Chapter 24
Assessment of Carbon Sequestration Potential in Coastal Wetlands

James T. Morris, James Edwards, Stephen Crooks, and Enrique Reyes

Abstract This paper describes model (Marsh Equilibrium Model) simulations of the unit area carbon sequestration potential of contemporary coastal wetlands before and following a projected 1 m rise in sea level over the next century. Unit rates ranged typically from 0.2 to 0.3 Mg C ha^{-1} $year^{-1}$ depending primarily on the rate of sea-level rise, tidal amplitude, and the concentration of suspended sediment (TSS). Rising sea level will have a significant effect on the carbon sequestration of existing wetlands, and there is an optimum tide range and TSS that maximize sequestration. In general, the results show that carbon sequestration and inventories are greatest in mesotidal estuaries. Marshes with tidal amplitudes <50 cm and TSS <20 mg l^{-1} are unlikely to survive a 1 m rise in sea level during the next century. The majority of the United States coastline is dominated by tidal amplitude less than 1 m. The areal extent of coastal wetlands will decrease following a 1 m rise in sea level if existing wetland surfaces <1 m fail to maintain elevation relative to mean sea level, i.e. expansion by transgression will be limited by topography. On the other hand, if the

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existing vegetated surfaces survive, coastal wetland area could expand by 71%, provided there are no anthropogenic barriers to migration. The model-derived contemporary rate of carbon sequestration for the conterminous United States was estimated to be 0.44 Tg C $year^{-1}$, which is at the low end of earlier accounts. Following a 1 m rise in sea level, with 100% survival of existing wetland surfaces, rates of carbon sequestration rise to 0.58 and 0.73 Tg C $year^{-1}$ at TSS = 20 and 80 mg l^{-1}, respectively, or 32–66% higher than the contemporary rate. Globally, carbon sequestration by coastal wetlands accounts for probably less than 0.2% of the annual fossil fuel emission. Thus, coastal wetlands sequester a small fraction of global carbon fluxes, though they take on more significance over long time scales. The deposits of carbon in wetland soils are large. There have been large losses of coastal wetlands due to their conversion to other land uses, which creates opportunities for restoration that are locally significant.

Keywords Marsh equilibrium model • Suspended solids • Carbon sequestration • Coastal ecosystems • Coastal wetlands • Tidal marshes • Mangroves • Carbon stocks • Autochthonous • Sea level rise • Anthropogenic disturbance • Holocene • Organic rich soil • Subsidence • Diking • Drainage • Digital elevation model • Tide range • Primary productivity • Tidal amplitude

Abbreviations

B_s	standing biomass density
C	carbon
D	depth of the marsh surface below MHW
DEM	Digital Elevation Model
EOS	end-of-season
GHG	greenhouse gas
MEM	Marsh Equilibrium Model
MHW	mean high water
MSL	mean sea level
Mg	megagram
NWI	National Wetlands Inventory
OM	organic matter
RSLR	rate of sea-level rise
k_r	refractory fraction of root and rhizome production
B_r	root and rhizome production
φ	root:shoot quotient
ρ	sediment dry bulk density
q	settling velocity
SRTM	Shuttle Radar Topography Mission
SOC	soil organic carbon
m	suspended solids

Tg	Teragram
T	tide range
TSS	total suspended solids
k_s	trapping coefficient

24.1 Introduction

Coastal wetlands, including tidal marshes and mangroves, hold significant stocks of carbon (C), mostly buried in long-term soils storage (Donato et al. 2011). The source of organic compounds is primarily, but not exclusively, autochthonous, derived from continuous production of root biomass. The in-situ decayed products together with mineral sediments contribute to soil as the marsh builds with sea level rise. Storage in wet conditions with low oxygen availability protects these organics from microbial degradation, effectively removing sequestered C from circulation (Hedges et al. 1999; Freeman et al. 2001).

The global extent of coastal wetlands prior to major anthropogenic disturbance represented the long-term accumulation of organic-bearing coastal alluvium throughout the mid to late Holocene; a relatively quiescent period of gradual eu-static sea-level rise (typically 1 mm or less per year) (Gehrels et al. 2011). Gradual sea-level rise over this time fostered conditions favoring the accumulation of deep sequences of organic–rich soil, commonly of 3–5 m in depth and in some places deeper (Redfield and Rubin 1962). In locations subject to subsidence, either through soft sediment compaction in deltaic areas or tectonic crustal movement, the contribution of mineral sediments is a critical component of the marsh building process in the face of enhanced relative sea-level rise. Under conditions of low or even negative rates of sea-level rise, marshes with soils consisting predominantly of organic material may be found. Their existence is unbuffered by mineral sediment supply and is potentially sensitive to accelerated rates of sea-level rise if space is not available for landward migration.

