Dynamics of carbon sequestration in a coastal wetland using radiocarbon measurements

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[1] Coastal wetlands are sensitive to global climate change and may play an important role in the global carbon cycle. However, the dynamics of carbon (C) cycling in coastal wetlands and its response to sea level change associated with global warming is still poorly understood. In this study, we estimated the long-term and short-term rates of C accumulation, using C and C isotopic measurements of peat cores collected along a soil chronosequence, in a coastal wetland in north Florida. The long-term C accumulation rates determined by examining the C inventory and the radioactive decay of radiocarbon as a function of depth in the peat cores decrease with time from $\sim$130 ± 9 g C/m^2/yr over the last century to $\sim$13 ± 2 g C/m^2/yr over the millennium timescale. The short-term C accumulation rates estimated by examining the differences in the radiocarbon and C contents of the surfacial peat between archived (1985, 1988) and present (1996 and 1997) samples range from 42 to 193 g C/m^2/yr in low marsh, from 18 to 184 g C/m^2/yr in middle marsh, and from -50 to 181 g C/m^2/yr in high marsh. The high end-values of our estimated short-term C accumulation rates are comparable to the estimated rates of C sequestration in coastal wetlands reported by *Chmura et al.* [2003], but are significantly higher than our estimated long-term rates in the marshes and are also much higher than the published rates of C sequestration in northern peatlands. The higher recent rates of C accumulation in coastal marshes, in comparison with the longer-term rates, are due to slow but continuous decomposition of organic matter in the peat over time. However, other factors such as increased primary production in the coastal wetland over the last decades or century, due to a rise in mean sea level and/or CO_2 and nitrogen fertilization effect, could also have contributed to the large difference between the recent and longer-term rates. Our data indicate that salt marshes in this area have been and continue to be a sink for atmospheric carbon dioxide. Because of higher rates of C sequestration and lower CH_4 emissions, coastal wetlands could be more valuable C sinks per unit area than other ecosystems in a warmer world. *INDEX TERMS:* 1030 Geochemistry: Geochemical cycles (0330); 1040 Geochemistry: Isotopic composition/chemistry; 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); *KEYWORDS:* C accumulation, coastal wetland, radiocarbon

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1. Introduction

[2] Wetlands are perhaps the largest sinks of carbon (C) among the soil ecosystems. It is estimated that the amount of carbon stored in wetland soils is $\sim$498 Pg [*Eswaran et al.*, 1995], which amounts to more than one third of the total world pool of soil C. Wetland soils play an unusual role in the global carbon cycle. On one hand, they sequester the major greenhouse gas, carbon dioxide (CO_2), from the atmosphere as organic C, while on the other hand, they (with the exception of coastal wetlands) emit large quantities of the second most important greenhouse gas, CH_4 [*Gorham*, 1991; *Moore and Knowles*, 1987, 1989; *Whiting and Chanton*, 2001]. In addition, wetlands are being drained for agricultural and other purposes in many parts of the world and as a result are becoming a significant source of atmospheric CO_2. The importance of the wetland soil C in the global C budget has been recognized over the years. Because of a lack of fundamental knowledge of wetland soil C dynamics, the magnitude and timing of the response of this C reservoir to changes in climate and land use contribute to the large uncertainties in global carbon cycle models. In order to understand the role of wetland soil

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carbon in the global carbon cycle and to predict future atmospheric CO_2 concentration, it is crucial to understand the dynamics of C cycling in wetland soils.

[3] Coastal wetlands have been formed in the last several thousand years due to sea level rise [*Coultas*, 1996a]. Among the many ecological consequences of coastal wetland formation, increased C sequestration is a significant one [*Rabenhorst*, 1995]. Soil investigations in Florida have shown that coastal marsh soils have accumulated 30–100 kg/m^2 soil organic C (SOC), whereas the adjacent upland forests have accumulated only 5–10 kg/m^2 SOC [*Coultas*, 1996b]. Consequently, landward expansion of coastal wetlands could increase the C sequestration in the soil up to 10 times over the replaced upland forests if peat accretion keeps up with sea level rise.

[4] Radiocarbon (^{14}C) is very useful in the study of the C cycle. Briefly, the rationale for using ^{14}C as a tracer to study the C cycle is as follows. ^{14}C is a cosmogenic nuclide formed in the atmosphere. The atoms of ^{14}C are then incorporated into CO_2 molecules by reactions with oxygen or by an exchange reaction with stable carbon isotopes in molecules of CO_2. The molecules of $^{14}CO_2$ are mixed rapidly throughout the atmosphere and the hydrosphere, and attain relatively constant levels of concentration representing a quasi-steady-state equilibrium. Living plants exchange ^{14}C with the atmosphere through photosynthesis and have the same Δ^{14}C value [*Stuiver and Polach*, 1977] as that of the contemporary atmosphere. When plants die, they no longer absorb ^{14}C from the atmosphere, and their ^{14}C content declines as a result of radioactive decay. The ^{14}C content of organic matter can therefore serve as a clock to study the timing and rate of C accumulation in wetland soils over centuries and longer timescales [*Clymo*, 1984; *Glaser*, 1992; *McDowell et al.*, 1969; *Wang et al.*, 1996a].

[5] Radiocarbon can also be used to determine the rate of C cycling on years to decadal timescales. Prior to the early 1950s, the ^{14}C content of the atmosphere was more or less stable, fluctuating within a relatively small range. With the advent of atmospheric nuclear weapons testing in the late 1950s and 1960s, however, the ^{14}C content of the atmosphere increased by several orders of magnitude. This pulse of ^{14}C or "bomb" ^{14}C, which is steadily declining to prebomb levels, has provided an ideal tracer to measure the rates of C cycling in soils over decadal timescales [*Harrison and Broecker*, 1993; *Harrison et al.*, 1993; *O'Brien and Stout*, 1978; *Trumbore*, 1993, 2000; *Trumbore et al.*, 1990, 1996, 1995, 1989; *Wang et al.*, 2000, 1996b, 1999; *Wang and Hsieh*, 2002; *Wang et al.*, 1998]. The key to using this "bomb" ^{14}C tracer is (1) to find soils that were sampled both prior to and after the peak of nuclear weapons testing or a set of soils that were sampled over the last decades and (2) to resample those soils and to measure the differences in the C and ^{14}C contents of both archived and present samples. Changes in the ^{14}C and C content of soil organic matter can then be used, in conjunction with mathematical models, to calculate the rates of soil C cycling, and to determine the size and turnover time of soil C pools [*Harrison and Broecker*, 1993; *Harrison et al.*, 1993; *Trumbore*, 1993, 2000; *Trumbore et al.*, 1990, 1996; *Wang et al.*, 1999].

[6] In this study, we investigated the rates of C accumulation and decay in a coastal wetland in northwest Florida by examining the C and ^{14}C distribution in both archived and present soil cores collected along a soil chronosequence in the wetland. The depth functions of C and ^{14}C provide a time sequence that allows determination of long-term rates (over centuries and longer timescales) of C accumulation, whereas the archived and present samples from each site provide another temporal sequence that allows determination of C accumulation rate on decadal scale. By examining the long-term decay of ^{14}C as a function of depth, we estimated the long-term C accumulation rates in the peat soil. By examining the uptake of "bomb" ^{14}C in surfacial peat in archived and present cores, we estimated the C input rates and turnover times in the surfacial peat as well as the short-term C accumulation rates in the wetland.

