

# Carbon Storage in the Soils of a Mesotidal Gulf of Maine Estuary

**J. L. Jespersen**

Dep. of Plant, Soil and Environ.Sci.  
Univ. of Maine  
Orono, ME 04469-5722

present address:

FB Environmental  
1 India St.  
Portland, ME 04101

**L. J. Osher\***

Dep. of Plant, Soil and Environmental Sci.  
Univ. of Maine  
Orono, ME 04469-5722

Estuaries have the highest primary productivity of all ecosystems, yet the soils in estuarine environments have been largely overlooked in C sequestration studies. This research quantified organic C stored in the top 1 m of soils from the Taunton Bay estuary in Hancock County, Maine. Taunton Bay is centrally located within Maine's Island-Bay Coastal Complex, a physiographic region that encompasses 47% of the state's coastline. Riverine inputs of sediments and sediment-associated organic matter to this and most Maine estuaries are quite low. These estuary soils form by incremental additions of reworked glaciofluvial marine sediments and estuarine organic matter to the soil surface. The organics are protected from decomposition by anaerobic conditions. As sea level rises, the estuary area increases by inundating and submerging the soils at its edges. The average concentration of soil organic C in the top 1 m of these estuary soils is 2.4% and the average soil bulk density is 0.67 g cm<sup>-3</sup>. The organic C content is 136 Mg C ha<sup>-1</sup>, which is greater than the C content in the top 1 m of Maine's upland soils. These results suggest that systematically quantifying and dating the C in estuarine soils will provide valuable data for use in regional and global C budgets and climate models.

Abbreviations: BB, bay bottom landscape unit; CS, channel shoulder landscape unit; DEC, deep edge and cove landscape unit; FES, fine-silty and fine-loamy estuarine sediments; MS, mussel shoal landscape unit; OC, organic carbon; RSEC, recently submerged edge and cove landscape unit; SFSM, submerged fluvial stream and marshes landscape unit.

Soils play an important role in the global C cycle in that they store large amounts of C, and if managed to do so, may provide an enhanced sink for atmospheric CO<sub>2</sub>. Previous studies have shown that the organic matter in the world's soils contain as much as three times the C found in land vegetation (Schlesinger, 1986; Raymond and Bauer, 2001). In addition, soil C has much longer residence mean times than the C in the vegetation that the soils support. Storage of organic C in this long-residence-time pool is referred to as *carbon sequestration* (Wang and Hsieh, 2002).

The concern about increasing atmospheric CO<sub>2</sub> and its role in future global climate change (Fung et al., 2005; Matthews et al., 2005) has led soil scientists to quantify soil C content (also referred to as *storage* or *stocks*) and residence times in specific locations to better constrain global C budgets. Identification of age and turnover time is achieved using radiocarbon measurements (e.g., Knorr et al., 2005; Gaudinski et al., 2000). The common method of quantifying soil organic carbon (OC) is to use the total soil OC data for specific sites and scale up to regional or global estimates using soil maps (Lacelle et al., 2001) or soil-landscape modeling (Thompson and Kolka, 2005). Examples of such soil C accounting are the estimates of soil C stocks in Maine (Davidson and Lefebvre, 1993) and the conterminous USA (Guo et al., 2006).

The soils of swamps and marshes store the greatest amount of OC of all terrestrial ecosystems—up to 1000 Mg ha<sup>-1</sup> in the top 1 m (Houghton, 1995; Trumbore and Harden, 1997; U.S. Department of Energy, 1999)—and tend to have very long

turnover times (Choi and Wang, 2004). Carbon accumulates in these soils because anaerobic conditions limit the rate of organic matter decomposition (Brady and Weil, 1996). In an attempt to improve soil C budgets, OC storage in other landscapes with anaerobic conditions have been quantified. Examples are mangrove forests and tidal marshes (Chmura et al., 2003; Choi and Wang, 2004; Hussein et al., 2004), subsurface horizons of riparian soils (Blazewski et al., 2005), and reservoirs and other man-made impoundments (Smith et al., 2001).

Despite the focused efforts to balance the C budget, global change scientists have not been able to identify in what form some of the atmospheric CO<sub>2</sub> is being stored annually (Pacala et al., 2001). Models of the C cycle identify the location of this unknown sink as somewhere in the midlatitude terrestrial biosphere (Houghton, 2003). Approximately half of this C is being stored in the aboveground biomass of North American forests (Hurt et al., 2002; Pacala et al., 2001), but the location of the rest of the sink is unknown (Prentice et al., 2001). The challenge of finding the unknown C sink requires looking for other ecosystems in the region for which the aerial extent and soil C contents are, thus far, poorly quantified. The non-marsh estuarine ecosystems along the midlatitude Atlantic Coast fit into this category.

Estuaries have the highest primary productivity of all ecosystems (Odum, 1959). The allochthonous (photosynthesized in the estuary) and autochthonous (from outside the estuary) organic matter is processed within the estuary by filter feeders, decomposed and remineralized by benthic organisms, and moved through the system by tidal fluctuations (Potsma, 1967). Seagrasses, the rooted plants in non-marsh subtidal estuaries, stabilize sediments, dampen wave action, and collect particulates, including organic matter, from the water column (Gacia and Duarte, 2001; Gacia et al., 1999). The particles intercepted by the grasses are then deposited on the soil surface. As additional sediment is deposited, the

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\*Corresponding author (laurie@maine.edu).

