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Carbon accumulation in Bay of Fundy salt marshes: Implications for restoration of reclaimed marshes

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Abstract. Transformation of agricultural land to natural terrestrial vegetation has been suggested as a means to increase soil carbon storage. However, the capacity for carbon storage in terrestrial soils is limited as compared to soils of tidal salt marshes, the original vegetation of many coastal agricultural lands. In a number of countries, tidal salt marshes have been "reclaimed," that is drained and diked to prevent tidal flooding and create suitable conditions for dry land agriculture. In this study we examine spatial and temporal patterns of carbon accumulation in tidal salt marshes of the Bay of Fundy and estimate the carbon storage potential of the bay's extensive area of reclaimed marsh. Rates of carbon accumulation vary from the upper to the outer Bay, over which there is a gradient of decreasing tidal range and suspended sediment supply. In the outer bay, high-marsh densities are highest (0.042 ± 0.009 g C cm^{-3}), but carbon accumulation rates over the past 30 years are lowest (76 g C m^{-2} yr^{-1}). The reverse pattern occurs in the upper bay where carbon densities in the high-marsh environment are lowest (0.036 ± 0.002 g C cm^{-3}), but carbon accumulation rates over the past 30 years may be as high (184 g C m^{-2} yr^{-1}). Compared to other ecosystems, the rates of carbon accumulation presented in this study were similar over timescales of years to centuries. Increases in relative sea level (over time) and suspended sediment supply (across the bay) positively affect the marsh soil accumulation rate and the rate of carbon sequestration. Parameters such as %C are not useful predictors of a marsh's potential for carbon sequestration. Soil carbon densities of functioning marshes and reclaimed marsh soils are similar, but marsh soils have a storage capacity that increases with rising sea level, while agricultural soils, such as those in reclaimed marshes, have a fixed (or possibly decreasing in reclaimed marshes) volume over time.

1. Introduction

Enhancing ecosystems as carbon sinks to ameliorate the greenhouse effect has been suggested as a potential extension of international climate treaties. The focus of these discussions has been reforestation and afforestation, presumably through reversion of agricultural lands. In a recent assessment of climate impacts through land use change, the Intergovernmental Panel on Climate Change (IPCC) considered changes in management of terrestrial lands and wetlands [*Watson et al.*, 2000] (see www.grida.no/climate/ipcc/land_use/223.htm). Authors of the IPCC report recognized the absence of information on saltmarshes and made no mention of saltmarsh transformations, yet many countries (e.g., Canada, United Kingdom, France, Spain, Korea, and Netherlands) have agricultural lands created by diking and draining tidal salt marshes. There has been no discussion of these transformations, yet reversion of agricultural land to salt marsh would have greater potential for carbon sequestration than restoration of terrestrial systems.

Post and Kwon [2000] have examined rates of soil carbon sequestration when agricultural land is no longer used for cultivation and is allowed to revert to natural terrestrial vegetation. They found maximum rates of carbon accumulation during the early aggradation stage of perennial vegetation growth were usually much less than 100 g C m^{-2} yr^{-1}, and for forest or grassland establishment the rates of accumulation were similar: 33.8 and 33.2 g C m^{-2} yr^{-1}, respectively. Because of limitations of rooting, both systems have relatively unchanging soil depths available for storage of soil organic carbon. Assessment of the value of grasslands or forests as a long-term carbon sink also requires consideration of their natural disturbance regimes, primarily fire and windstorms, which cause a turnover of soil carbon on the scale of decades to centuries.

In contrast to grasslands and forests, the volume of soil in many wetlands increases with time and over timescales of thousands of years. Thus opportunity for carbon burial in wetlands is high. Reports of long-term rates of carbon accumulation (>1000 years) in northern fens and bogs range from 10 [*Tolenen et al.*, 1992] to 81 g C m^{-2} yr^{-1} [*Alm et al.*, 1992], and over century scales, rates may be in a similar range [*Robinson and Moore*, 1999]. Measurements of carbon accumulation rates on the decadal scale in northern peatlands are less common than over millenial scales, but studies through the BOREAS program in Thompson, Manitoba, Canada [*Trumbore and Harden*, 1997], suggest as much as 233 g C m^{-2} yr^{-1} in productive fens.

Although their rates of carbon burial are equal to or greater than that sequestered in recovering agricultural land, microbial activity in freshwater wetland soils ultimately transforms considerable amounts of CO_2 into CH_4 and releases N_2O. The greater greenhouse potential of the latter gases reduces the significance of the carbon sequestered in freshwater wetlands.

There have been few studies designed to measure the rate of carbon burial in tidal salt marsh soils. This is probably because

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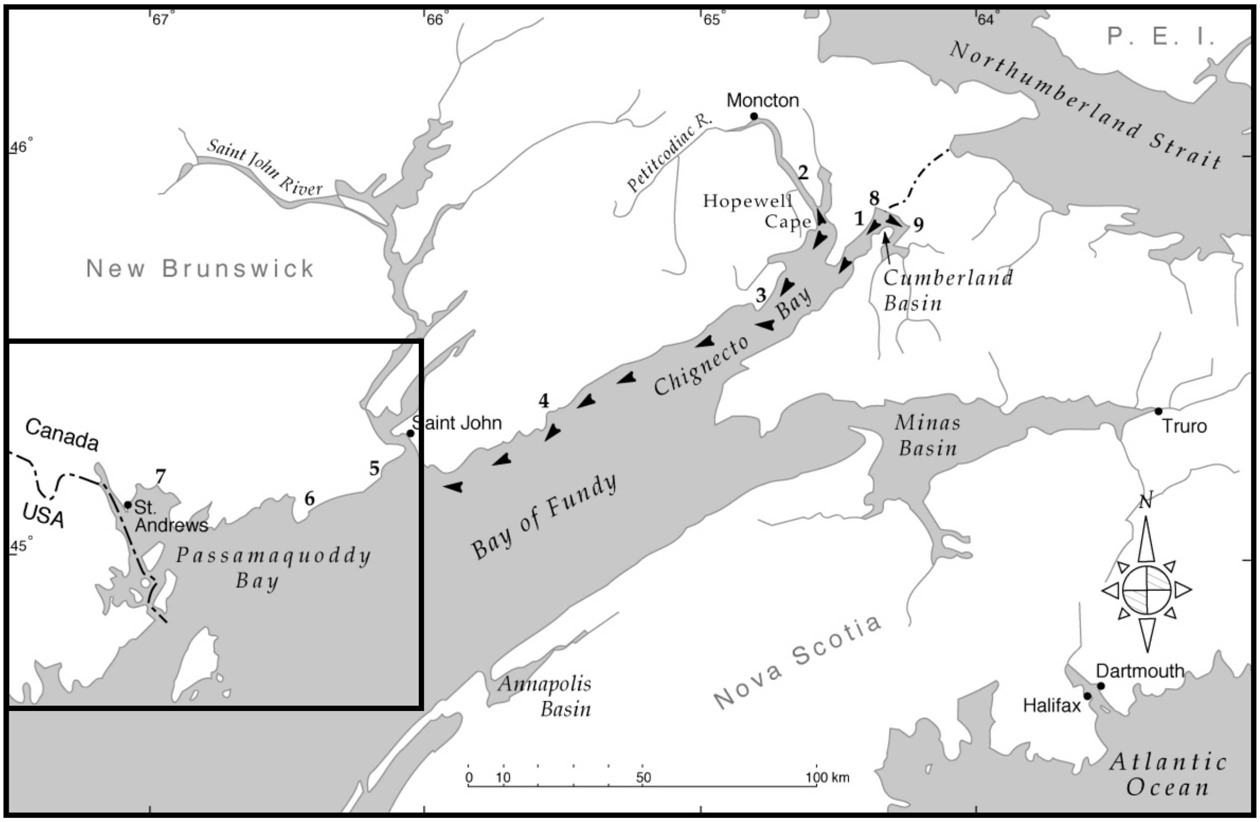