2. Methodology

2.1. Study Area and Sample Collection

[7] We selected a coastal temperate-subtropical peatland (30°05′N, 84°10′W) within the St. Marks National Wildlife Refuge of northwestern Florida (Figure 1) as our study area because of the availability of archived soil samples collected in 1985 and 1988. The wetlands in this study area can be divided into four vegetation zones: low marsh, middle marsh, salt barren, and high marsh (Figure 1). Low marsh and middle marsh are within the regularly flooded zone that is inundated twice daily by tidal water, and high marsh is in the irregularly flooded zone where inundation is less frequent [*Montague and Wiegert*, 1990]. The marshes are dominated by *Juncus roemerianus* (black needlerush) and have very high aboveground net primary production ranging from 1000 to 4000 g C m^{-2} yr^{-1}, which is significantly higher than the adjacent upland forests which are estimated at 200 to 400 g C m^{-2} yr^{-1} [*Hsieh*, 1996; *Kruczynski et al.*, 1978]. The soils have loamy sandy texture overlaying limestone at the depth of 90–120 cm. Soil cores were collected in 7.2-cm diameter PVC tubes with sharpened edges to minimize the compaction. Compaction was estimated by inspecting the surface of the soil inside and outside of the cores, and any cores with compaction more than 1 cm were excluded for the analysis. We collected 13 cores from high marsh, middle marsh, and low marsh in 1996 and 1997 to measure the carbon density and carbon isotopic composition. Archived soil samples collected in 1985 and 1988 from the marshes (kindly provided by Y. P. Hsieh of the Wetland Ecology Program at Florida A&M University) were also analyzed for C and C isotopic contents. These archived samples were dried and stored in sealed containers to minimize the loss of C during storage. In addition, we collected four offshore sediment cores for C density and stable C isotope analyses.

2.2. Sample Preparation and Analyses

[8] Samples of the wetland soils were weighed before they were oven dried at 60°C. After being dried, samples were weighed again to determine the water content and bulk density. Dried soil samples were hand picked of visible roots and leaves, and were then ground into powder and

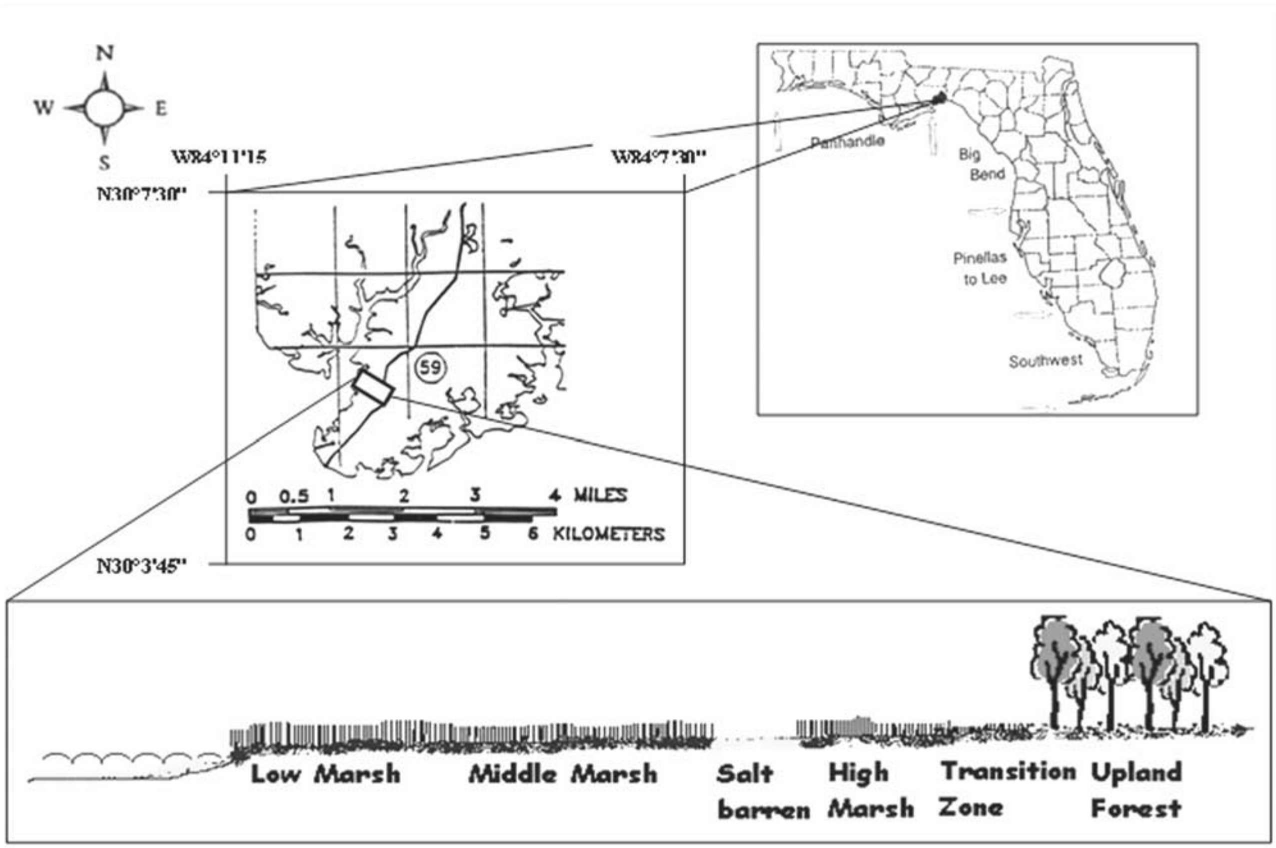

Figure 1. Map showing the study area and vegetation zones in the St. Marks Wildlife Refuge (Wakulla County, Florida). See color version of this figure in the HTML.

sieved with a 2-mm sieve. The powder was treated with 10% HCl for 3 hours to dissolve carbonate. After washing and neutralizing with distilled water, samples were freeze-dried and ground into fine powder again. The ground soil samples were combusted to produce CO_2 with CuO, Cu, and silver foil in a vycor tube under vacuum at 875°C for 2 hours. The resulting CO_2 was purified cryogenically, and its stable C isotope ratio was measured on a stable isotope ratio mass spectrometer at Florida State University. Weight percentage C content was determined from CO_2 yield on a manometer. For ^{14}C analysis, purified CO_2 was reduced to graphite with H_2 over Co, and its $^{14}C/^{13}C$ ratio was measured on an accelerator mass spectrometer (AMS) at the Lawrence Livermore National Laboratory. Some of the ^{14}C samples were measured in the AMS facility at the University of Arizona.

[9] Stable C isotopic data are reported in the standard permil notation relative to the PDB standard as

$$\delta^{13}C = \left[\left(R_{sample}/R_{PDB}\right) - 1\right] \times 1000.$$

Radiocarbon data are expressed in standard notations as "Radiocarbon Date" of years before present (yr. B. P.), "Fraction of Modern" carbon, or $\Delta^{14}C$ value [*Donahue et al.*, 1990; *McNichol et al.*, 2001; *Stuiver and Polach*, 1977].