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677 S. Segoe Rd. Madison WI 53711 USA

anoxic and light-limited conditions below the sediment surface inhibit microbial processing and photodegradation.

Despite these ideal conditions for production and preservation of organic matter, the soils of coastal ecosystems, specifically estuarine systems, have been largely overlooked in C sequestration studies (Chmura et al., 2003; Thom et al., 2003). This is, in part, because soil maps are limited for submerged environments (Bradley and Stolt, 2003). A few detailed soil maps have been completed for some midlatitude Atlantic coastal environments in the USA (Bradley and Stolt, 2003; Demas and Rabenhorst, 1999; Demas et al., 1996; New York City Soil Survey Staff, 2005). Several other soil maps of estuarine environments are in progress (Balduff and Rabenhorst, 2006; Coppock and Rabenhorst, 2003; Fischler et al., 2005; Payne and Stolt, 2006; Saunders and Collins, 2006). The soil map for Taunton Bay, Maine, was recently completed (Flannagan and Osher, 2006). The maps generated and samples collected for that study were used as resources for this research.

This research quantifies the total soil OC to a depth of 100 cm in the soils of Taunton Bay, a shallow, rock-bound, mesotidal estuary on the central Maine coast. This study is the first accounting of C storage in non-marsh estuarine soils for use in regional soil C budgets and climate models. These data were used to address the hypothesis that Maine's estuarine soils store more C per hectare than Maine's upland soils.

## STUDY SITE

Taunton Bay, a 1329-ha estuary, is located in Maine's Downeast region along the section of the coast characterized as the Island-Bay Complex (Jacobson et al., 1987; Fig. 1). This region includes the area from the western margin of Penobscot Bay to just north of Machias Bay, and encompasses 47% of Maine's total coastline (Kelley, 1987). Estuaries in this portion of Maine's north-central coast are glacially incised, have bedrock outcrops that form rounded granitic islands, and have extensive fine-grained mudflats (Jacobson et al., 1987; Larsen et al., 1980). In general, Maine's estuaries have large tidal ranges (2–11 m) and small riverine sediment supplies (Folger, 1972). The combined effects of low sediment input and bedrock relief in this area limit marsh formation; the only marshes in this coastal region are fringing marshes at the edges of the most quiescent coves (Kelley, 1987).

The sediments being deposited in these estuaries are silts and silty clays that have eroded from coastal bluffs (Kelley, 1987). The bluffs are composed of the thick glaciomarine sediment layer known as the Presumpscot Formation (Bloom, 1960; Schnitker, 1974). This material, which was deposited between 14 000 and 11 500 yr BP, blankets portions of eastern Maine's uplands as far as 100 km inland from the present coastline (Dorion et al., 2001).

Sea level has been rising consistently in Maine for the past 10 000 yr (Belknap et al., 1988), with a rapid increase of 30 to 40 cm in the last 200 yr (Gehrels et al., 2002). Sea-level rise causes wave erosion and destabilization of bluffs composed of glaciomarine parent materials (Kelley, 1987). Along the estuarine-terrestrial edges, unarmored and unvegetated soils formed in till and glaciomarine parent materials are easily dislodged, becoming the sediment source for the adjacent estuary (Anderson et al., 1981; Jordan, 1999). As sea level rises, the estuaries receive incremental additions of fine sediments and organic matter to the soil surface, and previously deposited material is buried (Belknap et al., 1988).

The Taunton Bay estuary is mostly shallow, with narrow channels as deep as 21 m below mean sea level. The average water depth at mean sea level is <3 m. Mean tidal range is 2.7 m and mean spring tidal range is 3.4 m (Flannagan and Osher, 2006). The streams entering the estuary include West Brook, Egypt Stream, and more than a dozen named and unnamed streams draining the western, northern, and southeastern portions of the watershed. Turbidity is low in these streams, as it is in most Maine rivers and streams (Belknap et al., 1988). The primary source of marine waters to the Taunton Bay is Frenchman Bay, located directly to the south.

All soils mapped in the estuary are in the suborder Aquents because they are permanently saturated (Soil Survey Staff, 2003). The parent materials for the surface soils in the entire estuary are fine-silty and fine-loamy estuarine sediments (FES; Flannagan and Osher, 2006). In the center of the estuary, the FES is >5 m deep. Close to the estuary edges, FES overlies soils that were subaerial before being submerged by the estuary's rising water level. A  $^{210}\text{Pb}$  analysis of three Taunton Bay soil profiles identified that the FES at 30-cm depth are approximately 100 yr old (Osher et al., 2006). This suggests that the most recent inundation and burial of the soils at the edges of the estuary began within the last 100 yr. Cesium-137 counts of the same samples identified minimal disturbance of the soil horizons between 20- and 40-cm depth. Above 20 cm, anomalous  $^{210}\text{Pb}$  ages are assumed to be a result of mixing of the surface soils by polychaete worms (Osher et al., 2006).