Figure 1. Map of the Bay of Fundy showing direction and divergence of suspended sediment transport near Hopewell Cape. (Data are from *Swift et al.* [1973] and *Hunter and Associates* [1982].) Location of salt marsh sites where marker horizons were established are denoted by number: 1, Wood Point; 2, Belliveau Village; 3, Cape Enrage; 4, St. Martins; 5, Lorneville; 6, Dipper Harbour; 7, Bocabec; 8, Westcock Marsh; and 9, Amherst Point. Box represents area shown in Figure 2. (Adapted from *Chmura et al.* [2001b]).

burial has been considered one of the least important components of the salt marsh carbon budget, comprising as little as 10% of the carbon fixed through photosynthesis [e.g., *Howes et al.*, 1985]. However, the rate of gross primary production in tidal salt marshes is exceptionally high. For example, *Howes et al.* [1985] estimated primary production to be more than 941 g C m^{-2} yr^{-1} in Great Sippewisset Marsh, Massachusetts. In contrast to freshwater wetlands, tidal salt marshes release only small amounts of CH_4 to the atmosphere and at times even may be small sinks for this greenhouse gas [*Bartlett and Harris*, 1993]. There is also evidence that emissions of the greenhouse gas N_2O are negligible [*Smith et al.*, 1983; *DeLaune et al.*, 1990]. As both CH_4 and N_2O have a greenhouse warming potential greater than CO_2, each unit of carbon sequestered in tidal salt marshes will have a greater impact than freshwater wetlands in reducing greenhouse warming.

Indirect determination of soil carbon densities and rates of burial can be made through extensive research programs that provide accurate accounting of carbon budgets [e.g., *Howes et al.*, 1985]. Alternatively, carbon burial can be estimated if care is taken during sampling of soils to minimize compaction so that bulk density can be accurately measured. The latter type of sampling has been conducted in salt marshes, but most investigators have not reported carbon densities of their samples [e.g., *Bricker-Urso et al.*, 1989; *Anisfeld et al.*, 1999] or simply report an average carbon accumulation rate [e.g., *DeLaune et al.*, 1981; *Craft et al.*, 1993]. This situation has made estimations of carbon storage in tidal salt marshes problematic. Indeed, the most comprehensive estimate of carbon storage in tidal salt marsh soils produced to date [*Rabenhorst*, 1995, 2000] relied primarily on estimates of bulk densities, rather than on actual measurements (M. C. Rabenhorst, personal communication, 2000).

In this study we examine the spatial variability in carbon density and the rate of carbon accumulation of surface soils from salt marshes along the Bay of Fundy coast of New Brunswick and consider the factors controlling variability. Sample sites were selected to represent a gradient in tidal range and rates of sediment deposition on this New Brunswick coast. Along this gradient we examine patterns in carbon density with depth and rates of carbon burial over timescales of years to centuries to estimate the magnitude of carbon sequestered in these northern macrotidal marshes. In the Bay of Fundy, as much as 85% of the original area of tidal marshes has been diked and drained. Using our observations of carbon accumulation in modern day marshes, we estimate how the Fundy tidal salt marsh carbon sink has been altered by centuries of diking.

2. Methods

2.1. Study Area

The Bay of Fundy is a macrotidal estuarine system that extends northeast from the Gulf of Maine. Tidal range increases from 6 m at the mouth of the bay to more than 16 m at its upper reaches [*Canadian Hydrographic Survey*, 1998]. The Bay of Fundy seldom experiences hurricanes, and because it has a macrotidal regime, storms are less important (in a sedimentological perspective) than

Table 1. Distance From Hopewell Cape and Average Rates of Surface Sediment Deposition and Standard Deviation Measured at Three Elevations for Each Marsh Sample Site: 1 m Landward From the Lower Limit of *S. Alterniflora* (Lower Low), 1 m Seaward of the Upper Limit of *S. Alterniflora* (Upper Low), and 1 m Inland of the Lower *S. Patens* border

		Rates of Surface Sediment Deposition					
		Lower Low		Upper Low		High	
Marsh	Distance From Hopewell Cape, km	Average, cm yr^{-1}	Standard Deviation	Average, cm yr^{-1}	Standard Deviation	Average, cm yr^{-1}	Standard Deviation
Bocabec	240	1.7	0.1	0.6	0.3	0.5	0
Dipper Harbour	183	2	0.6	0.9	0.8	0.3	0.1
Lorneville	163	1.4	0.7	1	0.2	0.3	0.1
St. Martins	108	2.6	0.5	1.1	0.1	0.5	0.2
Belliveau Village	58	2.4	0.5	1.8	0.4	3	1
Wood Point	50	3.7	0.8	2	0.3	1.4	0.3
Cape Enrage	40	4.5	0.4	1.8	1.2	0.8	0.3

on a microtidal coast, but storm surges of 2 m or more have been observed [*Greenberg*, 1984].

The character of suspended sediments and deposits varies within the Bay of Fundy [*Amos*, 1984]. Minas Basin, at the southeastern head of the bay (in Nova Scotia) is a sandy estuary characterized by sand flats and bars. In contrast, at the northeastern head, Chignecto Bay holds expansive mudflats and concentrations of suspended sediments an order of magnitude higher than in Minas Basin. Chignecto Bay exports sediment both into the estuaries of the upper bay, above Hopewell Cape, and to the outer Bay of Fundy, distributing it in a zone that extends along the northwestern part of the Bay (Figure 1). *Miller* [1966] measured the percent of organic matter of suspended sediments along the New Brunswick coast and reported that organic material comprises 1–5% of the total suspended sediment load. Thus sediments from tidal floodwaters likely contain <3% carbon (dividing organic matter by conversion factor of 1.724 [*Allen*, 1974]) when first deposited on marsh surfaces.

Our marsh study sites are located along this northwestern coastline extending above and below Hopewell Cape, a point we use as a geographical reference for peak suspended sediment concentration. The coastal reach that includes these marshes spans a distance of 250 km. It was difficult to find accessible study sites that were not disturbed in some manner, particularly in the upper bay, but we took care to locate sampling sites seaward of dikes or dike remnants.

By measuring deposition over clay marker horizons, *Chmura et al.* [2001b] found that rates of sediment deposition in these marshes increase with proximity to Hopewell Cape in the upper bay, indicating the importance of suspended sediment concentrations in tidal floodwaters (Table 1). Other factors control variation in sediment deposition within each of the marshes. Frequency of tidal flooding, and thus the supply of suspended sediment, decreases with increasing elevation of marsh surfaces. Rates of sediment deposition also decrease with distance from the edge of vegetation along marsh creeks [*Chmura et al.*, 2001b].

Hanson and Calkins [1996] inventory 1.10×10^9 m^2 of salt marsh on the Bay of Fundy. Their compilation categorizes salt marshes in five classes with respect to the proportion of low and high marsh. We use these classes to estimate area of low and high marsh in the upper and outer bay. (The upper portion of the outer bay is placed roughly at St. Martins, New Brunswick, and Digby, Nova Scotia.) The upper bay contains more high marsh than low marsh, while their areas are roughly equivalent in the outer Bay (Table 2).