[10] Carbon inventories were calculated from weight percent content and bulk density. Analytical precision for $\delta^{13}C$, $\Delta^{14}C$, and C content analyses were better than ±0.1‰, ±9‰, and ±3%, respectively.

3. Results and Discussion

3.1. Distribution of C and ^{14}C in Peat Soils

[11] Archived and present soil samples collected from low marsh, middle marsh, and high marsh were analyzed for C and ^{14}C contents (Table 1, Figures 2, 3, and 4). Both C and ^{14}C contents vary significantly with soil depth and among vegetation zones (Figures 2, 3, and 4). Carbon density in the upper 30 cm of the 1996 and 1997 soil profiles was 517.5 ± 55.9 g/m^2/cm (average of five cores) in low marsh, 246.7 ± 81.7 g/m^2/cm (average of four cores) in middle marsh, and 254.0 ± 58.4 g/m^2/cm (average of four cores) in high marsh. Below 30 cm depth, the C density was lower, 234.1 ± 67.3 g/m^2/cm in low marsh, 82.5 ± 10.9 g/m^2/cm in middle marsh, and 63.7 ± 14.3 g/m^2/cm in high marsh. The carbon density in the upper 20 cm of the archived soil cores (1 core per vegetation zone) is ~346 g/m^2/cm in low marsh, ~202 g/m^2/cm in middle marsh, and ~238 g/m^2/cm in high marsh. Comparison between archived and present samples shows that soil C content has generally increased at all sites with time despite large natural variations in C density in the marsh soils (Figures 2a, 3a, and 4a), indicating that C is sequestered in these wetland soils. This suggests that these wetland soils have been acting as a sink for atmospheric CO_2 over the last decades. The ^{14}C content of soil organic

Table 1. Depth Distribution of Radiocarbon Content of Organic Matter in Marsh Soils

	Fraction Modern	$\Delta^{14}C$, ‰	^{14}C Date, B.P.
	1997 Low Marsh		
0–2 cm	1.0699 ± 0.0063	63 ± 6	>modern
2–5 cm	1.1218 ± 0.0058	115 ± 6	>modern
5–10 cm	1.1001 ± 0.0057	94 ± 6	>modern
10–20 cm	0.9905 ± 0.0058	−15 ± 6	80 ± 50
20–30 cm	0.9241 ± 0.0057	−81 ± 6	630 ± 50
30–40 cm	0.8517 ± 0.0093	−153 ± 9	1290 ± 90
40–46 cm	0.7977 ± 0.0045	−206 ± 5	1820 ± 50
	1996 Low Marsh		
0–2 cm	1.066 ± 0.0063	60 ± 6	>modern
2–5 cm	1.0813 ± 0.0085	75 ± 9	>modern
5–10 cm	1.1332 ± 0.0057	126 ± 6	>modern
10–20 cm			
20–30 cm	0.9975 ± 0.0056	−8 ± 6	modern
30–40 cm	0.9101 ± 0.0052	−94 ± 5	760 ± 50
40–49.5 cm	0.7977 ± 0.0071	−206 ± 7	1820 ± 80
	1996 Middle Marsh		
0–2 cm	1.103 ± 0.0053	96 ± 5	>modern
2–5 cm	1.1515 ± 0.0056	145 ± 6	>modern
5–10 cm	1.0579 ± 0.0061	52 ± 6	>modern
10–20 cm	1.0141 ± 0.0070	8 ± 7	>modern
20–30 cm	1.0146 ± 0.0051	8 ± 5	>modern
30–40 cm	0.9734 ± 0.0094	−32 ± 9	215 ± 75
40–47.5 cm	0.9468 ± 0.0095	−58 ± 10	440 ± 80
	1996 High Marsh		
0–2 cm	1.1771 ± 0.0086	170 ± 9	>modern
2–5 cm	1.1803 ± 0.0083	173 ± 8	>modern
5–10 cm	1.0547 ± 0.0057	48 ± 6	>modern
10–20 cm	1.0165 ± 0.0063	10 ± 6	>modern
20–30 cm	0.9938 ± 0.0072	−11 ± 7	50 ± 60
30–40 cm	0.9348 ± 0.0094	−70 ± 9	540 ± 85
40–50 cm	0.9502 ± 0.0140	−55 ± 14	410 ± 120
	1988 Low Marsh		
0–10.2 cm	1.0699	65	>modern
10.2–20.3 cm	0.9905	−14	76
20.3–30.5 cm	0.9373	−67	520
30.5–40.6 cm	0.9323	−72	563
40.6–50.8 cm	0.8178	−186	1616
50.8–61 cm	0.7615	−242	2188
61–71 cm	0.7374	−266	2447
	1985 Low Marsh		
0–2 cm	1.142 ± 0.0064	137 ± 6	>modern
2–5 cm	1.0599 ± 0.0085	55 ± 9	>modern
5–10 cm	1.0037 ± 0.0056	−1 ± 6	>modern
10–20 cm	0.9629 ± 0.0069	−41 ± 7	303 ± 60
	1985 Middle Marsh		
0–2 cm	1.202 ± 0.0096	196 ± 10	>modern
2–5 cm	1.1073 ± 0.0088	102 ± 9	>modern
5–10 cm	1.0284 ± 0.0053	24 ± 5	>modern
10–20 cm	1.0133 ± 0.0050	9 ± 5	>modern
	1985 High Marsh		
0–2 cm	1.0315 ± 0.0071	27 ± 7	>modern
2–5 cm	1.1439 ± 0.0066	139 ± 7	>modern
5–10 cm	1.1285 ± 0.0070	123 ± 7	>modern
10–20 cm	1.0439 ± 0.0105	39 ± 10	>modern

matter is also higher in the upper part of the soil profiles and decreases with depth due to radioactive decay (Figures 2b, 3b, and 4b). The positive $\Delta^{14}C$ values in the surface soil in each vegetation zone indicate that most of the C at these depths was fixed since 1960 and that importation of old organic C to our sites from erosion of upland soils was insignificant.

3.2. Estimating the Rate of C Accumulation in the Marsh Soil

[12] Radiocarbon dating of peat soil provides a valuable tool for estimating the timing and long-term rate of peat accumulation [*Clymo*, 1984; *Glaser*, 1992; *Gorham*, 1991; *McDowell et al.*, 1969; *Schell*, 1983]. Using the radiocarbon dates and C inventory measurements on our peat cores (Table 1 and Figures 2, 3, and 4), we estimated the amount of C accumulated over time and the long-term rate of C accumulation in the marshes (Figure 5). The amount of C accumulated between a time in the past and the present was determined by adding the carbon inventory for all sampling intervals above the depth where a radiocarbon date was obtained [*Clymo*, 1984; *Trumbore et al.*, 1999]. The long-term C accumulation rates (LTCAR) were estimated using the following equations:

$$\mathrm{LTCAR} = \mathrm{C}_{\mathrm{tot}}, \tag{1}$$

where C_{tot} is total C inventory above a given depth/radiocarbon date at that depth.