## MATERIALS AND METHODS

Soil cores were extracted from the estuary using 7.6-cm-diameter Al pipes. The base of each pipe was fitted with a core catcher, an Al device designed to allow the sample to slide into the pipe as it is pushed down, but prevent the sample from sliding out of the bottom when the pipe is extracted from the surrounding soil. Each pipe was pushed into the soil surface using a vibrocorer (Hoyt and Demarest,

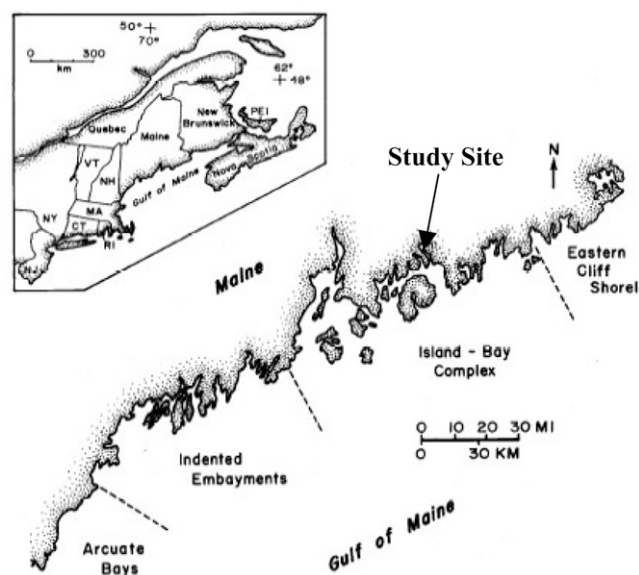
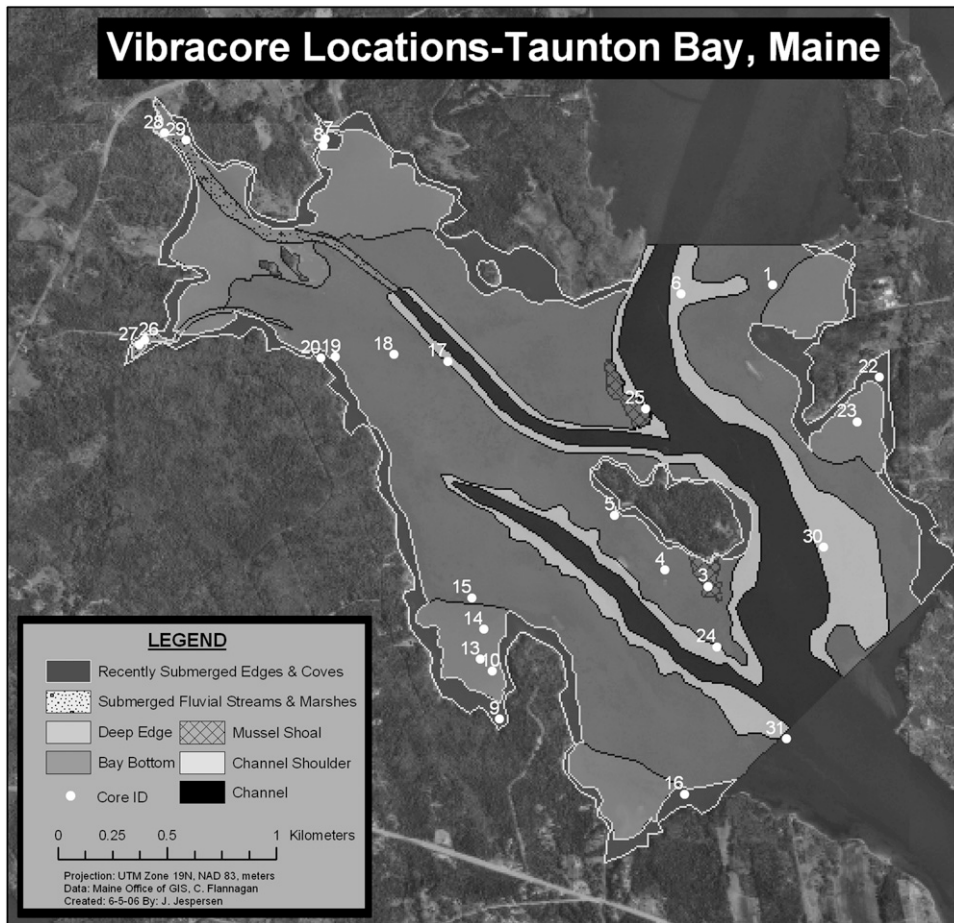


Fig. 1. Map of the Maine coast identifying the four coastal compartments as delineated by Kelley (1987) with an arrow identifying the location of Taunton Bay within the Island-Bay Complex. The inset map illustrates the location of the Maine coast within the Gulf of Maine Bight.



**Fig. 2.** Subaqueous landform map for Taunton Bay, Maine. The map shows seven landscape units as identified by Flannagan and Osher (2006). The locations of soil profiles studied for this research are identified by points and labeled with profile number.

1981) mounted on a 6.1-m (20-ft) pontoon boat. Before extraction of the Al pipe containing the soil core, the sampling team measured the distance from the top of the pipe to the soil surface (outside the pipe) and the distance from the top of the pipe to the top of the soil sample. The difference between these two measurements was used to estimate the amount of compaction of the profile within each pipe. Cores were transported to the University of Maine and stored in a cooler at 4°C. Sampling locations are shown on the landscape unit map in Fig. 2.

In the lab, the Al pipes were split in half using a circular saw. Soil profiles were described from the faces of the split cores according to National Soil Survey Center guidelines (Schoeneberger et al., 2002). Soils were sampled by horizon from one half of the core, dried, sieved to remove coarse fragments >2 mm, ground using a flail sieve (Custom Laboratory Equipment, Orange City, FL), placed in airtight bags, and stored in a cool, dark location. The soil in the other half of the core was covered, returned to the walk-in cooler, and later used to determine the bulk density for each horizon by dividing the horizon volume by the horizon (105°C) oven-dry weight (Blake and Hartge, 1986).