Table 2. Carbon Densities, Soil Accumulation Rates (SAR), and Carbon Accumulation Rates (CAR) Determined From Cores Collected in Salt Marshes of the Outer Bay of Fundy[a]

	30 Year Data			100 Year Data			160 Year Data		
	C Density, g cm^{-3}	SAR, cm yr^{-1}	CAR, g m^{-2} yr^{-1}	C Density, g cm^{-3}	SAR, cm yr^{-1}	CAR, g m^{-2} yr^{-1}	C Density, g cm^{-3}	SAR, cm yr^{-1}	CAR, g m^{-2} yr^{-1}
Low Marsh Cores									
DH Sa3	0.03463	0.54[b]	187	0.03658	0.45[b]	165	0.0366	0.39[b]	143
DH Sa2	0.03375	0.54[b]	182	0.03318	0.45[b]	149	0.0332	0.39[b]	129
DH Sa1	0.03611	0.54[b]	195	0.03605	0.45[b]	162	0.036	0.39[b]	141
Average	0.035	0.54	188	0.035	0.45	159	0.035	0.39	138
Standard deviation	0.001	0.00	6	0.002	0.00	8	0.002	0.00	7
High Marsh Cores									
Chance Harbour	0.038	0.19	72	0.034	0.17	58	0.036	0.15	54
Little Lepreau	0.059	0.15	89	0.055	0.15	83[b]	0.057	0.16	91
Dipper Harbour A	0.047	0.18	85	0.048	0.15	72	0.048	0.13	62
Dipper Harbour D	0.033	0.18[b]	60	0.030	0.15	45	0.031	0.13[b]	40
DH Sp3	0.047	0.18[b]	85	0.040	0.15	60	0.040	0.13[b]	52
DH Sp2	0.036	0.18[b]	64	0.034	0.15	50	0.033	0.13[b]	43
DH Sp1	0.043	0.18[b]	77	0.046	0.15	68	0.046	0.13[b]	59
Average	0.043	0.17	76	0.041	0.16	62	0.042	0.15	57
Standard deviation	0.009	0.02	11	0.009	0.01	13	0.009	0.02	17

[a] Accumulation rates are from *Chmura et al.* [2001a].

[b] Value is estimated from other cores as described in text.

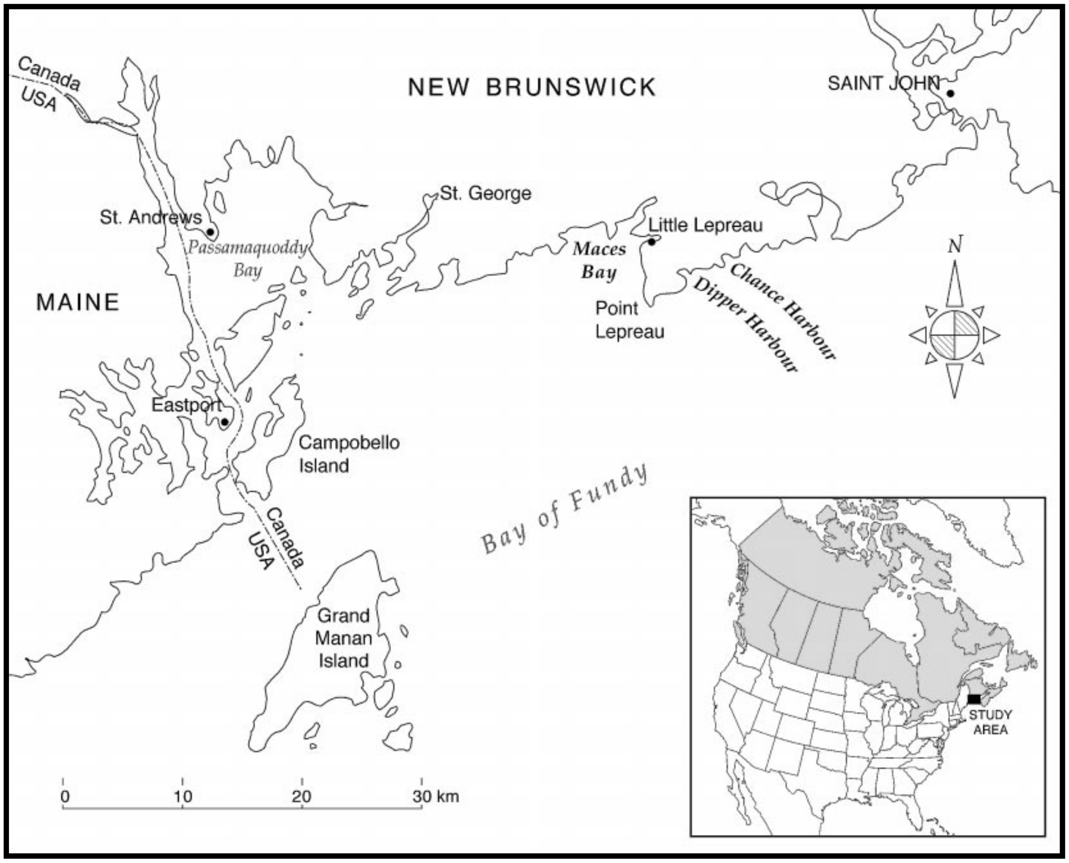

Figure 2. Location of outer Bay marshes where deeper soils were sampled: Dipper Harbour, Chance Harbour, and Little Lepreau (from *Chmura et al.* [2001a]).

2.2. Sample Collection and Analysis

2.2.1. Surface samples. Marker horizons were established by spreading a thin layer of white clay on the marsh surface at three elevations: ~1 m inland of the lower limit of *Spartina alterniflora*, the typical low-marsh vegetation (LL); ~1 m seaward of the upper limit of *S. alterniflora* (UL); and ~1 m inland of this border or the *Plantago* zone [*Chmura et al.*, 1997] when present (H). These series of plots were established along replicate transects in seven salt marshes along the New Brunswick coast of the Bay of Fundy (Figure 1). After 12 months the thickness of sediment accumulated over the marker horizons was measured from a sample collected with a cryogenic coring device [*Cahoon et al.*, 1996]. Complete details on sample sites and procedures are given by *Chmura et al.* [2001b].

In each marsh surface, soil samples were collected (for bulk density and loss on ignition (LOI)) at elevations corresponding to the location of marker horizons, with five replicate samples randomly collected at the same elevations as the marker horizons, comprising a total of 15 plots per marsh. Soil samples for bulk density and LOI were collected using a 3.6 cm diameter piston corer with a calibrated extruder. The corer retrieves about a 5 cm thickness of sediment with negligible compaction. Excess was extruded, and the surface 2 cm was retained. We also include additional samples taken at Belliveau Village the previous summer (1997). These consist of three replicate 2 cm deep samples (taken within a 0.5 m radius) cored at 1, 11, 21, and 38 m distance along a transect perpendicular to and beginning at the low-marsh/high-marsh border. Soil C accumulation rates were calculated as a product of average surface accretion rates and average C density of the five surface samples taken to correspond to the marker plot elevations.

2.2.2. Deep soil sections. Deeper soils were available for analysis through three other studies. Four cores (Chance Harbour, Little Lepreau, and Dipper Harbour A and D) were collected in comparable high-marsh settings at three different marshes on Point Lepreau in the outer bay, where tidal range is ~6 m (Figure 2). Coring methods, described by *Chmura et al.* [2001a], allowed collection of soils with negligible compaction. Soils were sectioned in 1 cm intervals in the core Dipper Harbour A. Dipper Harbour D and cores from the other two marshes, Little Lepreau and Chance Harbour, were sectioned at 0.5 cm intervals. This fine-resolution subsectioning was enabled using a core extruder calibrated to 1 mm increments. *Chmura et al.* [2001a] used three different dating techniques to determine rates of vertical soil accretion at Dipper Harbour, Little Lepreau, and Chance Harbour. The three methods were identification of peaks in cesium 137 concentration with depth [*Pennington et al.*, 1973; *DeLaune et al.*, 1978], identification of the pattern of lead 210 concentration with depth [*Flynn*, 1968; *Lynch et al.*, 1989], and identification of settlement horizons by increases in weed pollen [*Brugham*, 1978]. All soils were of salt marsh origin, with the exception of the base of the core from Little Lepreau. Microfossil analysis indicates that deposition of salt marsh soil at Little Lepreau began at ~24 cm depth, based upon the presence of pollen of salt marsh taxa, foram test linings, and dinoflagellate cysts in samples above 24 cm and absence in those below.