[13] Total C inventory in the upper 50 cm of the peat soil in our study area is ~25 ± 4 kg/m^2 in low marsh (oldest part of the wetland), ~10 ± 5 kg/m^2 in middle marsh, and ~10 ± 6 kg/m^2 in high marsh (youngest part of the wetland). The amount of C accumulated in the marsh soil increases with time as shown in Figure 5a. However, the long-term C accumulation rate determined using the above equation decreases with time from ~130 ± 9 g C/m^2/yr over the last century to ~13 ± 2 g C/m^2/yr over the millennium timescale (Figure 5b). The rates of C accumulation over the last 400–600 years are ~25 ± 2 g C/m^2/yr in low marsh, ~22 ± 7 g C/m^2/yr in middle marsh, and ~20 ± 9 g C/m^2/yr in high marsh (Figure 5b).

[14] The short-term C accumulation rates in the marshes can be estimated by examining the uptake of the "bomb" ^{14}C in the surfacial peat soil. Our study area is located within the "zero-energy zone" of the Big Bend coast where sand movement is minimal and beaches are virtually absent due to a lack of wave activity [*Tanner*, 1960]. Our data show that there are large differences in both C and ^{14}C contents between the archived and present soil samples in each vegetation zone (Figures 2, 3, and 4). Assuming no significant accretion and erosion from 1985 to 1997/1996, the time period represented by our archived and present samples, these differences in the C and ^{14}C contents between the present and archived soil samples can be used to estimate the rates of net annual C input and turnover time in surfacial peat soil using a time-dependent box model [*Trumbore*, 1993; *Trumbore et al.*, 1990, 1999, 1995, 1989; *Wang et al.*, 1996b, 1999; *Wang and Hsieh*, 2002],

$$\mathrm{C}_t = \mathrm{C}_{t-1} + \varphi - k\mathrm{C}_{t-1} \tag{2}$$

$$\mathrm{C}^{14}_t = \mathrm{C}^{14}_{t-1} + \varphi^{14} - (k+\lambda)\mathrm{C}^{14}_{t-1}, \tag{3}$$

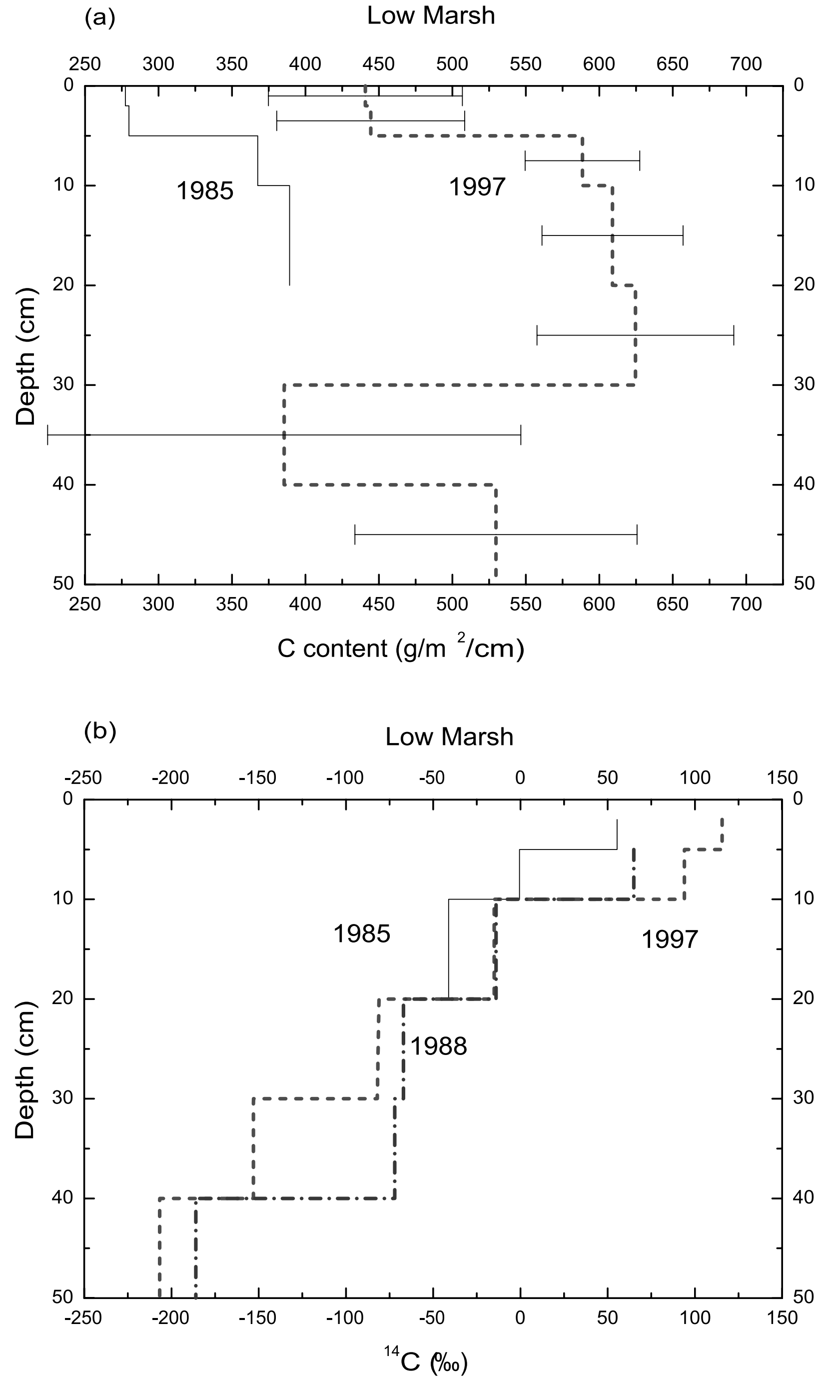

Figure 2. Carbon and ^{14}C contents in archived (1985) and present (1997) wetland soil samples from low marsh (oldest part of wetland). Horizontal bars indicate the standard deviation based on C density measurements on multiple cores. See color version of this figure in the HTML.

where C_{t-1} is C content in the previous year, C^{14}_{t-1} is ^{14}C content in the previous year, φ is net annual C input rate, k is organic C turnover rate = 1/turnover time (τ), and λ is decay constant of ^{14}C (0.0001245/year).

[15] In the marshes in our study area, live roots are found in the upper 20 cm of the soil, with most of the root biomass concentrated in the upper 10 cm of the soil. Because of strong bioturbation in the active root zone by burrowing animals such as fiddler crabs and other biological/physical processes, we combined 0–2 cm, 2–5 cm, and 5–10 cm sampling intervals into one box, the surfacial peat (0–10 cm), and used their weighed mean average values of C and ^{14}C for our modeling exercise (Table 2). By best fitting the observed changes in the C and ^{14}C contents of archived (1985) and present (1996 and/or 1997) soil samples using equations (2) and (3), we estimated the annual C input rate

