Global carbon sequestration in tidal, saline wetland soils

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[1] Wetlands represent the largest component of the terrestrial biological carbon pool and thus play an important role in global carbon cycles. Most global carbon budgets, however, have focused on dry land ecosystems that extend over large areas and have not accounted for the many small, scattered carbon-storing ecosystems such as tidal saline wetlands. We compiled data for 154 sites in mangroves and salt marshes from the western and eastern Atlantic and Pacific coasts, as well as the Indian Ocean, Mediterranean Ocean, and Gulf of Mexico. The set of sites spans a latitudinal range from 22.4°S in the Indian Ocean to 55.5°N in the northeastern Atlantic. The average soil carbon density of mangrove swamps (0.055 ± 0.004 g cm^{-3}) is significantly higher than the salt marsh average (0.039 ± 0.003 g cm^{-3}). Soil carbon density in mangrove swamps and *Spartina patens* marshes declines with increasing average annual temperature, probably due to increased decay rates at higher temperatures. In contrast, carbon sequestration rates were not significantly different between mangrove swamps and salt marshes. Variability in sediment accumulation rates within marshes is a major control of carbon sequestration rates masking any relationship with climatic parameters. Globally, these combined wetlands store at least 44.6 Tg C yr^{-1} and probably more, as detailed areal inventories are not available for salt marshes in China and South America. Much attention has been given to the role of freshwater wetlands, particularly northern peatlands, as carbon sinks. In contrast to peatlands, salt marshes and mangroves release negligible amounts of greenhouse gases and store more carbon per unit area. *INDEX TERMS:* 1890 Hydrology: Wetlands; 3020 Marine Geology and Geophysics: Littoral processes; 4235 Oceanography: General: Estuarine processes; *KEYWORDS:* salt marsh, mangroves, soil carbon density, greenhouse gas flux, wetland soil

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1. Introduction

[2] Wetlands represent the largest component of the terrestrial biological carbon pool [*Dixon and Krankina*, 1995] and thus play an important role in global carbon cycles [*Sahagian and Melack*, 1988]. Most global carbon budgets, however, have focused on dry land ecosystems that extend over large areas and have not accounted for the many small, scattered carbon-storing ecosystems such as mangrove swamps and salt marshes [*Atjay et al.*, 1979; *Olson et al.*, 1983]. Syntheses that do include wetlands typically exclude tidal saline wetlands (TSWs) because there have been no empirically based estimates of their carbon storage potential.

[3] In this study we used published and our own unpublished data to estimate the amount of carbon stored globally in soils of salt marshes and mangrove swamps. We then examine spatial patterns in carbon density and storage with respect to climate parameters, as well as local variability, to determine which are important controls.

[4] Tidal saline wetlands, i.e., salt marshes and mangrove swamps, are found on sheltered marine coastlines. The former, dominated by herbaceous vegetation, exist in climates ranging from arctic to subtropical. Mangrove swamps replace salt marshes in the subtropics, around 25°N and S and are dominated by woody vegetation [*Mitsch and Gosselink*, 2000]. Mangrove swamps and salt marshes are intertidal ecosystems; in order to persist, their surface elevations must increase with rising sea level.

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Table 1. Soil Carbon Density, Soil Carbon Accumulation Rates, and Climate Normals at Salt Marsh Sites[a]

Location: Site Name or Core Number, State/Province, Country	Latitude	Longitude	Density, g cm^{-3}	Rate, g m^{-2} yr^{-1}	C Data Source[b]	Average Annual Temperature, °C: Minimum	Average Annual Temperature, °C: Maximum	Average Annual Temperature, °C: Overall	Normals Period[c]
Gulf of Mexico	°N	°W							
Aransas, Tex.	28.4	96.8	0.040	178	1	17.2	25.3	21.2	1
Fina la Terre, La.	29.0	91.0	0.027	136	2	15.5	24.5	20.0	1
Fina la Terre, La.	29.0	91.0	0.018	18	2	15.5	24.5	20.0	1
San Bernard, Tex.	29.1	95.6	0.033	203	1	16.6	25.3	20.9	1
Old Oyster Bayou, La.	29.3	91.1	0.019	84	3	15.5	24.5	20.0	1
Bayou Chitigue, La.	29.3	90.6	0.016	516	3	15.4	25.3	20.4	1
Rockefeller Refuge, La.	29.5	92.7	0.028	309	2	15.2	25.2	20.2	1
Rockefeller Refuge, La.	29.5	92.7	0.033	27	2	15.2	25.2	20.2	1
Lafourche Parish, La.	29.5	90.3	0.019	186	4	15.4	25.3	20.4	1
Cameron Parish, La.	29.5	93.2	0.010	41	4	15.9	24.7	20.3	2
Cameron Parish, La.	29.5	93.2	0.010	115	4	15.9	24.7	20.3	2
Barataria Basin, La.	29.5	90.0	0.013	185	5	15.4	25.3	20.4	1
Barataria Basin, La.	29.5	90.0	0.012	71	5	15.4	25.3	20.4	1
Barataria Basin, La.	29.5	90.0	0.012	93	5	15.4	25.3	20.4	1
Unit 1, Marsh Island Refuge, La.	29.5	91.9	0.110	318	6	15.2	25.2	20.2	1
Unit 1, Marsh Island Refuge, La.	29.5	91.9	0.109	763	6	15.2	25.2	20.2	1
Unit 15, Rockefeller Wildlife Refuge, La.	29.6	92.7	0.120	349	6	15.2	25.2	20.2	1
Unit 15, Rockefeller Wildlife Refuge, La.	29.6	92.7	0.119	657	6	15.2	25.2	20.2	1
Three Bayous, La.	29.6	90.1	0.014	116	3	15.2	25.2	20.2	1
Rockefeller Wildlife Refuge unit 14, La.	29.7	92.7	0.116	337	6	15.2	25.2	20.2	1
Rockefeller Wildlife Refuge unit 14, La.	29.7	92.7	0.093	448	6	15.2	25.2	20.2	1
McFaddin National Wildlife Refuge, Tex.	29.7	94.1	0.012	95	3	15.1	25.6	20.4	1
Sabine National Wildlife Refuge unit 3, La.	29.9	93.5	0.190	1713	6	15.9	24.7	20.3	1
Sabine National Wildlife Refuge unit 3, La.	29.9	93.5	0.121	714	6	15.9	24.7	20.3	1
St. Bernard Parish, La.	30.0	89.9	0.028	140	7				
St. Marks, Fla.	30.1	84.2	0.025	44	3	14.1	25.6	19.9	2
Biloxi Bay, Miss.	30.4	88.9	0.027	153	1	15.0	24.4	19.7	2
Northeastern Atlantic	°N	°E							
St. Annaland, Netherlands	51.5	4.1	0.041	277	8				
St. Annaland, Netherlands	51.5	4.1	0.041	139	8				
Scheldt, Netherlands	51.5	4.1	0.029	587	9				
Scheldt, Netherlands	51.5	4.1	0.020	650	9				
Dengie Marsh, UK	51.7	0.9	0.041	187	8	7.2	12.9	10.1	2
Dengie Marsh, UK	51.7	0.9	0.041	139	8	7.2	12.9	10.1	2
Dengie Marsh, UK	51.7	0.9	0.041	159	8	7.2	12.9	10.1	2
Dengie Marsh, UK	51.7	0.9	0.041	110	8	7.2	12.9	10.1	2
Hut marsh, UK	53.0	0.7	0.027	165	10				
Hut marsh, UK	53.0	0.7	0.027	77	10				
Skallingen, Denmark	55.5	8.4	0.021		11				
Skallingen, Denmark	55.5	8.4	0.027		11				
Mediterranean	°N	°E							
Rhone Delta, France	43.3	4.6	0.073	161	12				
Northeastern Pacific	°N	°W							
Tijuana Slough, Calif.	32.5	117.1	0.018	343	13	12.8	22.4	17.6	1
Tijuana Slough, Calif.	32.6	117.1	0.017	43	14	12.8	22.4	17.6	1
Tijuana Slough, Calif.	32.6	117.1	0.040		14	12.8	22.4	17.6	1