Additional samples of the high-*n*-value (fluid) surface horizons were collected from almost all sampling locations 1 yr after the vibracore samples were collected. The surface soils of the mussel shoals were not collected because these soils do not have a high-*n*-value surface layer. Original vibracore sampling locations were identified using a global positioning system (GPS) unit. At each location, three samples were collected using a Macaulay sampler. The depth of the high-*n*-value horizon at each location was measured in the field and

compared with the profile description for that location. Samples from the top 4 cm were placed in plastic jars, sealed, labeled, transported on ice to the University of Maine-Orono campus, and stored in a refrigerator until analysis. Bulk densities were calculated using the mean weight and calculated volume of samples from the top 4 cm of the soils at each sampling location.

Organic C concentration was determined using a subsample of each horizon that had been dried, sieved, and ground. The subsamples were weighed and encapsulated in 9- by 10-mm tin cups. Total N and total C were measured using a PDZ Europa (Sandbach, UK) C/N elemental analyzer after combustion to CO<sub>2</sub> and N<sub>2</sub> at 1000°C. An additional subsample from each horizon was acidified with 0.5 M HCl to remove inorganic C (Midwood and Boutton, 1998). This subsample was rinsed with distilled water, frozen, freeze-dried, weighed, and encapsulated into 9- by 10-mm tin cups as described above. Organic C concentration in these samples was measured on the same elemental analyzer after sample combustion to CO<sub>2</sub> and N<sub>2</sub> at 1000°C. Inorganic C concentration was determined by calculating the difference between the C concentration before and after acid treatment.

Radiocarbon ages of soil OC were determined on acidified, dried, ground samples. Each sample was graphitized and analyzed at the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine. Radiocarbon concentrations were corrected for isotopic fractionation and backgrounds were subtracted based on measurements of <sup>14</sup>C-free coal following the procedures of Stuiver and Polach (1977).

Total soil (OC) contents were calculated using the following formula (Veldkamp, 1994):  $SOC = C_s \times L \times D_b \times 10^4$ , where  $C_s$  is the OC concentration (kg C kg<sup>-1</sup> soil),  $L$  is the soil layer thickness (m), and  $D_b$  is the bulk density of the soil (g cm<sup>-3</sup>). The SOC for each horizon to 1 m was calculated by plugging in the depth ( $L$ ), bulk density ( $D_b$ ), and the C content ( $C_s$ ) for each horizon into the equation. The soil OC content for each profile (to 1 m) was calculated as the sum of all horizons in the profile from 0 to 100 cm.

### Groupings of Profiles

Soil profiles were grouped into the landscape units identified by Flannagan and Osher (2006) in an effort to interpret the role of landscape position on soil OC contents and distribution. Next, soils were regrouped, taking into account the depth of the FES and presence of another parent material, in addition to location on the landscape. All profiles with <45 cm of FES over some other, low-OC-content parent material were collected from the estuary edge or coastal cove landscape units. These profiles were grouped together and named *recently submerged edge and cove* soils. In the remainder of the profiles from the estu-



ary edges and coastal cove landscape units, FES extended to a depth >90 cm but <200 cm. These profiles were grouped together and named *deep edge and cove* soils. The four profiles from areas mapped as submerged fluvial stream or submerged marsh soils (Flannagan and Osher, 2006) were grouped together and given the eponymous name *submerged fluvial stream and marsh* soils. The profiles in which FES was the only parent material to a depth of at least 2 m were grouped together and named *bay bottom* soils. The pairs of soil profiles from the mussel shoals and from the channel shoulder landscape units were placed in their own eponymous groups.

The mean OC content for each group was calculated as the grand mean OC content for the set of profiles within that group. The mean OC content for the entire Taunton Bay estuary (to 1-m depth) was calculated by multiplying the grand mean for each group by the estimated aerial extent of estuary occupied by each group. The OC stored at the base of the channel was not included in this calculation.

## Data Analysis

The weighted mean OC concentration for the top 1 m of soil in each landscape unit was determined as the product of the OC concentration and the horizon depth for each horizon in each profile. The sum of the weighted values from each horizon was calculated and divided by the total depth of the profile to determine a weighted value for each individual profile. The final value represents the average of the weighted means of profiles within each landscape unit. Statistical analyses were conducted in SYSTAT (Systat Software, 2004). A one-way ANOVA ( $\alpha = 0.05$ ) was used to test for differences in the mean soil OC contents and mean bulk densities for each landscape unit. The Bonferroni correction factor was used to correct  $p$  values for the increased probability of Type I errors.

## RESULTS

### Organic Carbon Age

Individual radiocarbon ages for samples collected from the horizon spanning the 1-m depth in Profiles 13 and 19 are  $3460 \pm 15$  and  $3435 \pm 15$  yr BP, respectively (Table 1). The radiocarbon measurements for these and the seven other horizons in the FES and at the interface of the FES and the Presumpscot Formation identify a pattern of incremental linear change in OC age ( $y$ ) in years before present with depth ( $x$ ) in centimeters ( $r^2 = 0.77$ ).