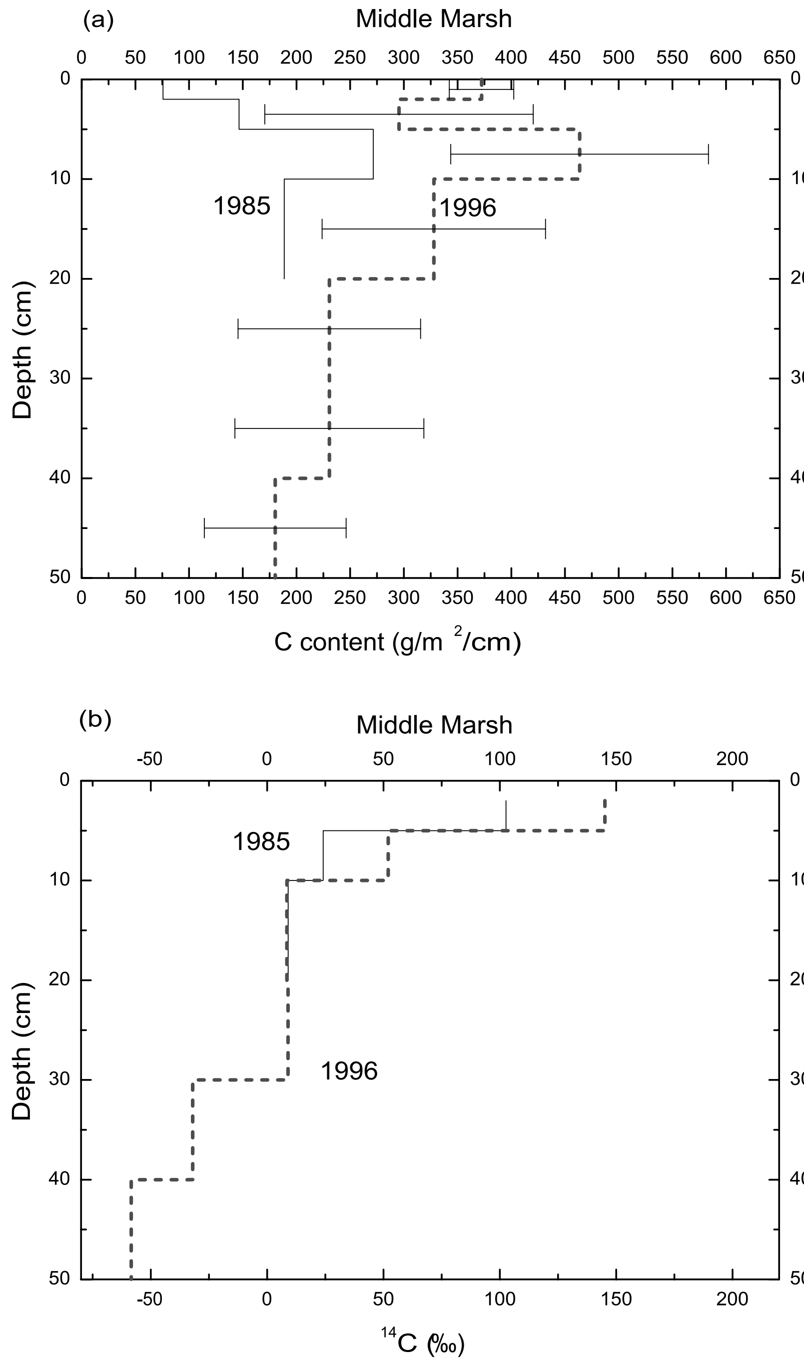

Figure 3. Carbon and ^{14}C contents in archived (1985) and present (1996) wetland soil samples from the middle marsh (intermediate stage of wetland). Horizontal bars indicate the standard deviation based on C density measurements on multiple cores. See color version of this figure in the HTML.

and turnover time in the top 10 cm layer of the peat soil (Figure 6 and Table 3).

[16] The model-derived C input rates in the surfacial peat are 0.00025–0.0003 moles/cm^3/yr in low marsh, 0.00013–0.00022 moles/cm^3/yr in middle marsh, and 0.00004–0.00025 moles/cm^3/yr in high marsh (Table 3). The estimated C turnover times in the surfacial peat are 16–31 years in low marsh, 18–57 years in middle marsh, and 10–38 years in high marsh (Table 3). The low and high estimated values for the C input rate and turnover time correspond to the range of variation in C content of the present (i.e., 1996/1997) soil in each vegetation zone (Tables 2 and 3). These model-derived C input rates and turnover times were used to calculate the short-term C accumulation rate (STCAR) over the last 2 decades using the following equation:

$$\mathrm{STCAR} = \mathrm{IR} - \mathrm{C_{sl}}/\mathrm{T}, \tag{4}$$

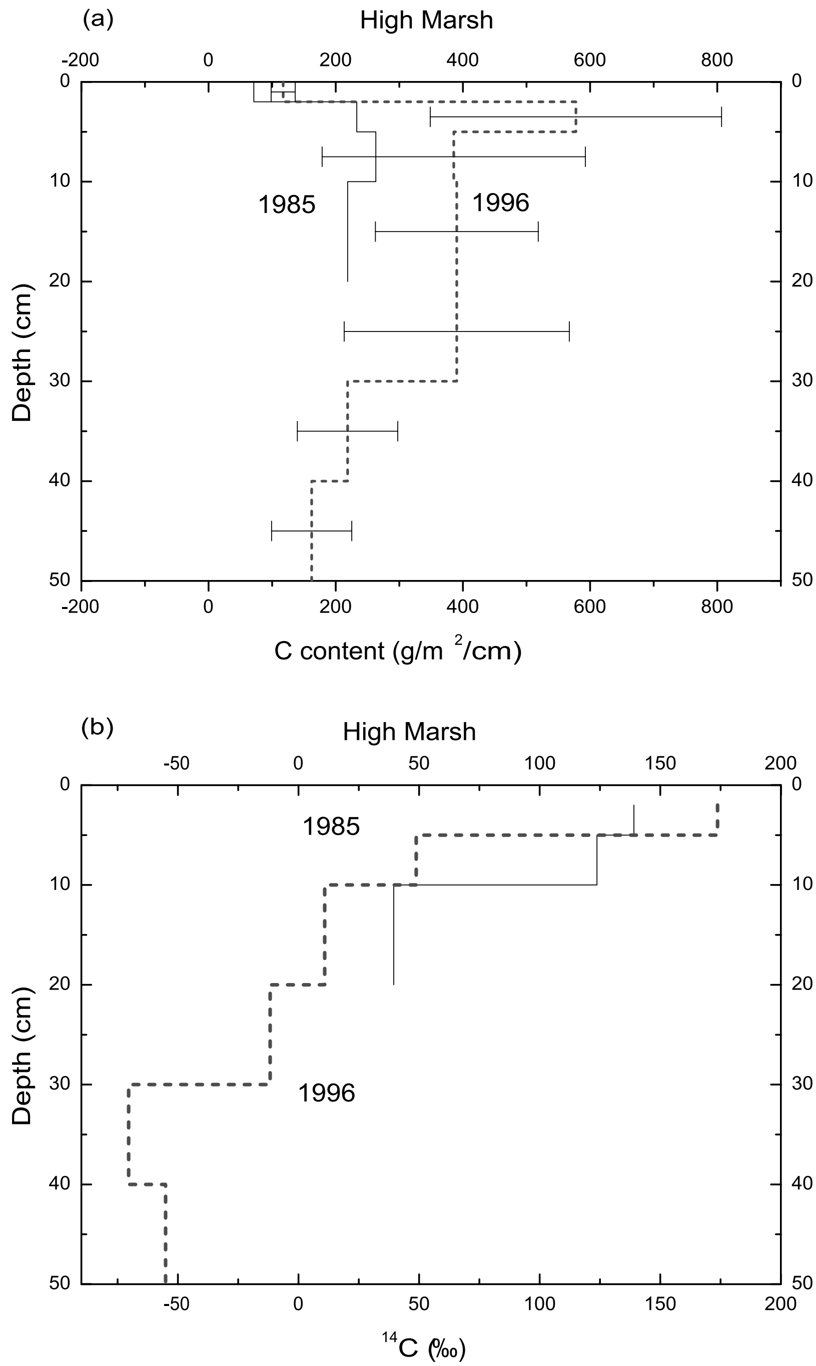

Figure 4. Carbon and ^{14}C contents in archived (1985) and present (1996) wetland soil samples from the high marsh (youngest part of wetland). Horizontal bars indicate the standard deviation based on C density measurements on multiple cores. See color version of this figure in the HTML.

where IR is input rate, C_{sl} is C content in surface layer, and T is turnover time.