Table 1. (continued)

Location: Site Name or Core Number, State/Province, Country	Latitude	Longitude	Density, g cm^{-3}	Rate, g m^{-2} yr^{-1}	C Data Source[b]	Average Annual Temperature, °C Minimum	Maximum	Overall	Normals Period[c]
Alviso, San Francisco Bay, Calif.	37.5	122.0	0.009	385	15	10.4	20.6	15.5	1
Bird Island, San Francisco Bay, Calif.	37.6	122.2	0.014	54	15	10.4	20.6	15.5	1
Uculet, B. C.	48.9	125.5	0.017		16	5.5	12.7	9.1	4
Northwestern Atlantic	°N	°W							
Cedar Island National Wildlife Refuge, N. C.	35.0	76.4	0.022	70	3	12.1	22.0	17.0	2
Oregon Inlet, N. C.	35.9	75.6		59	17	12.3	20.8	16.6	1
Oregon Inlet, N. C.	35.9	75.6		21	17	12.3	20.8	16.6	1
Jacob's Creek, N. C.	35.3	76.8		146	17	12.3	20.8	16.6	1
Jacob's Creek, N. C.	35.3	76.8		107	17	12.3	20.8	16.6	1
MC4, Chesapeake Bay, Md.	38.3	75.9	0.040	308	18	8.7	20.2	14.4	1
MCL8, Chesapeake Bay, Md.	38.3	75.9	0.027	213	18	8.7	20.2	14.4	1
MCL15, Chesapeake Bay, Md.	38.3	75.9	0.044	340	18	8.7	20.2	14.4	1
Sybil 1, Conn.	41.2	72.6	0.054	136	19	5.3	15.2	10.3	1
Hoadley 1, Conn.	41.2	72.0	0.037	154	19	5.3	15.2	10.3	1
Hoadley 2, Conn.	41.2	72.0	0.040	169	19	5.3	15.2	10.3	1
Hoadley 3, Conn.	41.2	72.0	0.035	114	19	5.3	15.2	10.3	1
East River 1, Conn.	41.2	72.7	0.030	134	19	5.3	15.2	10.3	1
East River 2, Conn.	41.2	72.7	0.060	204	19	5.3	15.2	10.3	1
Sluice 1, Conn.	41.2	72.7	0.026	99	19	5.3	15.2	10.3	1
Sluice Core 2, Conn.	41.2	72.7	0.045	85	19	5.3	15.2	10.3	1
Leetes 1, Conn.	41.2	72.7	0.039	153	19	5.3	15.2	10.3	1
Leetes 2, Conn.	41.2	72.7	0.030	93	19	5.3	15.2	10.3	1
Sybil 2, Conn.	41.2	72.6	0.029	72	19	5.3	15.2	10.3	1
Sybil 3, Conn.	41.2	72.6	0.046	116	19	5.3	15.2	10.3	1
Branford River 1, Conn.	41.2	72.6	0.029	182	19	5.3	15.2	10.3	1
Branford River 2, Conn.	41.2	72.6	0.026	181	19	5.3	15.2	10.3	1
Farm River, Conn.	41.2	72.9	0.025	70	20	5.3	15.2	10.3	1
Bloom's Point, Little Narragansett Bay, Conn.	41.3	71.9	0.036	62	21	5.3	15.2	10.3	1
Inlet 1, Nauset Bay, Mass.	41.5	70.0	0.028	105	22	5.7	14.0	9.8	1
Nauset Bay, Mass.	41.5	70.0	0.041	155	22	5.7	14.0	9.8	1
Wells National Estuarine Research Reserve, Maine	43.3	70.5	0.020		16	1.5	12.5	7.0	1
Dipper a, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.048	85	23	−0.2	9.8	4.8	5
Dipper d, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.033	63	23	−0.2	9.8	4.8	5
Little Lepreau, Bay of Fundy, N. B.	45.1	66.5	0.059	80	23	−0.2	9.8	4.8	5
Chance Harbour, Bay of Fundy, N. B.	45.1	66.3	0.038	72	23	−0.2	9.8	4.8	5
DH SA 3, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.035		23	−0.2	9.8	4.8	5
DH SA 2, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.034		23	−0.2	9.8	4.8	5
DH SA 1, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.036		23	−0.2	9.8	4.8	5
DH Sp3, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.047		23	−0.2	9.8	4.8	5
DH Sp2, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.036		23	−0.2	9.8	4.8	5
DH Sp1, Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.043		23	−0.2	9.8	4.8	5
Bocabec River, Bay of Fundy, N. B.	45.1	67.0	0.034	456	16	−0.2	9.8	4.8	5
Bocabec River, Bay of Fundy, N. B.	45.1	67.0	0.046	113	16	−0.2	9.8	4.8	5
Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.030	445	16	−0.2	9.8	4.8	5
Dipper Harbour, Bay of Fundy, N. B.	45.1	66.4	0.033	94	16	−0.2	9.8	4.8	5
Cape Enrage, Bay of Fundy, N. B.	45.6	64.8	0.018	582	16	−0.2	9.8	4.8	5
Cape Enrage, Bay of Fundy, N. B.	45.6	64.8	0.023	186	16	−0.2	9.8	4.8	5
Lorneville, Bay of Fundy, N. B.	45.2	66.2	0.028	277	16	−0.2	9.8	4.8	5
Lorneville, Bay of Fundy, N. B.	45.2	66.2	0.033	330	16	−0.2	9.8	4.8	5