Three additional cores were collected in the same vegetation community in the Dipper Harbour high marsh, and another three

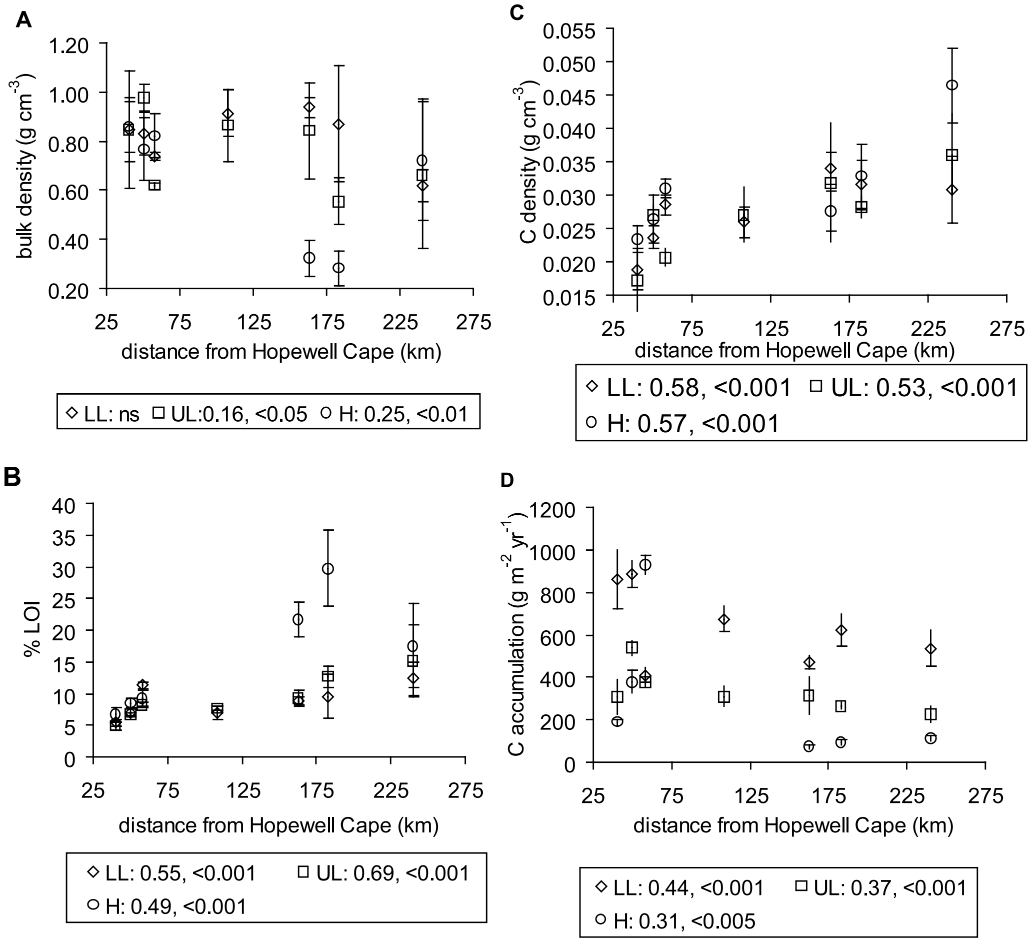

Figure 3. Relationship of marsh distance from Hopewell Cape to average: (a) bulk density, (b) %LOI, (c) carbon density, and (d) rate of carbon accumulation in the lower low marsh (LL), upper low marsh (UL), and high marsh (H) in tidal salt marshes along the Bay of Fundy coast. The first number in the legend is r^2; the second is the probability. Vertical bars represent ±1 standard deviation.

were collected in the Dipper Harbour low marsh as part of a study of belowground productivity [*Connor and Chmura*, 2000]. These cores were sectioned in 2 cm increments, and subsamples of known volume were collected for carbon analyses.

A comparable means of core collection was not possible in the upper bay because of dense clay soils. Instead, we took advantage of erosive cliffs at Amherst Point and Westcock Marsh (Figure 1). At both sites extensive sections of high-marsh soil are exposed at the seaward edge of the marsh. The eroding marsh cliffs rise ~1.5 m above the mudflats seaward of the marsh. In an attempt to avoid sampling of reworked or extensively oxidized soils (due to the greater drainage from this exposure) we cleared away 50 cm back from the marsh edge before removing known volumes of soil. At Wood Point, soil samples were collected from the side of a hole dug into the high marsh.

Our attempts to date soil accumulation rates with radionuclides have not been successful. Concentrations of cesium 137 and lead 210 are extremely low, probably because the high inputs of sediments from tidal waters dilute the concentration of these atmospherically derived radionuclides.

2.2.3. Carbon analysis. Soil samples were oven or freeze dried to constant weight. Bulk densities were calculated on the basis of this weight and the known volume of the samples. Soils were ground to a homogenous texture using an electric coffee grinder. Ground soil was placed in a muffle furnace (1 hour at 350°C, then 4 hours at 550°C) to determine loss on LOI. The entire subsample (21.5 cm^3) from the six Dipper Harbour core sections described by *Connor and Chmura* [2000] was combusted to determine LOI. For all remaining core and surface samples, two replicates of >1 g of soil were combusted, and additional replicates were run if the difference between replicates was >10%. Carbon content was calculated from LOI using the relationship determined by *Craft et al.* [1991] for tidal salt marsh soils. Carbon densities were calculated as a product of percent carbon content and whole sample bulk density. Carbon accumulation rates were calculated as a product of vertical soil accumulation rates and average carbon density of the soil section dated.

3. Results and Discussion

3.1. Bulk Density, LOI, and Carbon Density

The %LOI of marsh soils is generally greater than the %LOI in suspended sediments (≤5%) that deposit on marsh surfaces. In the upper bay, %LOI is low but is still higher than the %LOI of suspended sediments. As %LOI increases in the outer bay where suspended sediment loads are much lower, we must assume that increased %carbon in the marsh soils is not transported in but is fixed through local marsh production.

3.1.1. Surface sample set. Bulk densities in the set of surface (2 cm) samples range from 0.18 to 1.3 g cm^{-3}, the greatest found in low-marsh samples of the upper bay where tidal floodwaters carry extremely high concentrations of suspended sediment (Figure 3). Although there is considerable variability in measurements of bulk density, there is a significant, albeit minor, decrease in bulk density of high-marsh and upper low-marsh samples with distance from the point of sediment dispersion at Hopewell Cape (Table 2). There is a more obvious pattern in LOI, which varies from 5 to 69%, the highest values found toward the outer bay (Figure 3). At all elevations, LOI significantly increases with distance from Hopewell Cape, relationships that are much closer than those demonstrated for bulk density (Figure 3).

Carbon densities in surface samples range from 0.009 to 0.055 g cm^{-3}, with the highest densities in the high-marsh samples of the outer bay and the lowest in the low-marsh samples from sites closest to Hopewell Cape (Figure 3). As with LOI, the increase in carbon density with distance from Hopewell Cape is significant at all elevations.

In surface samples collected along a transect in the Belliveau Village, marsh carbon density increases with distance from the high-marsh/low-marsh border (Figure 4). This distance corresponds to increasing the distance from the tidal creek and probably corresponds to slight increases in elevation (unfortunately, not measured in this study) and thus to a decreased frequency of flooding by tidal waters that carry mineral sediment. A comparison of the seven marshes representing the Fundy tidal range does not reveal significant differences between low- and high-marsh samples, but these were more closely spaced (~2 m) than those from the Belliveau Village high marsh.