[17] There are large natural variations in soil C content even within the same marsh zone in our study area (Figures 2–4). The calculated short-term C accumulation rates from 1985 to 1997, in correspondence to the low and high end values of C density in the present soil, range from 42 to 193 g C/m^2/yr in low marsh, from 18 to 184 g C/m^2/yr in middle marsh, and from −50 to 181 g C/m^2/yr in high marsh (Table 3). This modeling exercise demonstrates that large uncertainties in soil C inventories could affect the source or sink interpretation of the "bomb" ^{14}C signature in a soil. Because only one archived soil core from a given time and a given vegetation zone is available for analysis and the exact sampling locations of the archived cores are not known, the degree of uncertainties in our estimated short-term C accumulation rates cannot yet be fully evaluated. Furthermore, our samples were treated with acid to

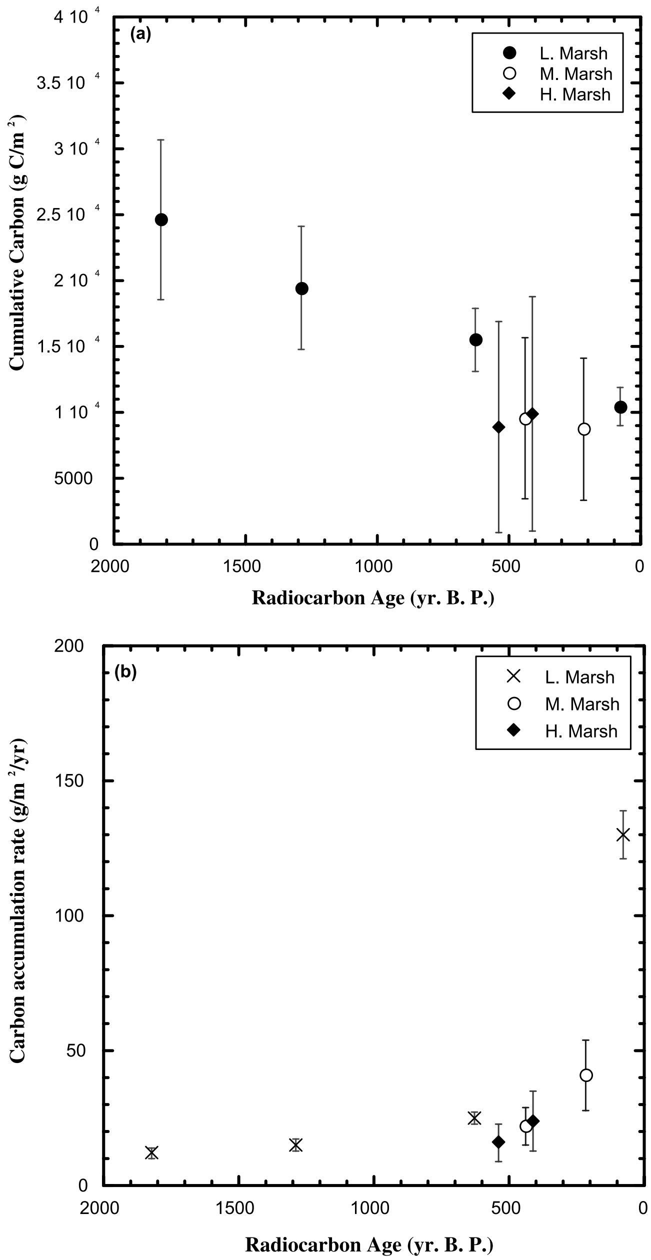

Figure 5. (top) Total amount of carbon accumulated and (bottom) long-term rate of carbon accumulation versus radiocarbon age at the depth above which carbon is inventoried. Vertical bars indicate the standard deviation based on C inventory measurements on multiple cores. See color version of this figure in the HTML.

remove inorganic carbon. This pretreatment may have removed some ^{14}C-enriched components of the soil organic matter [*Trumbore and Zheng*, 1996], which would lead to an underestimate of C storage and C accumulation rates in the marshes. However, the extent to which acid treatment, a standard procedure for removing carbonates in soils, may affect the ^{14}C content of soil organic matter in different soils has not been thoroughly investigated and warrants further study. The average short-term rates of C accumulation estimated from the "bomb" ^{14}C uptake in surfacial peat are ~117 g C/m^2/yr in low marsh, ~101 g C/m^2/yr in middle marsh, and ~65 g C/m^2/yr in high marsh (Table 3), suggesting that the low marsh is sequestrating atmospheric CO_2 into the soil as soil organic matter about twice as fast as the high marsh. Both our long-term and short-term rate estimates suggest that these wetland soils have been and continue to be a significant sink for atmospheric CO_2.

3.3. Comparison of C Sequestration Rates in Wetland and Upland Soils and its Implication for the Global C Cycle

[18] The amount of soil organic matter in most upland ecosystems (desert, boreal and temperate forest, and grassland) is likely to have been fairly constant before human disturbances of soils. However, many wetland ecosystems may have been a long-term C sink. Studies have shown that various upland ecosystems accumulate C at a rate of about 0.2–12 g C/m^2/yr [*Schlesinger*, 1990]. *Chmura et al.* [2003] recently used published data in literature and their own data to estimate the rate of C accumulation in mangrove swamps and in salt marshes dominated by *Spartina alterniflora* and *Spartina Patens*. They suggested a global average rate of C accumulation of 210 ± 20 g/m^2/yr for coastal wetlands [*Chmura et al.*, 2003], which is an order of magnitude higher than the rates of C sequestration in northern peatlands [*Belyea and Warner*, 1996; *Billings*, 1987; *Botch et al.*, 1995; *Cohen*, 1974; *Francez and Vasander*, 1995; *Roulet*, 2000; *Whitehead*, 1981]. Their rate estimates for coastal wetlands are based on measurements of ^{137}Cs associated with peak fallout in 1963 or unsupported ^{210}Pb in the soil or employment of clay-marker horizons in the field [*Cahoon and Turner*, 1989; *Chmura et al.*, 2001, 2003; *DeLaune et al.*, 1978] and therefore represent rates over years to century timescales.