Table 1. (continued)

Location: Site Name or Core Number, State/Province, Country	Latitude	Longitude	Density, g cm^{-3}	Rate, g m^{-2} yr^{-1}	C Data Source[b]	Average Annual Temperature, °C Minimum	Maximum	Overall	Normals Period[c]
St. Martins, Bay of Fundy, N. B.	45.3	65.5	0.027	265	16	−0.2	9.8	4.8	5
St. Martins, Bay of Fundy, N. B.	45.9	65.5	0.024	928	16	−0.2	9.8	4.8	5
Wood Point, Bay of Fundy, N. B.	45.8	64.4	0.026	264	16	−0.2	9.8	4.8	5
Wood Point, Bay of Fundy, N. B.	45.8	64.4	0.025	253	16	−0.2	9.8	4.8	5
Kouchigouguacis Lagoon, Gulf of St. Lawrence, N. B.	46.7	64.9	0.031	102	24	0.6	10.0	5.3	6
Bay St-Louis, Gulf of St. Lawrence, N. B.	46.8	64.9	0.032	93	24	0.6	10.0	5.3	6
Tabusintac Bay, Gulf of St. Lawrence, N. B.	47.4	65.0	0.033	66	24	0.6	10.0	5.3	6
Malpeque Bay, Gulf of St. Lawrence, Prince Edward Island	46.5	63.7	0.029	71	24	0.9			3
Brackley Bay Gulf of St. Lawrence, Prince Edward Island	46.4	63.2	0.035	89	24	0.9			3
Pubnico Harbour, Gulf of Maine, N. S.	43.6	65.3	0.041	113	24	2.8	10.7	6.8	7
Cheboque Harbour, Gulf of Maine, N. S.	43.8	66.1	0.045	75	24	2.8	10.7	6.8	7
Little River Harbour, Gulf of Maine, N. S.	43.7	66.1	0.078	304	24	2.8	10.7	6.8	7
Cole Harbour, N. S.	44.7	63.4	0.042	161	24	0.4	11.6	6.0	1
Lawrencetown Lake, N. S.	44.7	63.4	0.024	60	24	0.4	11.6	6.0	1
Chezzetcook Inlet, N. S.	44.7	63.4	0.038	106	24	0.4	11.6	6.0	1
Rustico Bay, Prince Edward Island	46.4	63.2	0.034	125	24	0.9			3

[a]Carbon values are calculated according to the formula of *Craft et al.* [1991].

[b]1, *Callaway et al.* [1997]; 2, *Cahoon* [1994]; 3, D. R. Cahoon and J. C. Lynch, unpublished data, 1993; 4, *Cahoon and Turner* [1989]; 5, *Hatton* [1981]; 6, *Bryant and Chabreck* [1998]; 7, *Markewich et al.* [1998]; 8, *Callaway et al.* [1996]; 9, *Oenema and Delaune* [1988]; 10, *French and Spencer* [1993]; 11, *Morris and Jensen* [1998]; 12, *Hensel et al.* [1999]; 13, *Cahoon et al.* [1996]; 14, D. R. Cahoon, unpublished data, 1993; 15, *Patrick and DeLaune* [1990]; 16, G. L. Chmura, unpublished data, 1997; 17, *Craft et al.* [1993]; 18, *Kearney and Stevenson* [1991]; 19, *Anisfeld et al.* [1999] and S. C. Anisfeld, unpublished data, 1995; 20, *McCaffrey and Thomson* [1980]; 21, *Orson et al.* [1998]; 22, *Roman et al.* [1997]; 23, *Connor et al.* [2001]; 24, *Chmura and Hung* [2003].

[c]Climate normals were calculated over different periods: 1, 1961–1990; 2, 1971–2000; 3, over history of station (93 years); 4, 1957/1959–1990; 5, 1946–1990; 6, 1965–1990; 7, 1940–1990; and 8, 1951–1980.

Table 2. Soil Carbon Density, Soil Carbon Accumulation Rates, and Climate Normals at Mangrove Sites