The primary source of the mineral material in these soils is the silty-clay-textured glaciomarine Presumpscot Formation. The Presumpscot Formation was encountered at the base of some of the soil profiles from the estuary edge and coastal cove landscape units. The mean OC concentration of this material is  $0.17 \pm 0.15\%$  and the median OC concentration is 0.11%. Radiocarbon ages of the top of the Presumpscot Formation were  $5830 \pm 20$  and  $5060 \pm 15$  yr BP in Profiles 13 and 19, respectively (Table 1).

### Organic Carbon Concentration

When profiles were grouped by the landforms identified on Fig. 2, there were no significant differences in soil OC concentration between any of the groups. In addition, the means for the terrestrial edge and coastal cove landscape units had large ranges in soil OC concentration and large standard deviations. The four other landscape unit groups—submerged fluvial stream, fluvial marine terrace, mussel shoal (MS) and channel shoulder (CS)—had small ranges in soil OC concentrations and small standard deviations of the mean.

**Table 1. Radiocarbon dates of samples for ten horizons from the Taunton Bay estuary profiles.**

Profile no.	Horizon depth			Parent material <sup>‡</sup>	<sup>14</sup> C age yr BP	UCIAMS no. <sup>§</sup>
	Upper	Lower	Midpoint <sup>†</sup>			
	cm					
13	78	109	93.5	FES	$3435 \pm 15$	25435
13	134	143	137.5	FES & OM	$3900 \pm 15$	25436
13	157	175	166.0	PF	$5830 \pm 20$	25437
17	97	102	99.5	FES	$2285 \pm 15$	25438
19	113	129	126.0	FES	$3460 \pm 15$	25439
19	176	180	178.0	OM	$4080 \pm 20$	25440
19	180	190	185.0	OM & PF	$5060 \pm 15$	25441
20	14	29	21.5	FES	$1500 \pm 30$	25442
20	29	40	34.5	FES	$1640 \pm 15$	25443
31	96	109	102.5	FES	$4890 \pm 20$	25444

<sup>†</sup> The midpoint of the horizon was used as the sample depth for the regression analyses.

<sup>‡</sup> FES is fine estuarine sediment, PF is the Presumpscot Formation, and OM is organic matter.

<sup>§</sup> Sample number assigned by the University of California Irvine AMS Laboratory.

By regrouping the profiles according to depth of the FES parent material and then according to landscape position, specific patterns of OC concentration change with depth were more visible (Fig. 3). The soils of the recently submerged edge and cove (RSEC) group have large decreases in OC concentration from the surface to the underlying horizons (Fig. 3a). The OC concentrations of individual horizons range from close to 4.0% at the surface to as little as 0.11% at depth (Fig. 3a). The mean OC concentrations of RSEC soils are 2.4% at the surface and 0.86% at 1 m. The surface horizons have a large range in OC concentration. The horizons at depths >45 cm have a very small range in OC concentration. The pattern of rapid decrease in OC with depth below the surface is commonly observed in upland soils.

The submerged fluvial stream and marshes (SFSM) profiles have the most irregular decreases and increases in OC concentration from one horizon to the next, as would be expected for soils formed from parent materials deposited by streams and tidal wetlands. Organic C concentrations range from 1.8 to 5.0% (Fig. 3b). The mean OC concentrations are 3.1% at the surface and 1.8% to 100 cm. The range in OC concentration in the surface horizons of the SFSM soils is similar to the surface horizons of the RSEC profiles. At depths >45 cm, the OC concentration range is much greater in the SFSM profiles than in the RSEC profiles.

The profiles in the bay bottom (BB) group have OC concentrations ranging from 1.7 to 3.3% (Fig. 3d). The mean OC concentrations are 2.5% at the surface and 2.4% to 100 cm. The five soil profiles in the BB group have the least variability in OC concentration from the surface to 1-m depth of sets of soils from any landscape units (Fig. 3). The soils from the MS have OC concentrations ranging from 1.8 to 3.7% (Fig. 3e) and have an average concentration of 2.9%. The two profiles sampled were remarkably similar from the soil surface to approximately 60 cm. At depths >60 cm, however, the difference in OC concentration between the two profiles was as much as 1%.

The weighted mean OC concentration for the top 1 m of soil in the six C groups is presented in Table 2. The mean OC

concentration of the soils in the RSEC group is  $0.9 \pm 0.33\%$ . The RSEC is significantly less than the OC concentration in the rest of the landscape units. The mean OC concentration for the soils of the other groups ranges from  $2.0 \pm 0.03\%$  in the CS group to  $2.9 \pm 0.21\%$  in the MS group, but are not significantly different from one another. The mean OC concentration in all horizons in the top 1 m with FES parent materials is  $2.4 \pm 0.34\%$ . The concentrations are all close to this mean, fluctuating only slightly from one horizon to the next.

### Bulk Density

The  $D_b$  of these estuary soils ranges from fluid ( $0.02 \text{ g cm}^{-3}$ ) at the soil–water interface, to as much as  $2.34 \text{ g cm}^{-3}$  at 100 cm (Fig. 4). The  $D_b$  of the high- $n$ -value surface layers ranges

between  $0.10$  and  $0.16 \text{ g cm}^{-3}$ . This layer is present in all but the MS soils (Fig. 4e). The  $D_b$  of the surface horizons collected by vibracore range between  $0.02$  and  $0.35 \text{ g cm}^{-3}$ . Bulk density increased below these surface horizons in all profiles. The profiles with highest and the greatest range in  $D_b$  are those in the RSEC group (Fig. 4a). The mean  $D_b$  of the profiles all other groups is  $0.67 \pm 0.18 \text{ g cm}^{-3}$ . The profiles with the lowest and the smallest range in  $D_b$  are those in the MS group ( $0.37$ – $0.85 \text{ g cm}^{-3}$ ). The mean  $D_b$  of the RSEC profiles are significantly higher ( $p < 0.05$ ) than the mean  $D_b$  in the SFSM, BB, and MS groups (Table 2).