[19] The high end values of our estimated short-term C accumulation rates (Table 3) are comparable to the estimated rates for coastal wetland soils of *Chmura et al.* [2003], considering that the C input into (and loss from) depths below the surface active root zone is not included in our estimates of short-term C accumulation rates. Our estimated

Table 2. Model Parameters Used to Estimate the C Input Rate and Turnover Time in the Surfacial Peat of St. Marks Soils

	C Contents 1985, moles/cm^3	C Content 1996/1997, moles/cm^3		Δ^{14}C 1985	Δ^{14}C, 1996/1997
		Low	High		
Low Marsh (0–10 cm)	0.0027	0.0034	0.0043	38	95
Middle Marsh (0–10 cm)	0.0019	0.0021	0.0038	55	92
High Marsh (0–10 cm)	0.0018	0.00082	0.0038	121	124

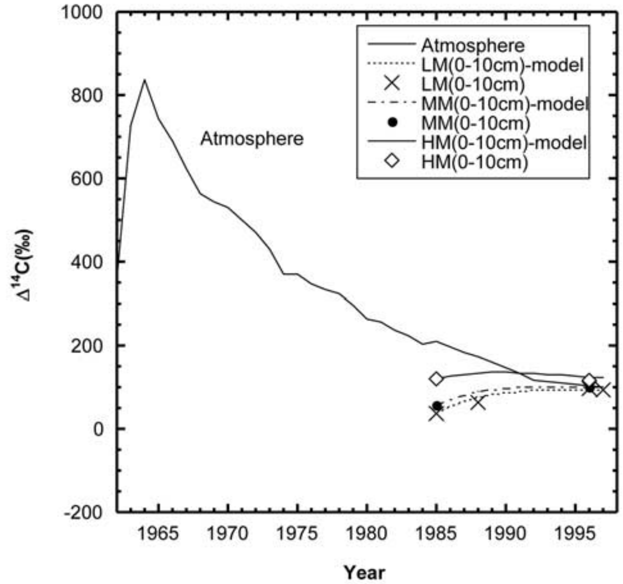

Figure 6. "Bomb" ^{14}C uptake in wetland soils. Various curves representing the ^{14}C content of the atmosphere and the model-derived ^{14}C content of the surfacial peat (0–10 cm) in low, middle, and high marshes (LM: low marsh, MM: middle marsh, HM: high marsh). Different symbols represent the measured ^{14}C contents of soil organic matter from different marsh soils collected from 1985 to 1997.

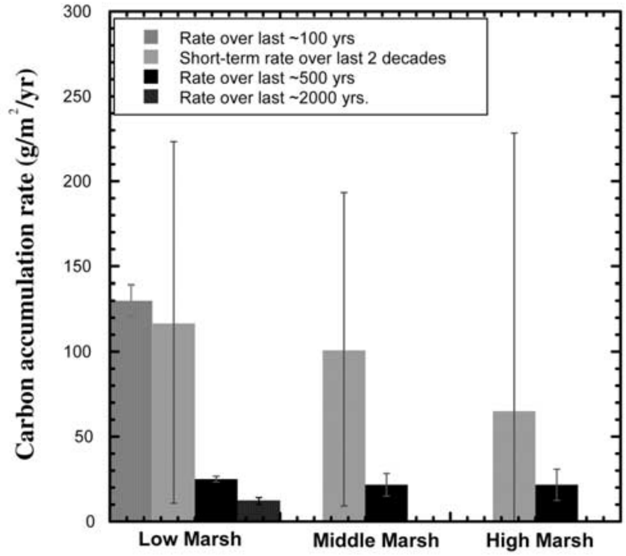

Figure 7. Comparison of short-term C accumulation rates over the past 2 decades and long-term C accumulation rates in the marshes. Short-term C accumulation rate is input rate (moles/cm^3/yr) minus total carbon contents (moles/cm^3) times decay rate (yr^{-1}), and long-term C accumulation rate is total C inventory above a given depth/^{14}C date at that depth. See color version of this figure in the HTML.

long-term rates over millennium timescale are comparable to the rates of C sequestration in northern peatlands but are significantly lower than the rate estimates of *Chmura et al.* [2003] and our own estimated rates over century and shorter timescales (Figure 7). The decrease in the rates of C accumulation over time as shown in Figure 5b is due to slow but continuous anaerobic decomposition of soil organic matter in the wetland soils over time. However, it is also likely that the higher recent rates of C accumulation are in part the result of increased primary production in the coastal wetlands over the last decades or century.

[20] An increase in primary production in coastal wetlands could have occurred in response to changes in a number of factors. Interactions among sea level, land elevation, primary production, and sediment accretion regulate the elevation of the marsh surface toward an equilibrium with mean sea level [*Morris et al.*, 2002]. A rise in relative mean sea level brings about an increase in production and biomass density that will enhance sediment deposition, a positive feedback essential to marsh stability [*Morris et al.*, 2002]. Studies have also shown that elevated atmospheric CO_2 stimulates photosynthesis-CO_2 fertilization effect [*Hungate et al.*, 1997; *Long and Drake*, 1992; *Smith et al.*, 2000], creating the possibility that the terrestrial biosphere will sequester C in response to rising atmospheric CO_2 concentration. The atmospheric CO_2 concentration has increased by about 30% since the industrial revolution, which could have resulted in increased primary production in the marshes. In addition, enhanced nitrogen (N) mineralization from warming -enhanced decomposition of organic matter as well as N deposition from air pollution in recent decades may have also caused higher C accumulation from stimulated plant growth [*McGuire et al.*, 1995; *Melillo et al.*, 1996; *Rastetter et al.*, 1992]. Net primary production in wetlands is often limited by nutrients like N and phosphorus (P). Most wetlands show shortages of

Table 3. Model-Derived Input Rate, Turnover Time, and Short-Term Accumulation Rate of Soil Organic C in the Surfacial Peat of St. Marks Soils

	Input Rate,[a] moles/cm^3/yr		Turnover Time,[a] Years		Short-Term Rate of C Accumulation, G C/m^2/yr		
	Low	High	Low	High	Low	High	Average
Low Marsh (0–10 cm)	0.00025	0.0003	16	31	42	193	117
Middle Marsh (0–10 cm)	0.00013	0.00022	18	57	18	184	101
High Marsh (0–10 cm)	0.00004	0.00025	10	38	−50	181	65

[a]The low and high values of the estimated C input rate, turnover time, and short-term rate of C accumulation correspond to the range of variation in C content of the "present" soil in each vegetation zone (see model parameters in Table 2). Short-term C accumulation rate is input rate (moles/cm^3/yr) minus total carbon contents (moles/cm^3)/Turnover time (yr).