3.1.2. Soil cores. Although bulk density increases and %LOI decreases (Figure 5) with depth in 8 of the 10 cores (Figure 6) from the outer bay, it is not likely due to carbon loss. The change in bulk density and LOI are predictable on the basis of the pattern in surface samples. It has long been recognized that under regimes of rising sea level, vertical accretion in low marshes (as they are usually higher than the rate of sea level rise) may increase surface elevations enough to support high-marsh vegetation [e.g., *Shaler*, 1886; *Redfield*, 1965; *Orson et al.*, 1987]. Thus soils at lower depths may have formed under the higher-frequency flooding regimes of lower relative elevations. We have observed roots of species characteristic of middle- and low-marsh elevations (*Plantago maritima* and *S. alterniflora*, respectively) at 30 cm depth in cores collected from high-marsh zones at Dipper Harbour. Greater input of mineral sediment at lower elevations, corresponding to lower depth in the cores, can easily explain the increase in bulk density and decrease in %LOI.

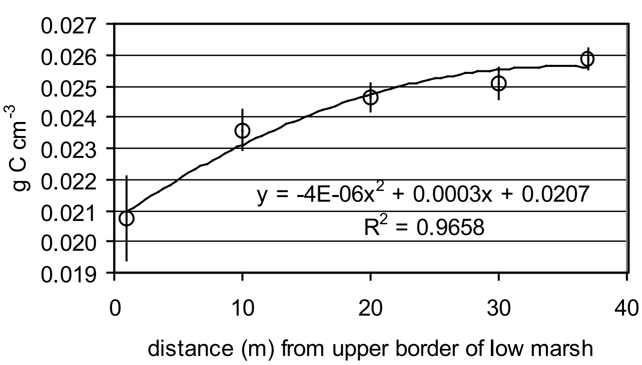

Figure 4. Carbon density of soils collected along a high-marsh transect at Belliveau Village, New Brunswick. Points represent average of three samples, and vertical bars represent ±1 standard deviation.

In cores from the upper bay, there is no change in LOI or bulk density with depth (Figure 7). Inspection of roots within the top 30 cm revealed that all sediments were deposited in a high-marsh system (i.e., dominated by *Spartina patens*). Soils in cores from Amherst Point and Westcock Marsh, in the upper bay, have bulk densities greater than outer bay soils, surface samples, and the Wood Point core. Because of their proximity to the eroding scarp, these soils may be better drained and their organic matter more decomposed than those from the Wood Point section or the surface samples. Enhanced decomposition may have accelerated the collapse of root channels and the autocompaction of soils, increasing bulk density. The same process may be responsible for the slightly lower %LOI in these two soil sections.

In cores from the outer bay, carbon densities (Table 2) fall within the range of surface samples collected at Dipper Harbour (LL = 0.028 ± 0.002 g cm^{-3}, UL = 0.032 ± 0.004 g cm^{-3}, H = 0.038 ± 0.005 g cm^{-3}). A comparison of the eight cores from Dipper Harbour shows a range in carbon densities similar to that found in cores from the two other outer bay marshes. Thus the variability among the marshes may simply be a result of spatial variability within a marsh. Besides variability in carbon sources and tidal flooding discussed above, there is another factor likely responsible for variability in carbon densities in these cores. In this region, winter ice is a common phenomenon within the marsh system. During low tide it freezes onto creek banks and channels. As tides rise, the ice is lifted and, at monthly highs, drifted to high-marsh surfaces where it is strands and eventually melts, often leaving patches of mineral sediment ranging from clay size to gravel. Such layers, characterized by high bulk density and low LOI, were observed in each core.

Only in two cores from the outer bay is there indication of any trend in carbon density with depth, but neither relationship is close (Figure 8). An explanation could be that autocompaction of sediments countered the loss of carbon through decomposition, but this is unlikely as vertical accumulation rates calculated over the past 200 years are higher than those calculated over shorter time periods [*Chmura et al.*, 2001a]. Thus the absence of any systematic decrease in carbon density with depth suggests that net losses of carbon over the >100 year period of deposition are negligible.

Although carbon densities remain fairly constant, the relative importance of carbon sources is likely to vary over time and depth. Studies of belowground production at Dipper Harbour [*Connor and Chmura*, 2000] have shown that surface soils (top 2 cm) contain minimal belowground growth (i.e., roots and rhizomes). Thus greatest contributions of carbon from photosynthetic organisms would be in the form of decomposing leaves and stems of vascular plants and the carbon produced by benthic microflora. *Pinckney and Zingmark* [1993] measured production of intertidal benthic microalgae in salt marshes of North Carolina and estimated production of 98–234 g C m^{-2} yr^{-1} in *S. alterniflora* communities. Net primary production of benthic algal communities may be >90% of their gross production [*Pomeroy*, 1959], thus microalgae can provide a significant input of carbon to marsh surfaces. Although microalgal production alone could account for carbon densities in our salt marsh soils, microalgal carbon is more labile than that produced by marsh grasses, which contain relatively high proportions of lignin. The importance of microalgal contributions should decrease with depth as decomposition proceeds and less labile vascular plant contributions increase.

In studies at Dipper Harbour in the outer bay the most dynamic zone of live rooting extends from 2 to 16 cm [*Connor and Chmura*, 2000]. We expect carbon contributions from live roots to be the most important at these depths. Associated with metabolizing roots are root exudation products, another source of carbon. Dead roots