The  $D_b$  in the BB, SFSM, and deep edge and cove (DEC) profiles (Fig. 4b–4d) increase regularly with depth. Within these three groups of profiles, the range in  $D_b$  is smallest for the BB group and greatest for the DEC group. The CS profiles have an irregular pattern of change in subsurface  $D_b$  with depth.

### Total Organic Carbon

The weighted mean OC content for all estuary soils in Taunton Bay is  $136 \text{ Mg ha}^{-1}$ . The mean OC content in the RSEC profiles,  $67 \pm 30 \text{ Mg ha}^{-1}$ , is significantly less than the other soil profile groups. The OC in the RSEC profiles is not equally distributed. Almost all of the OC in the soils is in the top 30 to 45 cm. There is very little OC in the portion of these soils that is below the FES. The mean OC contents of the SFSM and DEC groups are  $177 \pm 46$  and  $164 \pm 29 \text{ Mg ha}^{-1}$ , respectively. These OC contents are significantly greater than the OC contents in all other soil groups (Table 2). The mean OC contents in the profiles of the BB, MS, CS, and DEC groups range from  $126 \pm 6.0$  to  $147 \pm 59 \text{ Mg ha}^{-1}$  and are not significantly different from one another. Variability in OC content between individual profiles is highest in the SFSM group.

### DISCUSSION

The top 1 m of the majority of the soils of Taunton Bay are composed of FES, with an average  $D_b$  of  $0.67 \text{ g cm}^{-3}$ . The exception is the group of soils referred to as the RSEC. The RSEC soils have FES parent material to approximately 20 to 40 cm. Below these fine estuarine sediments are submerged upland and coastal landscapes including upland soils, beaches, or fluvial delta soils. The DEC soils are similar to the RSEC soils in that their profiles (top 2 m) have surface horizons with FES parent material over the inundated and submerged soils that were previously subaerial. The FES layers have  $D_b$  similar or slightly greater than the other FES horizons in the estuary. The  $D_b$  of the FES surface is  $<0.35 \text{ g cm}^{-3}$ , and the  $D_b$  of the FES horizons beneath the soil–water interface are all  $<1.0 \text{ g cm}^{-3}$  at depth. The horizons buried beneath the FES materials have OC contents and bulk densities similar to the nonsubmerged