Outside Europe, North America and Australia, the extent of tidal wetlands is poorly documented, and the extent of drained wetlands less so (Armentano and Menges 1986). It is now known that Europeans diked and drained most of their coastal wetland areas beginning around the Roman Era and continued with real enthusiasm during the seventeenth and eighteenth centuries. This practice spread to the New World. Between 1850 and the 1960s (when protective legislation was put in to place), extensive areas of coastal wetlands along the east and west coasts of the United States were diked. In states such as California more than 95% of all coastal wetland areas were converted to other land uses.

China also has long history of coastal wetland diking and drainage, beginning during the late Han Dynasty (BC 202 to AD 220). For example, of the 30,000 km^2 of wetland that built up over the past 4,000 years at the mouth of large rivers in Jiangsu Province only 900 km^2 remained undeveloped by the turn of the twenty-first century (An et al. 2007). Of the 43,000 km^2 of coastal wetlands that existed across China in 1950, 51% were converted to other land uses by the end of the century (He and Zhang 2001; An et al. 2007). It is estimated that a total of 133,500 km^2 of croplands, fishponds, saltponds and residential land was created from conversion of coastal wetlands in China (Yang and Chen 1995, reported in An et al. 2007).

This chapter presents results of simulations of the unit area C sequestration potential of coastal wetlands under current conditions before and after a projected 1 m rise in sea level. A methodology is described that arrives at an estimate of wetland area based on a digital elevation model of the coastline coupled with a sampling of tide ranges. Satellite altimetry-derived estimates of current wetland area and future wetland area in the United States following a 1 m rise in sea level are shown, allowing for transgression, with and without survival of existing wetland area. Applying model-derived unit area C sequestration to estimates of wetland areas yields the spatially integrated potential C sequestration in wetlands with different sea-level rise scenarios. Finally, the data are extrapolated to a global scale and the rates of C sequestration are placed in the context of the global C cycle.

24.2 Development of the Marsh Equilibrium Model (MEM)

Fundamental to the analysis presented are the predictions of a theoretical model that describe feedbacks among the plant community, sediments and tides and that explain the dependency of the relative elevation of a salt marsh on rising sea level (Morris et al. 2002). The model assumes that the sedimentation of suspended solids carried by tides over the marsh surface increases with the concentration of suspended solids (m), duration of flooding (Krone 1985; Friedrichs and Perry 2001), and standing biomass density (B_s) (Morris et al. 2002). Flood duration is proportional to the depth (D) of the marsh surface below mean high water (MHW) divided by the tide range (T).

In addition to surface deposition, production of organic matter (OM), primarily of roots and rhizomes, contributes to the total accumulation rate (Reed 1995; Turner et al. 2001). These surface and subsurface processes can be expressed as:

$$dS / dt = m(q + k_s B_s) D^2 / T + k_r B_r \tag{24.1}$$

Parameter q is the settling velocity, k_s is a trapping coefficient, and k_r is the refractory fraction of annual root and rhizome production (B_r). The production of roots and rhizomes (B_r) is proportional to the end-of-season (EOS) standing biomass density (B_s) by way of a belowground turnover rate and a root:shoot quotient (φ). Biomass density (B_s) is a function of the depth of the marsh surface below mean high water (MHW) (Morris et al. 2002):

$$B_s = aD + bD^2 + c \tag{24.2}$$

Coefficients a, b, and c determine the growth range and optimum depth below MHW. Their values were determined by bioassay (Morris 2007). Substituting for B_s into Eq. 24.1 gives:

$$dS/dt = c\varphi k_r + aD\varphi k_r + D^2(ck_s m + mq + b\varphi k_r T)/T + aD^3 k_s m/T + bD^4 k_s m/T \tag{24.3}$$

For the purposes of this paper, a root:shoot quotient of 2.2, a root and rhizome turnover of 1.5 $year^{-1}$ and $k_r = 0.02$ were applied, which gives an effective sequestration rate of 0.066 $year^{-1}$ of the EOS standing biomass. This combination of parameter values best described the vertical profile of sediment OM at North Inlet, South Carolina, USA. These and other assumptions can be explored using an interactive version of the model that can be found on the world-wide-web at http://jellyfish.geol.sc.edu/model/marsh/mem.asp. From Eq. 24.3 it can be seen that the depth of the marsh surface (D) below MHW and the rate of sea-level rise (RSLR) are proportional when the marsh surface and mean sea level are in equilibrium:

$$RSLR \propto dS/dt \propto D \tag{24.4}$$

Thus, as the rate of sea-level rise increases, the depth of the marsh surface must increase, or in other words its elevation relative to mean sea level (MSL) must decrease.

