes occurred in coastal Maine and southwestern New Brunswick from 1790 to 1830 (Smith et al. 1989*b*). Hence we conclude that high marsh accretion rates during this period must have been in part, if not largely, a result of decreased marsh elevations due to neotectonic activity.

Summary and conclusions

Averaged marsh accretion rates range from 1.3 ± 0.4 to 4.4 ± 1.6 mm·year^{-1} over the last two centuries (Table 2). Recent rates are similar to the rate of sea-level change recorded at Eastport, Maine, suggesting that they are in equilibrium with recent sea-level change. In the outer Bay of Fundy, marsh accretion appears to be highly sensitive to local changes in relative sea level, as indicated by tide gauge records. For this reason it is important to consider rates calculated as the slope of the overall rise and the difference in sea level from the beginning to the end of the period under consideration.

Based on the pollen stratigraphy in the marsh sediments, we find higher rates of marsh accretion during the late 18th century to early 19th century. This is likely due to neotectonic activity causing increased relative sea levels in the region. However, we also have evidence of ice rafting, which would have enhanced marsh sediment accretion. Further investigation of regional climate variation is needed. If ice rafting was not the primary mechanism responsible for these increased rates of accretion, then local marsh accretion could maintain equilibrium with the low and middle projections of sea-level rise estimated as a result of greenhouse-gas warming (Warrick et al. 1996). However, if ice rafting is an essential contribution for marsh accretion, then marsh accretion rates could decrease with climate warming. To assess the relative importance of these mechanisms it is essential that we increase our understanding of the importance of organic production to marsh sediment accretion in northern marshes.

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