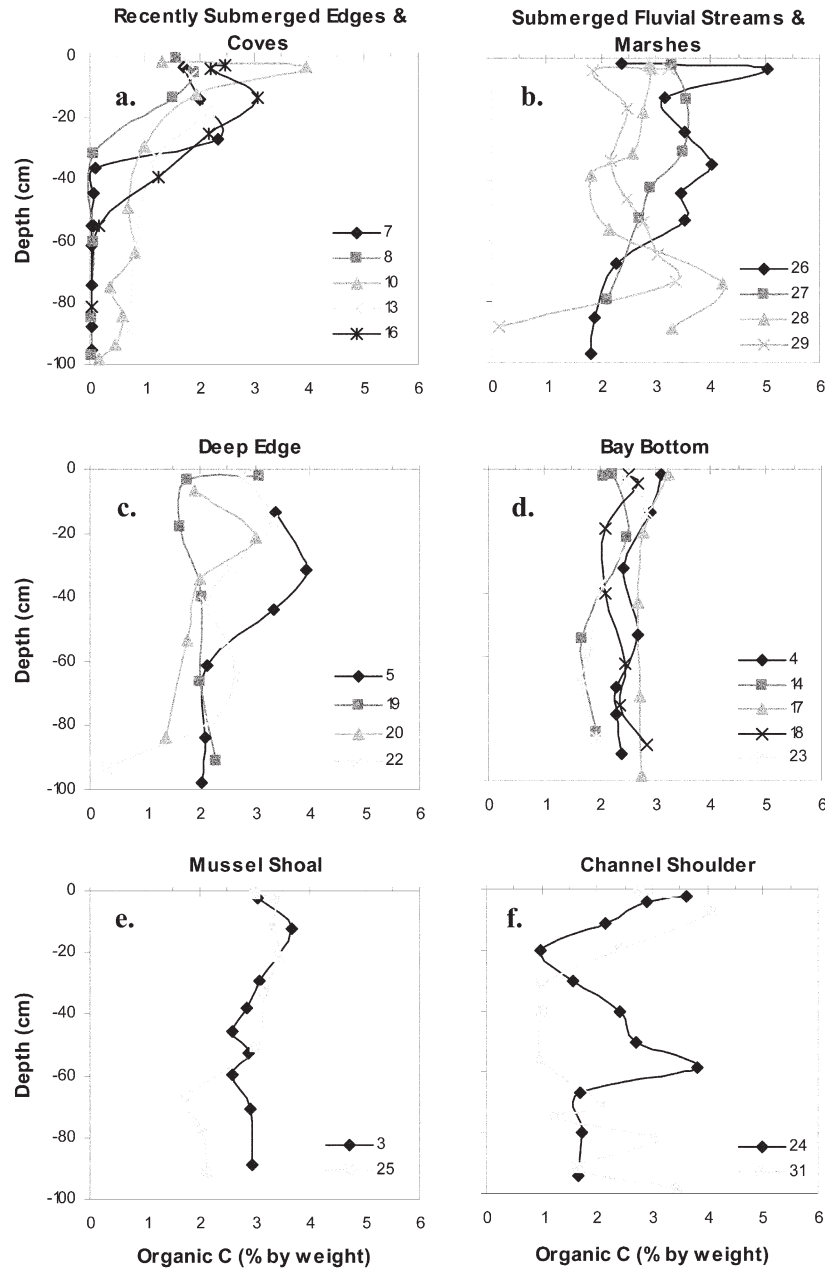


Fig. 3. Organic C concentrations for soil horizons from all profiles from each of the six profile groups: (a) recently submerged edges and coves, (b) submerged fluvial streams and marshes, (c) deep edge soils, (d) bay bottom, (e) mussel shoal, and (f) channel shoulder. Individual points represent the midpoint of each soil horizon.

upland soils upslope from the water's edge (NRCS, 2006). Few of the soils in the RSEC and DEC groups are deeper than 200 cm. Most have bedrock or glaciomarine sediment within 150 cm of the soil–water interface.

### Organic Carbon Content in Taunton Bay Soils vs. Soils of Other Ecosystems

The weighted mean OC content for all estuary soils in Taunton Bay is 136 Mg ha<sup>-1</sup>, which is 35% to >100% greater than the upland soils that commonly occur within 161 km (100 mi) of Maine's Island–Bay coast (Table 3). The OC content of these estuary soils is similar to, and in some cases greater than, the OC stored in the upland soils of Maine and double the global average soil OC content for Entisols. When compared to freshwater wetlands, however, the mean OC content for these estuary soils is quite low. The Taunton Bay soils have OC contents equivalent to only half of the OC in Maine's Fluvaquents, 20% the OC in wetland soils around the globe, and 15% of the OC stored in boreal forest soils (Table 3).

The Taunton Bay soils with FES parent materials to a depth of at least 1 m occupy 78% of the total estuary area, and have OC contents of 126 Mg ha<sup>-1</sup> and greater (Table 2). There are soils with FES to 1 m from the edges of the estuary across the entire bay bottom and to the edges of the channels. Their OC contents are greater than the most common off-drained (somewhat poorly, poorly, and very poorly drained) upland soils of Downeast Maine (Table 3). This category includes two groups of soils with significantly higher OC contents: the SFSM soils (177 Mg ha<sup>-1</sup>) and soils at the edges of the estuary and in coves (DEC, 164 Mg ha<sup>-1</sup>).

The soils of the SFSM and DEC have mean OC concentrations similar to the soils of the BB, but have greater  $D_b$  (Table 2). It is the increased  $D_b$  that results in their OC content being significantly higher than the other soils. Before becoming submerged by the saline estuary waters, the SFSM soils would have been mapped as Fluvaquents (Flannagan and Osher, 2006). As such, it is not a surprise that their OC contents are similar to the Fluvaquents (regularly flooded, nonsaline soils) mapped throughout Maine.

The RSEC soils have the lowest OC contents of all Taunton Bay estuary soils (Table 2). These are the only soils in the estuary with OC contents equivalent to the global average for the Entisol soil order. They occupy approximately 7% of the estuary, and have OC contents similar

**Table 2.** Area of each profile group, number of profiles described in each group, mean organic carbon content and mean bulk density for the six groups of soil profiles.