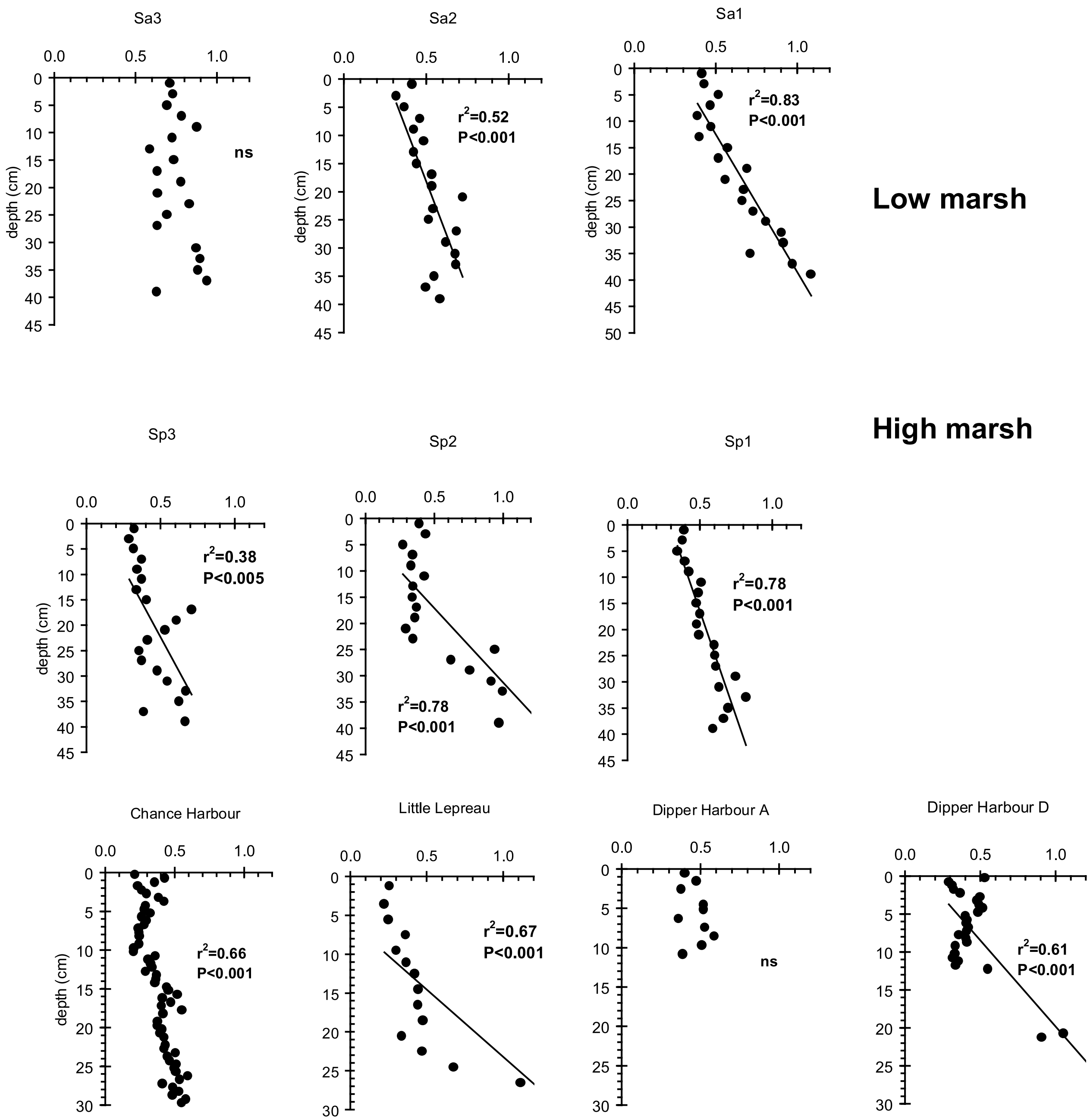

Figure 5. Bulk density (g cm^{-3}) with depth from cores taken in tidal salt marshes in the outer Bay of Fundy.

are found at all depths but are the dominant form of macro-organic matter below 16 cm. Fine particulate organic matter and decomposition products occur at all depths, but these components have not been measured individually in our studies.

3.2. Carbon Accumulation Rates

Many conclusions of the potential for carbon storage in salt marsh soils have been based on the assumption of a direct and positive relationship between %LOI and accumulation rates. However, our resluts show that %LOI is not a good predictor of carbon storage. Although carbon density and LOI decrease with increasing mineral sediment input, a reverse pattern is seen in carbon accumulation rates.

3.2.1. Surface patterns. The rate of sediment deposition seems to be a critical control of the rate of carbon burial in Fundy marshes. Carbon density and rate of surface sediment deposition (Table 1) both decrease with distance from Hopewell Cape (from the upper outer Bay). However, rates of carbon accumulation in surface samples decrease with distance from Hopewell Cape (Figure 3). The differences in sediment deposition rates, which are 2–6 times greater in marshes of the upper bay than of the outer bay, are much greater than differences in carbon densities.

With the exception of Belliveau Village, rates of carbon accumulation also increase with decreasing elevation (Figure 4). It is likely that burial of benthic microflora is also a factor with decreased elevation. *Pinckney and Zingmark* [1993] note that vertical migration of benthic microalgae is generally limited to the top 5 mm of sediments, yet photopigments of microalgae can be measured at greater depths, indicating burial of algal biomass.

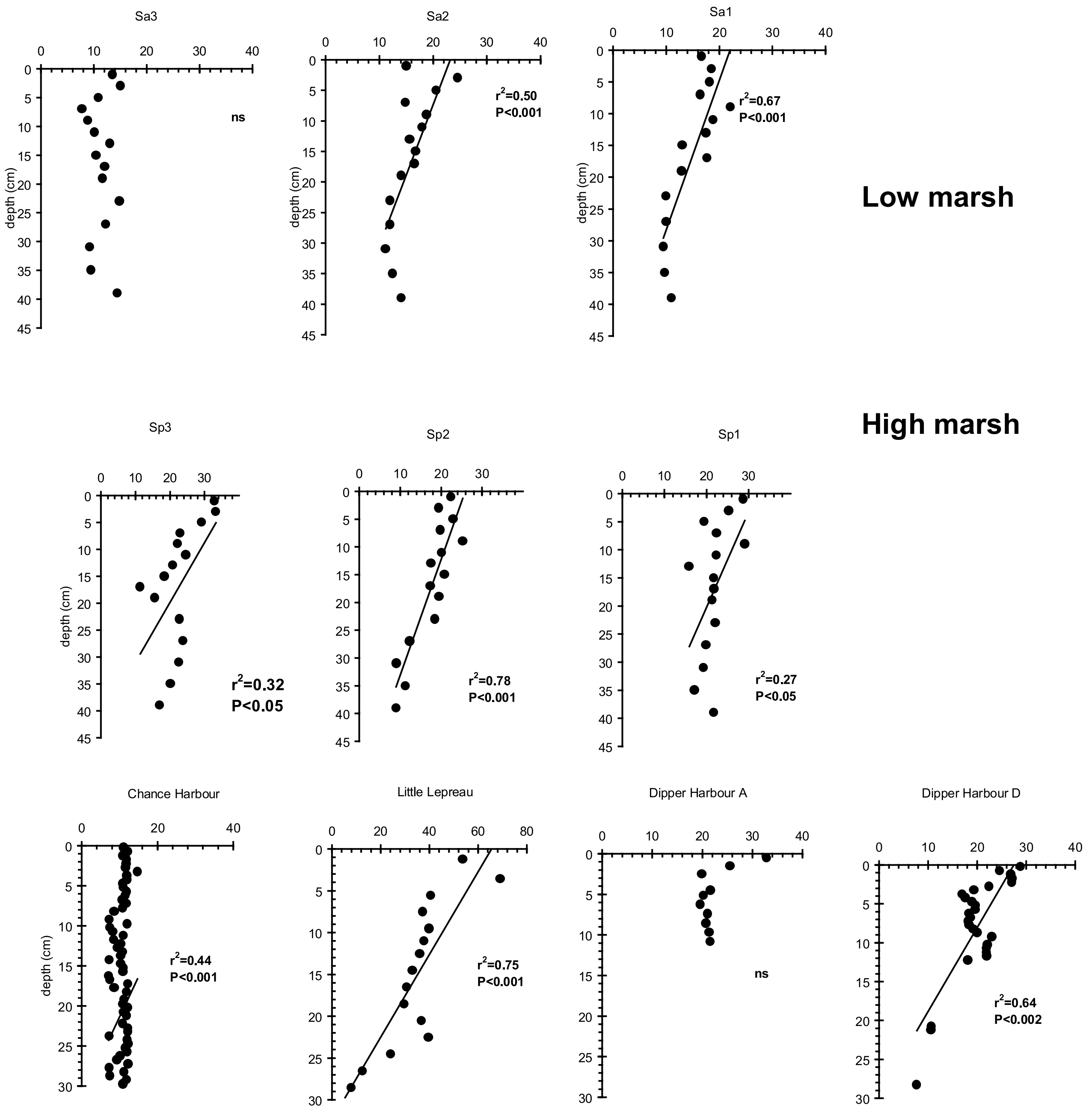

Figure 6. Percent LOI with depth from cores taken in tidal salt marshes in the outer Bay of Fundy.

Higher sediment deposition at lower elevations serves to trap algal biomass, protect it from surface deposit feeders, and slow its rate of turnover through consumption and decomposition. Increased sediment deposition thus would reduce the relative importance of belowground production and increase the relative importance of aboveground vascular plant tissue and epibenthic microflora, if they are incorporated into the soil more rapidly and effectively.

3.2.2. Patterns with Depth. Long-term accretion rates were measured in three high-marsh cores: Chance Harbour, Little Lepreau, and Dipper Harbour A [*Chmura et al.*, 2001a]. Use of the three dating methods (cesium 137, lead 210, and pollen horizons) provides three different time periods and three depths over which to calculate carbon accumulation rates (Table 2). To calculate rates of carbon accumulation over each time period, carbon densities are averaged over the corresponding depth and multiplied by the vertical accretion rate. The carbon densities, soil accretion rates, and calculated carbon accumulation rates are listed in Table 2. Long-term accretion rates for Dipper Harbour high-marsh cores are assumed to be equivalent to those measured in Dipper Harbour A. Without direct measurements of long-term soil accretion in the low marsh we make the assumption that long-term rates are proportional to our 1 year rates. In surface samples, sediment accumulates from 3 to as much as 6 times faster at "lower" low-marsh elevations than at high-marsh elevations. As rates of accretion at a fixed point in the low marsh presumably would have decreased over time, we make the conservative estimate that low-marsh vertical accretion rates are 3 times those measured in high-marsh cores and use this value to estimate carbon accumulation rates in low-marsh soils.