Location: Site Name or Core Number, State/Province, Country	Latitude	Longitude	Density, g cm^{-3}	Rate, g m^{-2} yr^{-1}	C Data Source[a]	Average Annual Temperature, °C: Minimum	Maximum	Overall	Normals Period[b]
Gulf of Mexico	°N	°W							
CAR, Columbia	11.0	74.2	0.071		4				
RIN, Columbia	11.0	74.2	0.061		4				
HON, Columbia	11.0	74.2	0.058		4				
Terminos Lagoon, Boca Chica, Mexico	18.7	91.5	0.047	308	5	21.3	31.1	26.2	3
Terminos Lagoon, Estero Pargo, Mexico	18.7	91.5	0.052	194	5	21.3	31.1	26.2	3
Terminos Lagoon, Estero Pargo, Mexico	18.7	91.5	0.058	146	5	21.3	31.1	26.2	3
Terminos Lagoon, Boca Chica, Mexico	18.7	91.5	0.051	654	5	21.3	31.1	26.2	3
FL keys: Lignumvitae, to Key Largo	25.0	80.6	0.036	143	1	21.7	28.7	25.2	2
FL keys: Lignumvitae, to Key Largo	25.0	80.6	0.037	100	1	21.7	28.7	25.2	2
S1, Shark River Estuary, Fla.	25.0	80.8	0.051		6	18.9	28.3	23.6	2
S3, Shark River Estuary, Fla.	25.0	81.1	0.039		6	18.9	28.3	23.6	2
S4, Shark River Estuary, Fla.	25.0	81.1	0.046		6	18.9	28.3	23.6	2
S6, Shark River Estuary, Fla.	25.0	81.1	0.050		6	18.9	28.3	23.6	2
Rookery Bay, Fla. (Fringe)	26.0	81.7	0.036	265	7	17.6	29.4	23.5	2
Rookery Bay, Fla. (Basin)	26.0	81.7	0.066	381	7	17.6	29.4	23.5	2
Rookery Bay, Fla. (Exposed Island)	26.0	81.7	0.052	338	7	17.6	29.4	23.5	2
Rookery Bay, Fla. (Sheltered Island)	26.0	81.8	0.049	222	7	17.6	29.4	23.5	2
Southeast Everglades, Fla.	25.3	80.6	0.040		8	17.9	28.5	23.2	2
Southeast Everglades, Fla.	25.3	80.6	0.033		8	17.9	28.5	23.2	2
Southeast Everglades, Fla.	25.3	80.6	0.027		8	17.9	28.5	23.2	2
Rookery Bay, Fla.	26.0	81.7	0.043	142	5	17.6	29.4	23.5	2
Rookery Bay, Fla.	26.0	81.7	0.050	154	5	17.6	29.4	23.5	2
Rookery Bay, Fla.	26.0	81.7	0.044	154	5	17.6	29.4	23.5	2
Rookery Bay, Fla.	26.0	81.7	0.067	170	5	17.6	29.4	23.5	2
Rookery Bay, Fla.	26.0	81.7	0.024	20	2	17.6	29.4	23.5	2
Rookery Bay, Fla.	26.0	81.7	0.033	39	2	17.6	29.4	23.5	2
Pacific and Indian Ocean	°N	°E							
Kosrae	5.3	163.0	0.023		3	22.7	31.2	26.9	2
Kosrae	5.3	163.0	0.040		3	22.7	31.2	26.9	1
Kosrae	5.3	163.0	0.031		3	22.7	31.2	26.9	1
	°S	°E							
HM 2, Hinchinbrook Channel, Australia	18.5	146.3		67	9	18.8	28.8	23.8	1
HMF 3, Hinchinbrook Channel, Australia	18.5	146.3		48	9	18.8	28.8	23.8	1
HMF 4, Hinchinbrook Channel, Australia	18.5	146.3		336	9	18.8	28.8	23.8	1
Core 576, Herbert River region, Australia	18.5	146.3		26	10	18.8	28.8	23.8	1
Core 577, Herbert River region, Australia	18.5	146.3		168	10	18.8	28.8	23.8	1
Core 582, Herbert River region, Australia	18.5	146.3		84	10	18.8	28.8	23.8	1
Core 583, Herbert River region, Australia	18.5	146.3		336	10	18.8	28.8	23.8	1
Core 584, Herbert River region, Australia	18.5	146.3		300	10	18.8	28.8	23.8	1
Core 585, Herbert River region, Australia	18.5	146.3		100	10	18.8	28.8	23.8	1
Core 586, Herbert River region, Australia	18.5	146.3		71	10	18.8	28.8	23.8	1
Core 587, Herbert River region, Australia	18.5	146.3		97	10	18.8	28.8	23.8	1
Umengi estuary, Durban, South Africa	22.4	31.0	0.107		11	17.0	25.0	21.0	1
Umengi estuary, Durban, South Africa	22.4	31.0	0.105		11	17.0	25.0	21.0	1
Umengi estuary, Durban, South Africa	22.4	31.0	0.115		11	17.0	25.0	21.0	1
Umengi estuary, Durban, South Africa	22.4	31.0	0.109		11	17.0	25.0	21.0	1

Table 2. (continued)

Location: Site Name or Core Number, State/Province, Country	Latitude	Longitude	Density, g cm^{-3}	Rate, g m^{-2} yr^{-1}	C Data Source[a]	Average Annual Temperature, °C			Normals Period[b]
						Minimum	Maximum	Overall	
Umengi estuary, Durban, South Africa	22.4	31.0	0.097		11	17.0	25.0	21.0	1
Umengi estuary, Durban, South Africa	22.4	31.0	0.106		11	17.0	25.0	21.0	1

[a]1, *Callaway et al.* [1997]; 2, D. R. Cahoon and J. C. Lynch, unpublished data, 1994; 3, D. R. Cahoon, unpublished data, 1997; 4, *Cardona and Botero* [1998]; 5, *Lynch* [1989]; 6, *Chen and Twilley* [1999]; 7, *Cahoon and Lynch* [1997]; 8, *Ross et al.* [2000]; 9, *Alongi et al.* [1999]; 10, *Brunskill et al.* [2002]; 11, *Naidoo* [1980].

[b]Climate normals were calculated over different periods: 1, 1961–1990; 2, 1971–2000; and 3, 1951–1980.

[5] Both types of wetlands are noted for exceptional rates of production, rivaling that of productive agricultural lands [*Odum*, 1959]. Root to shoot ratios of salt marsh plants range from 1.4 to 50 [see review in the work of *Smith et al.*, 1979], thus a large portion of the primary production is found in belowground biomass that contributes to vertically extensive deposits, as great as 8 m deep [e.g., *Scott and Greenberg*, 1983]. Mangrove deposits can attain comparable depths [e.g., *Woodroffe et al.*, 1993]. In mangrove swamps, peat formation primarily occurs through deposition and slow turnover of mangrove roots as aboveground tissues rapidly decay or are transported from the system [*Middleton and McKee*, 2001].

[6] The global importance of wetlands as carbon sinks is widely recognized [*Adams et al.*, 1990; *Watson et al.*, 2000]. Because of their great expanse, the role of peatlands as carbon sinks has received the greatest attention by researchers [*Roulet*, 2000], who report rates of soil carbon sequestration from 20 to 30 g C m^{-2} yr^{-1}. However, decomposition of peatland soils results in high rates of CH_4 flux [*Bartlett and Harriss*, 1993], reducing their value as a means to moderate greenhouse warming. The soil chemistry and carbon accumulation patterns of TSWs differ in several respects from those of peatlands or other freshwater wetlands. For one thing, carbon concentrations in TSWs are often lower than in peatlands, since tidal wetlands can receive significant inputs of fine-grained minerals (through tidal exchange with adjacent coastal waters), which dilute the inputs of organic matter from above- and belowground production. On the other hand, rates of soil accumulation in tidal wetlands tend to be higher than in peatlands, so net carbon sequestration is potentially substantial. Perhaps most important is that the presence of abundant sulfate in TSW soils hinders CH_4 production, so these ecosystems are considered to be negligible sources of CH_4, if not CH_4 sinks [*Bartlett and Harris*, 1993; *Magenheimer et al.*, 1996; *Giani et al.*, 1996]. Studies of gas fluxes in TSWs suggest that emissions of the greenhouse gas N_2O are also negligible [*Smith et al.*, 1983; *DeLaune et al.*, 1990].