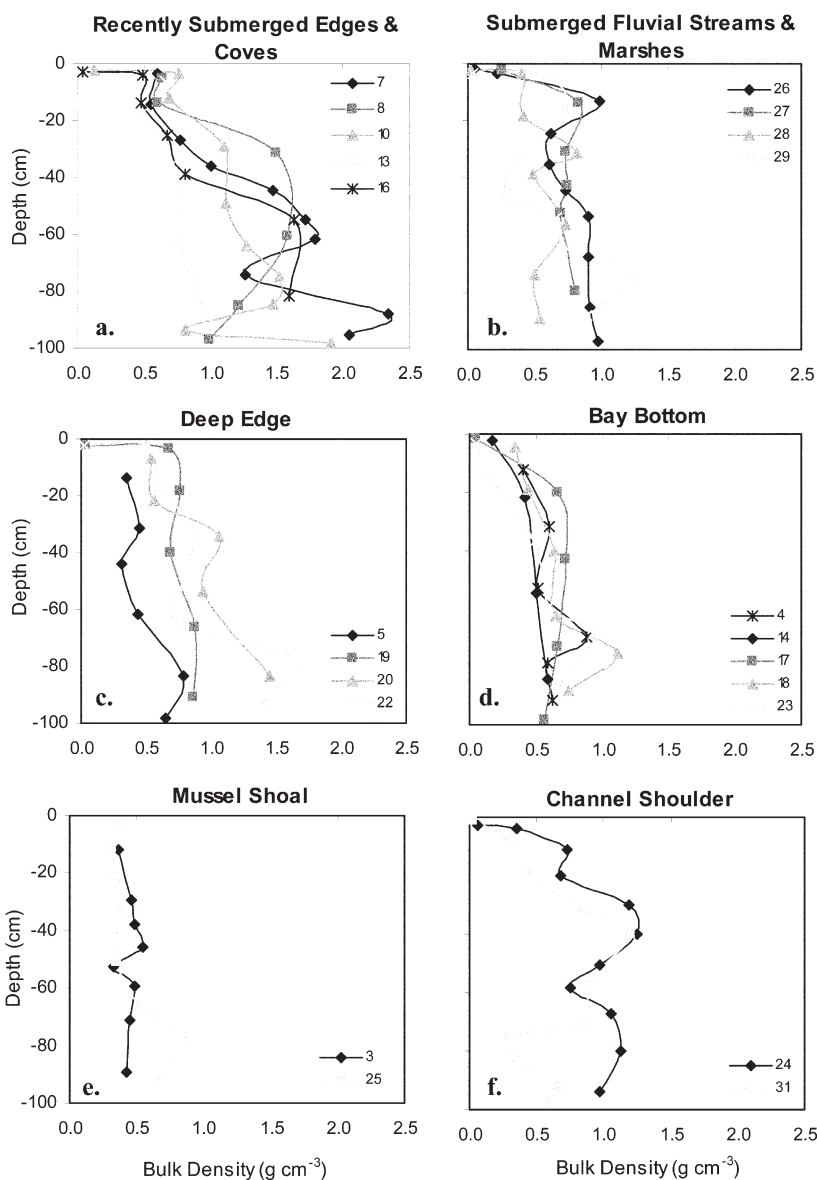
Name of profile group	Area†	n‡	Organic C§		Bulk density§
			Content	Conc.	
	%	no.	Mg ha <sup>-1</sup> (SD)	% (SD)	g cm <sup>-3</sup> (SD)
Recently submerged edges & coves	7	5	67 a¶ (30)	0.9 a (0.33)	1.13 a (0.21)
Submerged fluvial streams & marshes	3	4	177 b (46)	2.6 b (0.47)	0.70 b (0.10)
Deep edge & cove	6	4	164 b (29)	2.3 b (0.43)	0.81 ab (0.23)
Bay bottom	51	5	134 ab (34)	2.4 b (0.28)	0.57 b (0.07)
Mussel shoal	1	2	126 ab (6)	2.9 b (0.21)	0.46 b (0.04)
Channel shoulder	17	2	147 ab (59)	2.0 b (0.34)	0.80 ab (0.21)

† Estuary area occupied by soils of this group based on Flannagan and Osher (2006). The sum of these areas is 85%, the channel occupies the other 15% of the estuary.

‡ Number of profiles used to calculate mean organic C and bulk density for profile groups.

§ Means for top 1 m of soil.

¶ Means in the same column with the same letter indicate no significant difference at  $\alpha = 0.05$ .



**Fig. 4.** Bulk density for soil horizons from all profiles from each of the six soil profile groups: (a) recently submerged edges and coves, (b) submerged fluvial streams and marshes, (c) deep edge soils, (d) bay bottom, (e) mussel shoal, and (f) channel shoulder. Individual points represent the midpoint of each soil horizon.

**Table 3. Organic C concentrations and contents to the 1-m depth for a range of soils and sediments compared with soils from Taunton Bay estuary.**

Description	Location	Organic C†		Reference
		%	Mg ha <sup>-1</sup>	
<u>Upland soils</u>				
Colonel (well drained)	Maine	1.3	63	Rourke (1994)
Monadnock (well drained)	Maine	1.6	75	Rourke (1990)
Nicholville (mod. well drained)	Maine	0.2	15	Rourke (1990)
Scantic (poorly drained)	Maine	0.9	101	Rourke and Schmidt (1979)
Burnham (v. poorly drained)	Maine	0.8	91	Rourke (1990)
Fluvaquents (v. poorly drained)	Maine average	1.1	260	Davidson and Lefebvre (1993)
Entisols	Global average		69	Kern (1994)
Wetland soils	Global average		720	U.S. Dep. of Energy (1999)
Boreal forest wetland soils	Manitoba, CA		1000	Trumbore and Harden (1997)
<u>Estuary soils and sediments</u>				
Submerged edges and coves	Maine	1.1	67	this study
Bay bottom	Maine	2.6	134	this study
Channel shoulder	Maine	2.4	147	this study
Submerged streams and marshes	Maine	3.2	177	this study
Weighted mean, entire estuary	Maine	1.1–3.2	136	this study
Estuarine sediment	Massachusetts	1.8–2.6		Latimer et al. (2003)
Coastal lagoon	Maryland	0–1.2		Demas et al. (1996)
Coastal lagoon	Rhode Island	1.0–4.0		Bradley and Stolt (2003)

† Organic C values for Maine upland soils are weighted means for the top 1 m of representative soil profiles.

to Colonel and Monadnock soils—well-drained soils formed from glacial till.

The mean OC concentrations of all soils in Taunton Bay are similar to near-shore marine sediments in Massachusetts and in the same range as OC in subaqueous soils of coastal lagoons in Maryland and Rhode Island (Table 3).

## CONCLUSIONS

This research is the first to quantify the OC stored to a depth of 1 m in estuary soils not dominated by marsh or mangrove vegetation. Because it is a first step, we made sure to begin this research by quantifying the range in soil OC across the entire landscape, and identifying differences in OC content between soils with varying parent materials and landscape position. As more estuary OC inventories are completed, it will be possible to scale up the results to regional or global estimates of soil OC in non-marsh estuarine ecosystems.

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