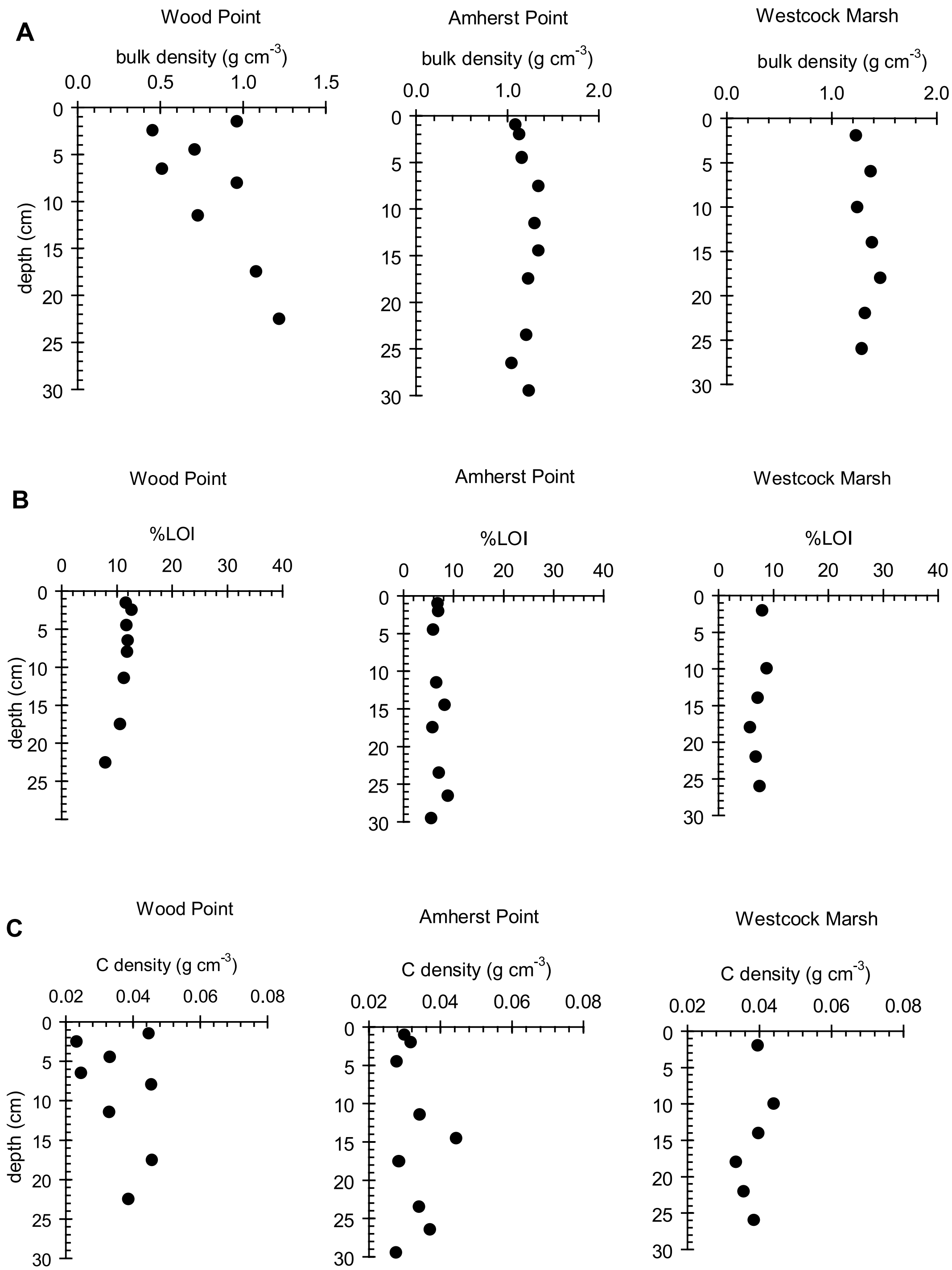

Figure 7. (a) Bulk density, (b) LOI, and (c) carbon density in soils from marshes in the upper Bay of Fundy.

Average carbon densities range from a low of 0.030 g C cm^{-3} over the 100 year period at Dipper Harbour D to a high of 0.059 g C cm^{-3} over the past ~30 years at Little Lepreau (Table 2). Highest carbon accumulation rates also occur in the shallow soils representing ~30 years of deposition at Little Lepreau and for all cores are highest during the past 3 decades. Declining rates in carbon accumulation over time correspond to declining rates of vertical accretion.

Carbon accumulation rates calculated on the basis of surface soil studies in the outer bay are comparable to, but slightly higher than, those obtained in the shallow soils of the dated cores. The surface rate calculated for Dipper Harbour high marsh is 94 g m^{-2} yr^{-1}. This value is 8–23% greater than that calculated for the high-marsh cores (76 ± 11 g m^{-2} yr^{-1}).

We have not been able to date cored soils from the upper bay, so we use the pattern in surface soil accumulation rates (Table 1) to estimate rates of vertical accumulation over longer terms. We can assume that long-term rates of vertical accumulation are equal throughout the bay, but the average rate of surface sediment deposition of the three upper bay high-marsh sites is 1.75 (LL