2. Methods

[7] We found 26 studies (Tables 1 and 2) that reported soil carbon densities or parameters necessary for calculation of soil carbon densities (soil bulk density and percent of soil organic matter or percent of soil carbon) in TSWs. From these studies (and our unpublished data) we compiled data for 154 sites in TSWs from the western and eastern Atlantic and Pacific coasts, as well as the Indian Ocean, Mediterranean Ocean, and Gulf of Mexico (Tables 1 and 2). The set of sites spans a latitudinal range from 22.4°S in the Indian Ocean [*Naidoo*, 1980] to 55.5°N in the northeastern Atlantic [*Morris and Jensen*, 1998]. Most of the data found (~75%) were from salt marshes (Table 1). Some of the measurements came from the same estuary or a contiguous wetland area, allowing us to compare local variability to large-scale variability.

[8] In most cases the carbon densities reported were derived from measurements of loss on ignition (LOI), but

Table 3. Area of Salt Marsh Reported

Region	Square Kilometers	Sources
United States	19,265	*Field et al.* [1991]
Europe and Scandinavia	2,302	*Dijkema* [1987]
Canada	328	*Letourneau and Jean* [1996] *Hanson and Calkins* [1996] Wetlands International Inventory
Tunisia	59	Wetlands International Inventory
Morrocco	34	Wetlands International Inventory
South Africa	170	*O'Callaghan* [1990]
Total	21,988	

the Walkley Black and dichromate digestion methods were also used, as well as percent of carbon determined from carbon analyzers. LOI measurements of mangrove soils were transformed to organic carbon by dividing by a factor of 1.724 [*Allen*, 1974], but for salt marsh soils we applied the quadratic relationship specific to salt marshes reported by *Craft et al.* [1991]:

$$\text{percent of organic carbon} = (0.04)\text{LOI} + (0.0025)\text{LOI}^2.$$

If data were reported as percent of carbon using other methods we transformed values to be consistent with our data set.

[9] Many investigators also reported rates of vertical soil accumulation, allowing us to compile carbon accumulation rates for 124 sites. (This includes the Australian mangroves for which only rates of carbon accumulation were reported [*Brunskill et al.*, 2002].) Vertical soil accumulation rates represent averages over variable periods, from 1 to ~100 years. The depth of the maximum concentration of ^{137}Cs (associated with peak fallout in 1963 [*DeLaune et al.*, 1978]) or the pattern of unsupported ^{210}Pb with depth was employed to determine long-term average rates of vertical accretion. Where reports made available both rates and carbon densities, we averaged carbon density over the dated depths.

[10] At 13 sites (Florida mangroves, Louisiana salt marshes, and Bay of Fundy salt marshes), we employed clay-marker horizons [*Cahoon and Turner*, 1989; *Chmura et al.*, 2001] to determine soil accumulation rates. Measurement of the thickness of soil accumulated over these horizons in a given period provides a short-term accretion rate. Although a few samples were lost because of erosion, we used only positive accretion values in our calculations. To estimate rates of carbon accumulation we multiplied rates by carbon density of the surface 2 cm of paired soil samples.

[11] A global inventory of mangrove area was compiled by *Spaulding et al.* [1997], who estimated 181,000 km^2 of mangrove swamps. No single global inventory of tidal salt marshes has been published. Regional or national salt marsh inventories are available for Canada [*Letourneau and Jean*, 1996; *Hanson and Calkins*, 1996], Europe [*Dijkema*, 1987], the United States [*Field et al.*, 1991], and South Africa [*O'Callaghan*, 1990]. Together these regions hold approximately 22,000 km^2 of salt marsh (Table 3). We found no data on the extent of salt marshes on the temperate coasts of Asia, South America, and Australia, but we expect these to be substantial.

[12] For most sites we were able to locate nearby meteorological stations for which climate normals, average monthly minima and maxima computed over at least three decades, were available. Where possible we located stations at low elevations and avoided large urban areas. Because data were compiled by various agencies such as the U.S. Weather Service (http://ggweather.com, http://cirrus.dnr.state.sc.us), the Meteorological Service of Canada (www.msc-smc.ec.gc.ca), Mexico's Servicio Meteorológico Nacional (http://smn.cna.gob.mx), the Australian Commonwealth Bureau of Meteorology (www.bom.gov.au), the South African Weather Service (www.weathersa.co.za), and the Met Office of the UK (www.metoffice.com), the period over which the averages were calculated varies (Tables 1 and 2).