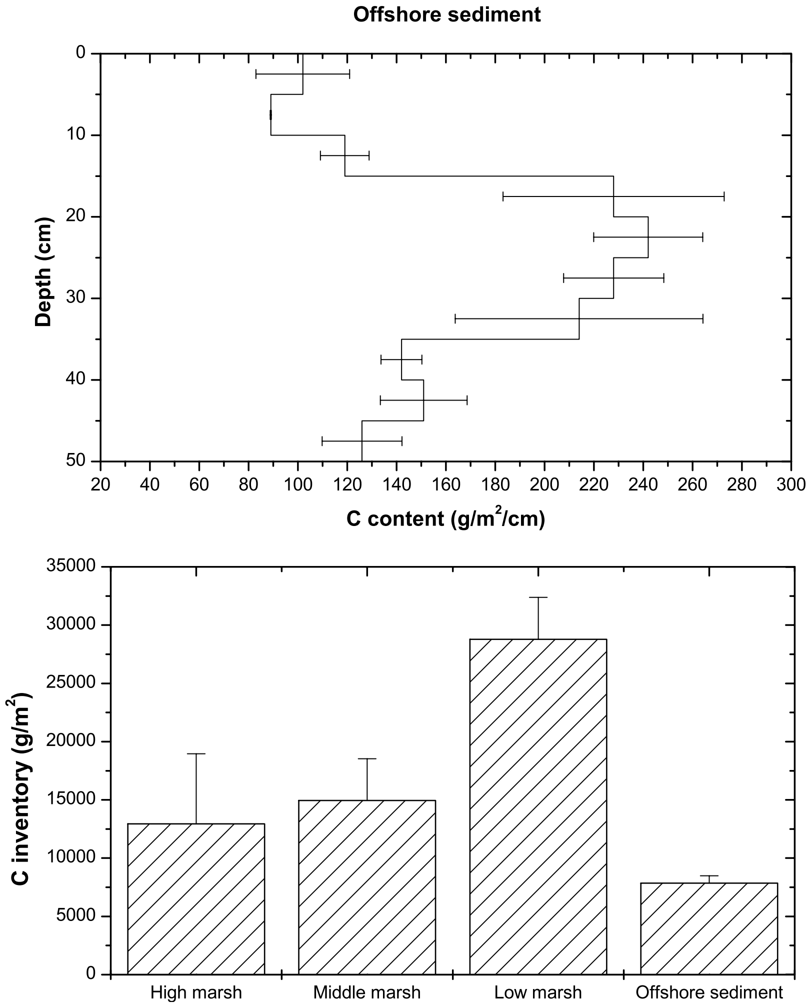

Figure 8. (top) Organic C content of sediment cores (average of four cores) collected about 1 m offshore and (bottom) comparison of C inventory (0–86.4 cm) in marsh soils and offshore sediment.

plant-available N than P, because significant portion of the P is mineralized before the burial [*Damman*, 1978]. In our study area, N seems to be a limiting nutrient [*Choi et al.*, 2001]. Therefore, higher recent rates of C accumulation in our study area and in other coastal wetlands [*Chmura et al.*, 2003], in comparison with longer-term C accumulation rates (Figures 5 and 7), may be in part caused by increased primary production due to a rise in relative mean sea level [*Morris et al.*, 2002], and CO_2 and N fertilization effect [*Hungate et al.*, 1997; *Long and Drake*, 1992; *Schindler and Bayley*, 1993; *Smith et al.*, 2000; *Townsend et al.*, 1996] during the last decades or century. However, more carefully designed studies are needed to test this hypothesis.

[21] The rate of C accumulation in various peat ecosystems was estimated to be about 8–38 g C m^2/yr [*Belyea and Warner*, 1996; *Billings*, 1987; *Botch et al.*, 1995; *Cohen*, 1974; *Francez and Vasander*, 1995; *Roulet*, 2000; *Whitehead*, 1981]. Our data and the data presented by *Chmura et al.* [2003] show that coastal wetlands in subtropical-temperate climates have even higher rates of C accumulation. Such high rates of C sequestration are likely due to high primary production and long growing season at the sites. As decomposition is impeded in flooded and saturated soils in wetlands, wetland soils show the largest accumulation of soil organic matter among terrestrial soils. Many inland wetland ecosystems have accumulated soil organic C since the retreat of the last continental glacier [*Harden et al.*, 1992], and are a large sink for atmospheric CO_2 but are also a significant source for atmospheric CH_4, a more efficient greenhouse gas than CO_2 [*Chanton et al.*, 1995; *Whiting and Chanton*, 2001]. If these areas are subjected to drainage and/or warmer climate conditions due to global warming, the rate of decomposition will increase, which could cause these wetlands to become a significant source of CO_2 for the atmosphere [*Armentano and Menges*, 1986; *Gorham*, 1991; *Hutchinson*, 1980; *Silvola et al.*, 1996; *Tate*, 1980]. Coastal wetlands, on the other hand, are not a significant source for atmospheric CH_4 because the presence of abundant sulfate in salt marshes inhibits methane production [*Stumm and Morgan*, 1981]. Low CH_4 emissions, combined with high rates of C sequestration, would make coastal wetlands more valuable C sinks per unit area than other ecosystems. Furthermore, coastal wetlands could expand landward and/or seaward in

response to sea level rise in a warmer world and could provide a negative feedback to global warming [*Choi et al.*, 2001].

[22] However, as the sea level rises, there can be a possibility of erosion of coastal wetland at the seaward edge if vertical accretion cannot keep up with the rate of sea level rise. Sediment cores taken offshore near the seaward edge of the low marsh reveal organic-rich peat buried by sediment. As shown in Figure 8, the organic C content in buried peat is much higher than in the overlying sediment. The total organic C inventory in offshore sediment cores was 8 kg ± 0.6 kg C/m^2 (average of four cores), which is about one third of what is found in the low marsh (Figure 8). The δ^{13}C values of buried peat in the offshore sediment cores range from −24 to −25‰ and are consistent with those of the low marsh peat [*Choi et al.*, 2001], but the surface sediment (0–15 cm) has enriched δ^{13}C values (∼−22‰), indicating that the organic C in surface sediment originated from both eroded peat and organic matter of marine origin such as seagrasses (−10 to −19‰), algae (−18 to −21‰), or phytoplankton (−21‰) [*Middelburg et al.*, 1996]. These data suggest that the seaward edge of the low marsh in this area is moving inland as a result of sea level rise. However, the extent to which the seaward edge of the low marsh has migrated over the recent decades or century as well as the fate of eroded soil organic matter associated with the lost low marsh is presently not known and warrants further research.

4. Conclusion

[23] Measurements of C density in peat cores collected from a coastal wetland in Florida revealed large temporal and spatial variations in soil C inventory in salt marshes. Large uncertainties in C inventory in the marsh soil will affect the short-term C accumulation rate derived from the "bomb" ^{14}C signature in the soil. The short-term C accumulation rates estimated by examining the uptake of the "bomb" ^{14}C in surfacial peat range from 42 to 193 g C/m^2/yr in low marsh, from 18 to 184 g C/m^2/yr in middle marsh, and from −50 to 181 g C/m^2/yr in high marsh, in correspondence to the low and high end values of C density in the present soil. Our data show that the seaward edge of the low marsh is partially being eroded due to sea level rise. However, the rate of erosion and the fate of soil organic matter associated with the receding edge of the low marsh are presently not know. The long-term C accumulation rates determined by examining the C inventory and the radioactive decay of radiocarbon as a function of depth decreased over time from ∼130 ± 9 g C/m^2/yr over the last century to ∼13 ± 2 g C/m^2/yr over the millennium timescale, whereas the amount of C accumulated in the marsh soil increased significantly over time. The long-term rates of C accumulation over the millennium timescale are much lower than the estimated short-term rates of C accumulation in the marshes and other coastal wetlands. The difference between the short-term and long-term rates may be caused by slow but continuous anaerobic decomposition of soil organic matter in the peat over time, and by increased primary production in the marshes over the last decades or century due to an increase in the rate of sea level rise and/or increased global CO_2 and/or nitrogen fertilization effect. Our data indicate that salt marshes in this area have been and continue to be a sink for atmospheric carbon dioxide. Because of higher rates of C sequestration and lower CH_4 emissions, coastal wetlands could be more valuable C sinks per unit area than other ecosystems in a warmer world.

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