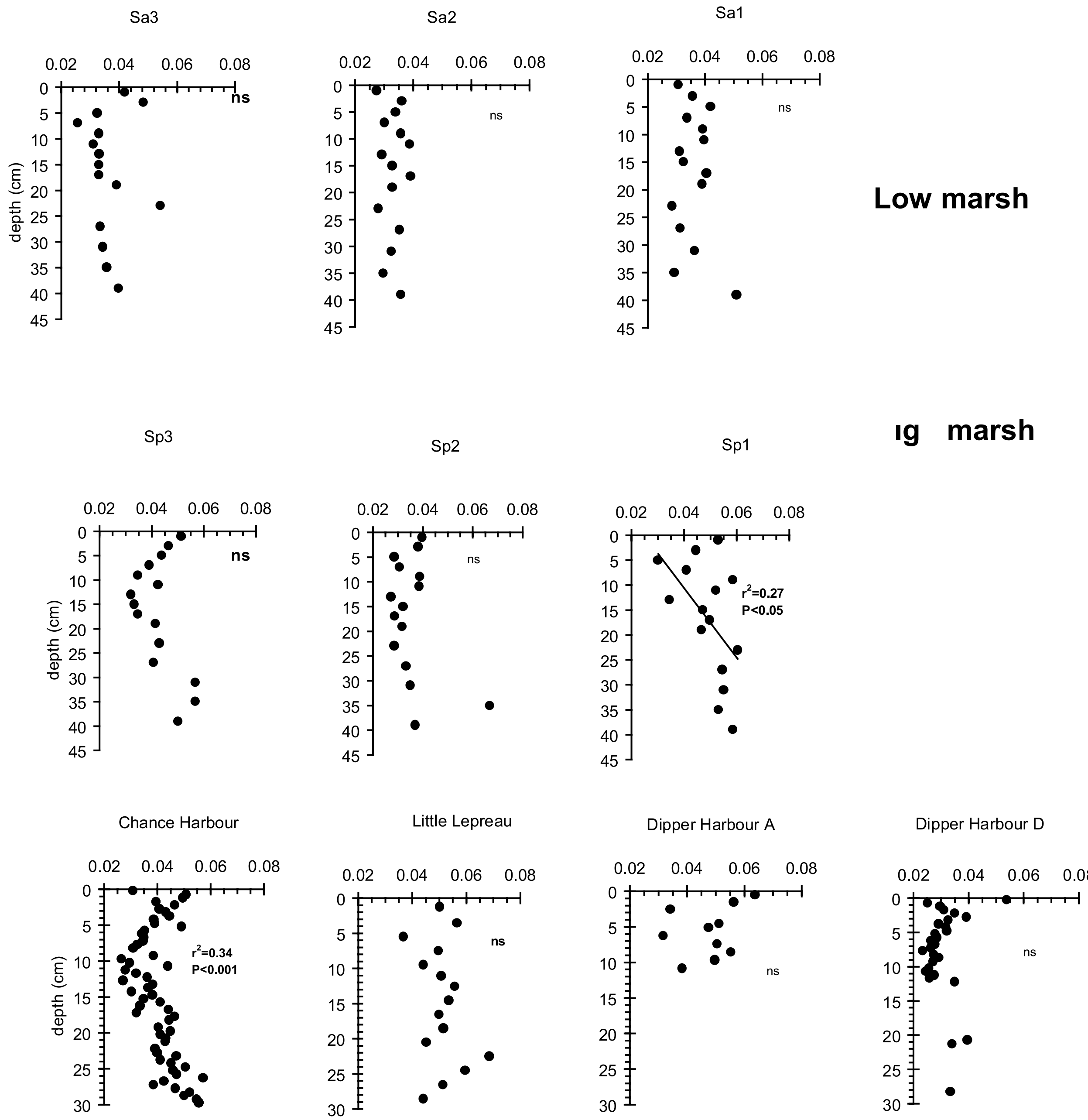

Figure 8. Carbon density (g cm^{-3}) with depth from cores taken in tidal salt marshes in the outer Bay of Fundy.

sites) to 2 (UL sites) times that of Dipper Harbour (Table 1). In Table 3 we apply equivalent rates and one 1.75 times higher to calculate rates of C accumulation in the upper bay. Average soil carbon densities for the three upper bay cores is 0.036 ± 0.002 g C cm^{-3}, and from surface samples, we estimate that low-marsh soils here contain 0.023 g C cm^{-3}.

3.3. Magnitude and Rates of Carbon Storage

Our calculation of inventories and rates of C accumulation uses the densities and rates estimated for both high and low marshes in the upper and outer bay. To estimate present-day rates of C annually stored by Fundy salt marshes, we multiply the soil accumulation rate measured (or estimated) over the past 30 years by the carbon density of that soil (Table 3). Multiplying this product by the area of low or high marsh in the upper and outer bay provides an estimate of the rate of carbon accumulating throughout the bay, $1.4–2.1 \times 10^{11}$ g C yr^{-1}.

The depth of marsh soil is variable and has not been extensively surveyed but extends more than 2 m in many marshes. However, as our investigation has been limited to the top 30 cm, we limit our estimation of the present carbon storage in Fundy marshes to this depth. Multiplying carbon densities of low- and high-marsh soils by their area in the two parts of the bay (Table 3), we calculate a total carbon inventory of 1.11×10^{13} g C in just the surface 30 cm of Fundy tidal marshes.

Ganong [1903] estimated that 85% of the original marsh area in the bay had been transformed into agricultural land through diking from the seventeenth to nineteenth centuries, primarily in the upper bay. Assuming that the present aerial inventory constitutes 15% of the original marsh area, the area of transformed marsh could be as

Table 3. Marsh Area, Soil Carbon Inventory, and Soil Carbon Accumulation Rates by Marsh Zone and Region of the Bay of Fundy

	Upper Bay			Outer Bay			
	Marsh Zone			Marsh Zone			
	Low	High	Total	Low	High	Total	Bay Wide
Area, 10^8 m^2	2.79	3.89	6.68	2.17	2.14	4.31	10.99
C density, g m^{-2}	227	360		432	348		
C in surface 30 cm, 10^{12} g	1.9	4.2	6.1	2.81	2.24	5.05	11.15
(assuming rates = outer Bay)							
Soil accumulation rate, cm yr^{-1}	0.17	0.54		0.17	0.54		
C accumulation rate, g C m^2 yr^{-1}	39	194		76	188		
C accumulation rate per unit, 10^{10} g C yr^{-1}	1.08	7.56	8.64	1.62	4.03	5.66	14.29
(assuming rates 1.75 times outer Bay)							
Soil accumulation rate, cm yr^{-1}	0.3	0.95					
C accumulation rate, g C m^2 yr^{-1}	68	340					
C accumulation rate per unit, 10^{10} g C yr^{-1}	1.88	13.23	15.12				20.77

high as 6.23×10^9 m^{-2}. Dikes were constructed at the upper edge of the low marsh, removing the ability of the former high-marsh area to collect sediment and sequester carbon as a tidal salt marsh system. We have found only one report of carbon density in dikeland soils. *Rodd et al.* [1993] report 3.86% organic matter (OM) and a bulk density of 1.48 g cm^{-3} in the upper 15 cm of a dikeland soil. Using a factor of 1.724 for conversion OM to organic carbon in this agricultural soil, we calculate that carbon density is 0.033 g cm^{-3}. Although comparable to carbon density in Fundy marshes, these agricultural soils have not been vertically accreting as have the marshes subjected to rising sea levels outside the dikes.

Using the estimate for rates of carbon burial in upper bay high marshes and the area of diked marshland, we can calculate how much additional carbon has been available to the atmospheric pool because of the construction of these dikelands. An additional 2.4–3.6 $\times 10^{11}$ g C yr^{-1} would have been sequestered by the marshes. If we assume that dikelands are at least 160 years old, then the difference in land use represents a "lost" sink equivalent of at least 3.8×10^{13} g of carbon over the past 160 years alone. Refining this estimate requires mapping of the boundaries of transformed marsh and further consideration of past soil accumulation rates in the upper bay.

4. Conclusions

There is a reciprocal relationship between carbon density and carbon accumulation rates in Fundy marshes. This is probably because high amounts of suspended sediment deposited in the upper bay dilute soil carbon concentrations but also help trap carbon while rapidly increasing storage capacity by forcing high rates of marsh soil accumulation. In the outer bay, suspended sediment supply is much lower, and soil accumulation rates are primarily controlled by relative sea level rise [*Chmura et al.*, 2001a]. Throughout the bay, marsh soil C inventories have been increasing for centuries and should continue to increase as sea level is expected to continue to rise [*Warrick et al.*, 1996].

Despite its northern latitude and shorter growing season, Fundy salt marshes accumulate carbon at rates $\geq 91-159 \times 10^{11}$ g C yr^{-1} reported by *Craft et al.* [2000] for natural marsh soils in North Carolina, 20° latitude to the south. Interestingly, *Craft et al.* [2000] found that "constructed" marshes (<25 years old) in North Carolina accumulated carbon at rates similar to those of natural marshes. Their results suggest that dikelands allowed to revert to salt marsh would eventually accumulate carbon at rates measured in this study. If all dikelands were to revert to salt marsh, the 2.4–3.6 $\times 10^{11}$ g C yr^{-1} likely to be sequestered would be equivalent to 4–6% of Canada's targeted reduction of 1990-level emissions of CO_2 (274.46×10^{11} g CO_2 yr^{-1} or 62.3×10^{11} g C yr^{-1}) under the Kyoto Protocol. It would not be practical nor desirable to revert all diked lands to their original state, but such land transformations should be considered in calculations of historical carbon budgets and in any extension of the Kyoto Protocol.

Rates of carbon sequestration in Fundy tidal marshes are as high as, or perhaps higher than, the highest estimated (80 g C m^{-2} yr^{-1}) for improved cropland management in temperate or tropical systems [*Watson et al.*, 2000]. Improved grassland or agroforest management techniques elsewhere could result in greater rates of C sequestration, but all these terrestrial carbon stocks will eventually become saturated. Our studies of historical rates of C accumulation on the Bay of Fundy suggest that carbon accumulation in these soils will continue at relatively constant rates over century scales.

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