3. Results and Discussion

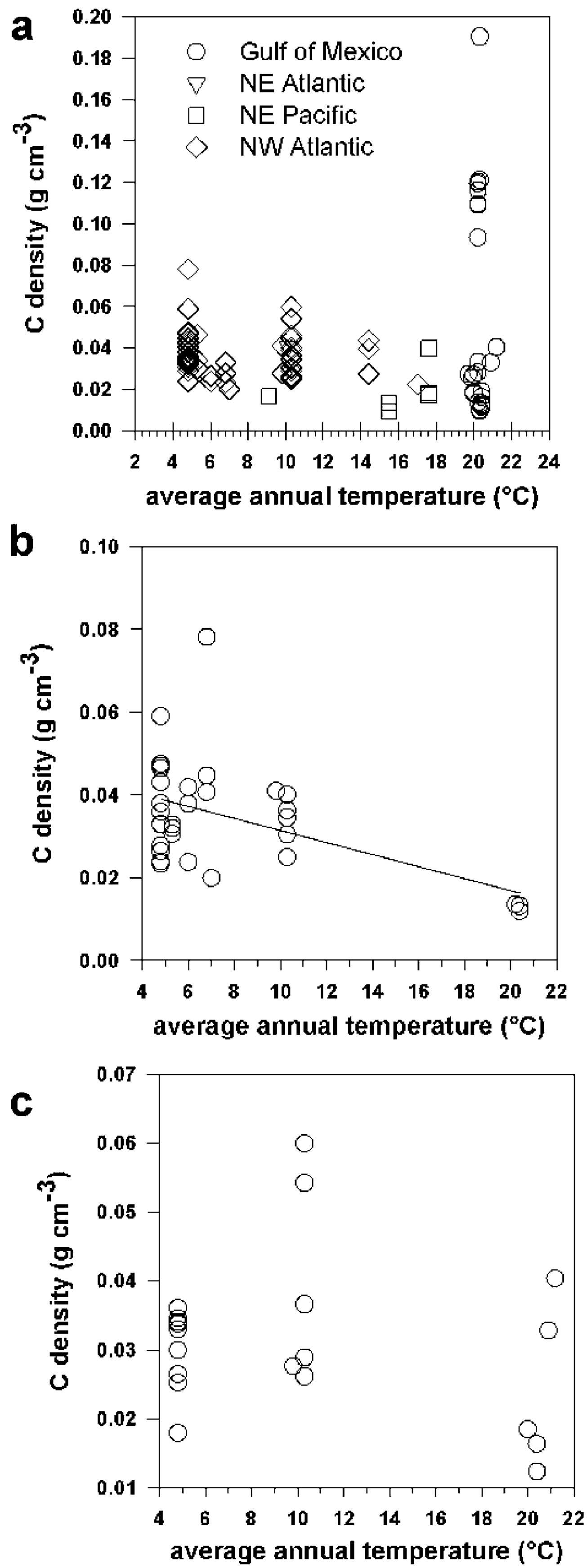
3.1. Climatic Controls

[13] The average soil carbon density of all sites is 0.043 ± 0.002 g cm^{-3}. A t test for difference of means ($P < 0.05$) shows that the average soil carbon density of mangroves

Table 4. Results of Simple Linear Regression of Soil Carbon Density and Rate of Sequestration to Average Annual Temperatures at Salt Marshes and Mangrove Swamp Sites (R, Coefficient of Correlation; P, Probability; N, Sample Number)[a]

	Average Annual Temperature			Annual Maximum			Annual Minimum		
	R	P	N	R	P	N	R	P	N
Carbon Density									
All sites	0.23	*	122	0.21	*	122	0.25	**	122
Mangroves	−0.70	***	33	−0.80	***	33	−0.49	***	33
Salt marshes	0.19	ns	90	0.18	ns	90	0.20	ns	93
S. alterniflora marshes	−0.21	ns	20	−0.21	ns	20	−0.20	ns	20
S. patens marshes	−0.50	***	21	−0.54	***	32	−0.54	***	35
Rate of Carbon Sequestration									
All sites	0.05	*	108	0.06	ns	113	0.08	ns	113
Mangroves	0.33	ns	28	0.43	*	28	0.21	ns	28
Salt marshes	0.14	ns	85	0.14	ns	85	0.15	ns	88
S. alterniflora marshes	−0.45	ns	19	−0.44	ns	19	−0.47	*	20
S. patens marshes	−0.13	ns	28	−0.13	ns	28	−0.11	ns	31

[a] *$P < 0.05$, **$P < 0.01$, ***$P < 0.005$, ns $P > 0.05$. Regressions run using SPSS 11.0.



swamps is significantly higher than the salt marsh average, 0.055 ± 0.004 versus 0.039 ± 0.003 g cm^{-3}. This difference could be due simply to higher productivity in warmer climates [*Turner*, 1976], yet average annual temperature explains only a small amount (<25%) of the variability in soil carbon density in the entire data set (Table 4).

[14] Production and decay rates could vary with plant species; so we tested average annual temperature as a predictor for carbon density in soils of salt marshes dominated by *Spartina patens* and those dominated by *Spartina alterniflora*, all on the northwest Atlantic and Gulf of Mexico (Figure 1). Rather than increase with temperature, soil carbon density in both vegetation types decreases with increasing average annual temperature, as well as annual maximum and minimum averages (Table 4). Only in the *S. patens* marshes do climate parameters explain a significant portion of the variability in soil carbon density. This relationship may be driven by a cluster of sites on the Gulf of Mexico that have low C density and high average annual temperature, but it is accepted that soil carbon decreases with average annual temperatures in terrestrial soils, presumably due to stimulated microbial decay [*Schimel et al.*, 1994].

[15] Climate parameters explain more of the variability in mangrove soils (Figure 2). Here carbon density also decreases with increasing temperatures (Table 4).

[16] Globally, rates of carbon sequestration average 210 ± 20 g m^{-2} yr^{-1}. A *t* test ($P < 0.05$) shows no significant difference between average rates of carbon sequestration in mangrove and salt marsh systems (Figure 3). Average annual temperature explains only 5% of the variability in rates of carbon sequestration. Climatic parameters have limited explanatory power when by wetland type (Table 4). The exception is soil of *S. alterniflora* salt marshes for which C accumulation rates decline with increasing average annual minimum temperature. Thus thermal controls on decomposition rates may be a factor in C accumulation rates, but regional or local factors must be the dominant controls on rates of carbon sequestration in TSW soils.

3.2. Local Controls

[17] What is most noticeable about the data is the high variability within a given region, such as the 14 salt marsh sites on the Connecticut coast of Long Island Sound (~41°N) and the 22 salt marsh sites on the Bay of Fundy (45.1°–45.9°N), as well as the 25 salt marsh (29°–30°N) and 20 mangrove (25°–26°N) sites on the northern Gulf of Mexico (Figure 3). Much of this variability can be explained by differences in suspended sediment supply and tidal water flooding.

[18] The range in carbon densities of individual surface samples (0–2 cm) from single wetlands is broad with respect to the global range (Figure 4). There are also significant differences (*t* test, $P < 0.05$) in carbon density

Figure 1. (opposite) Relationship of soil carbon density to annual average temperature in soils of (a) all salt marshes, (b) *Spartina patens* marshes, and (c) *Spartina alterniflora* marshes.

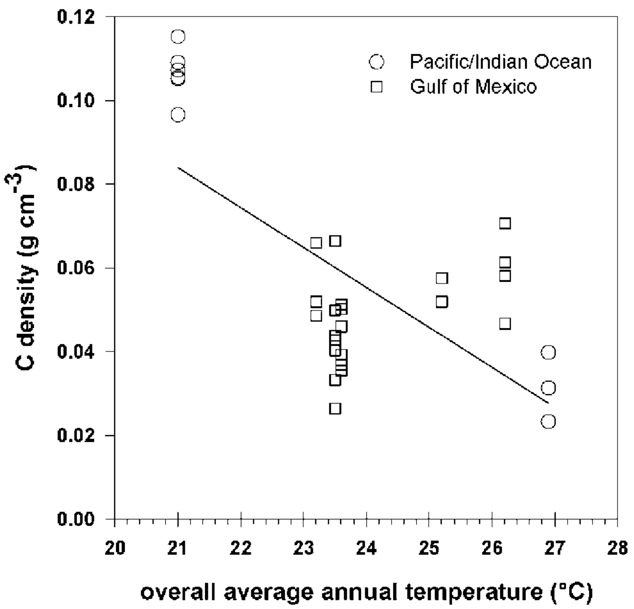


Figure 2. Relationship of soil carbon density to annual average temperature in soils of mangrove swamps of the Gulf of Mexico and Indian/South Pacific Ocean.

or carbon accumulation rates within distinct zones of single mangrove wetlands or salt marshes.

[19] At Shark River, Florida fringe mangroves (those adjacent to coastal waters) have lower soil carbon density than soils in basin mangroves located more distant from open waters. This relationship, however, is reversed for rates of soil carbon accumulation, as rates in fringe mangroves are significantly higher.

[20] The pattern seen in mangroves is repeated in salt marsh soils. In the Bay of Fundy, soil carbon densities can be significantly greater in the *S. patens* zone, where elevations are higher, tidal flooding is less frequent, and suspended sediment supply is lower with respect to the *S. alterniflora* zone [*Chmura et al.*, 2001]. Because sediment deposition is more rapid at lower marsh elevations, soil and soil carbon accumulation rates are significantly higher there. It is likely that sediment deposition enhances carbon sequestration by trapping organic matter from both macrophytes and microflora growing on the soil surfaces [*Connor et al.*, 2001]. Our Louisiana example actually comes from two sites on the Mississippi Delta that are 105 km apart. The average soil carbon density of the Louisiana *S. alterniflora* marsh is significantly higher than the *S. patens* marsh, but greater accretion rates (1.6 times greater in the *S. patens*) are enough to balance carbon accumulation rates in the two marshes.

3.3. Global Stocks and Rates

[21] Because there is no significant difference in carbon sequestration rates by ecosystem type (mangrove swamp or salt marsh) or climatic regime, we calculate an overall average rate of carbon sequestration per unit area: 210 g CO_2 m^{-2} yr^{-1}. This is an order of magnitude greater than C sequestration by peatlands (20–30 g CO_2 m^{-2} yr^{-1}) [*Roulet*, 2000]. Using the documented value of 203 $\times$ 10^3 km^2 of global wetland area (which is an underestimate, as discussed above), this means that at least 42.6 ± 4.0 Tg C are sequestered by TSWs each year. Using the TSW area estimate from the U.S. wetland inventory [*Field et al.*, 1991] we can assess the importance of the TSW carbon sink with respect to the total carbon sink estimated for the conterminous U.S. [*Pacala et al.*, 2001]. At a magnitude of 5 Tg C yr^{-1}, the TSWs would make up roughly 1–2% of the carbon sink (300–580 Tg C yr^{-1}) previously estimated for the conterminous U.S.

[22] Assessment of the potential value of TSWs as an enhanced carbon sink in the future must include consideration of methane as well, with a global warming potential of 23 times that of CO_2 (over a 100-year time horizon [*Ramaswamy et al.*, 2001]). Methane flux in TSWs has not been studied to the same degree as in peatlands, where a

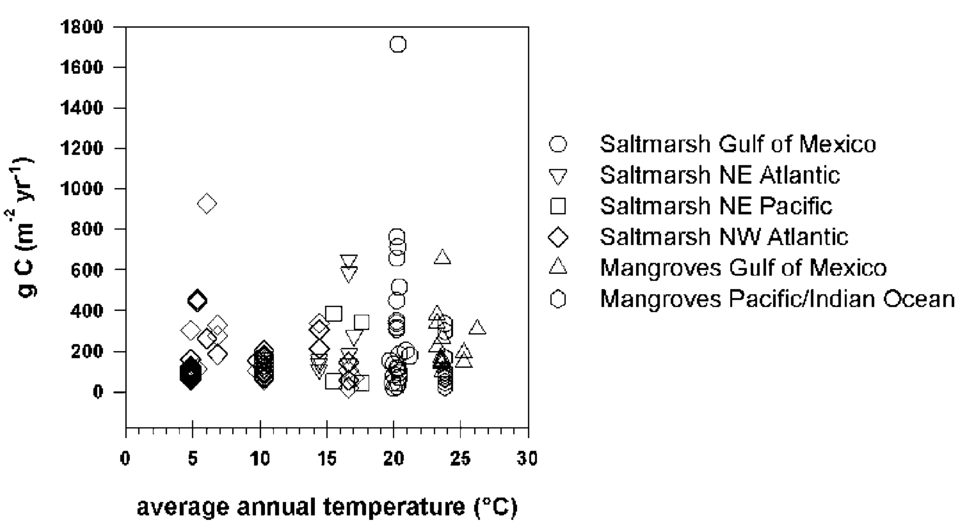


Figure 3. Relationship of soil carbon accumulation rates to annual average temperature in soils of all tidal saline wetlands.

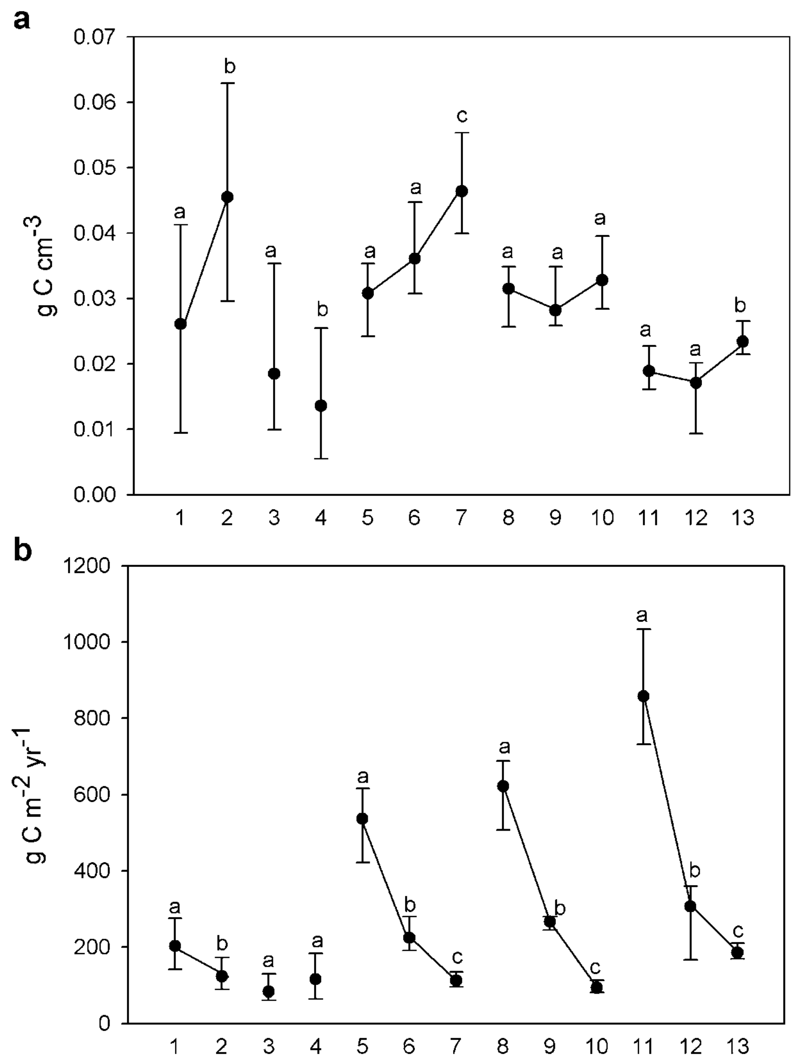


Figure 4. Local variability in carbon storage in tidal saline wetland soils. (a) Carbon density in surface soils (0–2 cm depth); (b) carbon accumulation rate in surface soils (0–2 cm depth). Vertical bars represent range of values, solid circles represent average, and averages from same wetland are connected. Averages within wetlands are significantly different if labeled with different letters; 1 and 2, fringe and basin mangroves, Shark River, Fl.; 3, *S. alterniflora* marsh, Old Oyster Bayou, La.; 4, *S. patens* marsh, Three Bayous, La.; 5 and 6, low- and high-elevation *S. alterniflora* zone, Bocabec River, Bay of Fundy, N. B.; 7, *S. patens* zone, Bocabec River; 8 and 9, low- and high-elevation *S. alterniflora* zone, Dipper Harbour, Bay of Fundy, N. B.; 10, *S. patens* zone, Dipper Harbour; 11 and 12, low- and high-elevation *S. alterniflora* zone, Cape Enrage, Bay of Fundy, N. B.; 13, *S. patens* zone, Cape Enrage.

range of 9.6–13.0 g CH_4 m^{-2} yr^{-1} has been reported [*Bartlett and Harris*, 1993]. The presence in TSWs of abundant SO_4^{-2} for organic matter decomposition through sulfate reduction means that CH_4 production is expected to be considerably smaller than in peatlands. Measurements indicate that methane flux in TSWs appears to decrease with increasing salinity and increase with temperature [*Bartlett et al.*, 1987; *Magenheimer et al.*, 1996]. Although fluxes as high as 22 g CH_4 m^{-2} yr^{-1} have been measured in some TSW sites [e.g., *Bartlett et al.*, 1987], other TSWs have been reported to be methane sinks [e.g., *Giani et al.*, 1996]. The combination of greater C burial and possibly lower CH_4 emissions means that TSWs could be more valuable as C sinks per unit area than peatlands if anthropogenic activity or natural processes were to increase ecosystem CO_2 assimilation and burial [*Whiting and Chanton*, 2001]. This could occur, for example, as a response to an increase in the rate of sea level rise [*Morris et al.*, 2002], nitrogen fertilization, or global area.

[23] As depths of TSW soil deposits are variable, we estimate the carbon stored in only the surface 0.5-m of soil. Salt marsh surface deposits store 430 ± 30 Tg C, while mangrove deposits store another 5000 ± 400 Tg C. Although adequate inventories have not been made, it is likely that average soil depths are closer to 1 m, and the magnitude of carbon storage is probably ≥10,000 Tg C.

[24] Projected climate changes caused by greenhouse warming are expected to alter processes related to carbon storage in wetlands. Higher temperatures should increase primary production but also increase decomposition rates in wetland soils. In TSWs, the net effect is expected to be minor in light of the limited relationship between annual average temperatures and soil carbon sequestration rate. Regional increases in aridity will result in lower water tables in inland peatlands and freshwater wetlands, increasing decomposition and release of CO_2 and CH_4 [*Gorham*, 1991]. This effect is not expected in tidal wetlands, as water tables are controlled by tidal flooding regimes, but increases in aridity great enough to cause shifts in TSWs from vegetated systems to salt flats would result in local losses of this carbon sink. However, salt marshes exist in areas with high evapotranspiration, such as the Tijuana Estuary on the Mexico/USA border [*Cahoon et al.*, 1996] and the Rhone Delta [*Hensel et al.*, 1999], where soil carbon accumulation rates are 343 and 161 g m^{-2} yr^{-1}, respectively.

[25] Greenhouse warming is likely to have the greatest impact on TSWs through an acceleration in the rates of sea level rise. Since TSWs vertically accumulate soil roughly in equilibrium with sea level rise [*Church et al.*, 2001], rates of soil carbon sequestration and the magnitude of the soil carbon pool also will increase. In addition, TSWs can expand inland over terrestrial soils that have a lower carbon storage capacity. However, there is a limit to the rates at which TSWs can vertically accrete, and submerged salt marsh peats found on the inner Scotian shelf [*Shaw and Forbes*, 1990] provide striking evidence that rapid sea level rise exceeded the rate of marsh elevation increase during the early Holocene. Where there is an accretion deficit, soil surfaces become submerged and edges of the remaining wetland are subject to lateral erosion, releasing carbon stored from their deposits. Wetland loss is expected to be particularly prevalent where coastal development limits the landward migration of the wetland [*Working Group on Sea Level Rise and Wetland Systems*, 1997] or where disturbances to hydrologic or sedimentological regimes prevent the wetland from adjusting to sea level rise [e.g., *Templet and Meyer-Arendt*, 1988; *Kearney and Stevenson*, 1991].

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