The rate of change of the marsh elevation is obtained by dividing the sedimentation rate dS/dt by bulk density (ρ), which is commonly expressed as a function of the OM content of the sediment (Jeffrey 1970; Harrison and Bocock 1981):

$$\rho = (\varphi k_r B_s)/(m(\varphi + k_s B_s)D^2/T + \varphi k_r B_s) \tag{24.5}$$

24.3 Digital Elevation Model

A coastal Digital Elevation Model (DEM) for the United States was constructed, and when combined with tide data, allowed estimates of potential wetland area. For the United States, the elevation data from the Shuttle Radar Topography Mission (SRTM) were applied (Farr et al. 2007). The SRTM-derived wetland estimates were compared with classified imagery from the National Wetlands Inventory data base to determine if the SRTM data, which has near global coverage, could be used as a reasonable proxy for classified imagery as a means of estimating the coverage of coastal wetlands. The SRTM data are available at a 3 arc-sec (about 90 m) resolution. Mean vertical accuracy was reported to range from –0.7 to 1.8 m with standard deviation of as great as 5.9 m, depending on location (Rodriguez et al. 2006).

The SRTM data were summarized spatially according to the tidal amplitude along the adjacent coast using bin sizes of 0–1, 1–2 and 2–3 m. The assumption was made that MSL has a SRTM elevation of 0 and that any surface within the 0–1 m contour and that lies within a region with tidal amplitude ≤1 m is potentially, intertidal emergent wetland. Similarly, surfaces within the 0–2 m contours in areas with tides of 1–2 m tidal amplitude were assumed to be wetland. Combining the topographic data with the spatial distribution of tidal amplitudes gives a rough picture of the frequency distribution of intertidal area.

Limited by the resolution of the SRTM, only the land area that lies between 1 m contours can be quantified. In areas where the tidal amplitude may be only a small fraction of a meter, the use of SRTM data should overestimate wetland area. For example, areas on coastlines with tidal amplitudes of 0.1 m are unlikely to support marsh at elevations that exceed perhaps 0.5 m, though by definition a potential wetland was operationally defined as a surface with an SRTM elevation of 0 m, i.e., 0 to <1 m. On the other hand, SRTM data should underestimate wetland area in a region with tidal amplitude of about 0.7–0.99 m, because vegetated wetland surface could exist at elevations above 1 m, exceeding the SRTM 0 m contour. Furthermore, the −1 m SRTM contour was assumed to be below the zone of vegetation, though wetland plants will grow at elevations lower than MSL, perhaps to −0.5 m in meso- and macrotidal regions (McKee and Patrick 1988).

Contemporary estimates of coastal wetland area in the United States are based on the National Wetlands Inventory (NWI) data base, which is derived from classified imagery (U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. http://www.fws.gov/wetlands/). From the NWI, the areas classified as estuarine, intertidal emergent or E2EM were extracted and summarized, and these were compared with the SRTM-derived estimates of potential and current wetland areas.

24.4 Tidal Data

In this chapter, the potential, vegetated intertidal area of the coastline is defined as land that falls within 1 tidal amplitude of MSL. Tidal data for 1,723 NOS/CO-OPS stations that have currently accepted datum were obtained from the U.S. National Oceanographic and Atmospheric Administration and mapped onto the coastal DEM (Fig. 24.1). The tide gage stations cover the United States and its territories only. Station data included the mean tide range (MN = mean high water level – mean low water level), the latitude, and longitude. Tide data were reported for the 1983–2001 epoch. Averaged over all stations, the grand mean tide range was 1.23 ± 1.08 m (± 1 SD).

24.5 Unit Area Carbon Sequestration

The MEM was used to compute the contemporary and future rates of unit area C sequestration (Fig. 24.2). The forecast was based on a future scenario in which sea level rise accelerates, rising ultimately to a level that is 1 m above present day MSL. Because the relative elevation of a coastal wetland will change with the rate of sea-level rise, and affects primary productivity, the rates of C sequestration over a century were integrated. The computations were made for combinations of two variables that affect sediment accretion and wetland response to rising sea level, namely the concentration of total suspended solids (TSS) and tidal amplitude

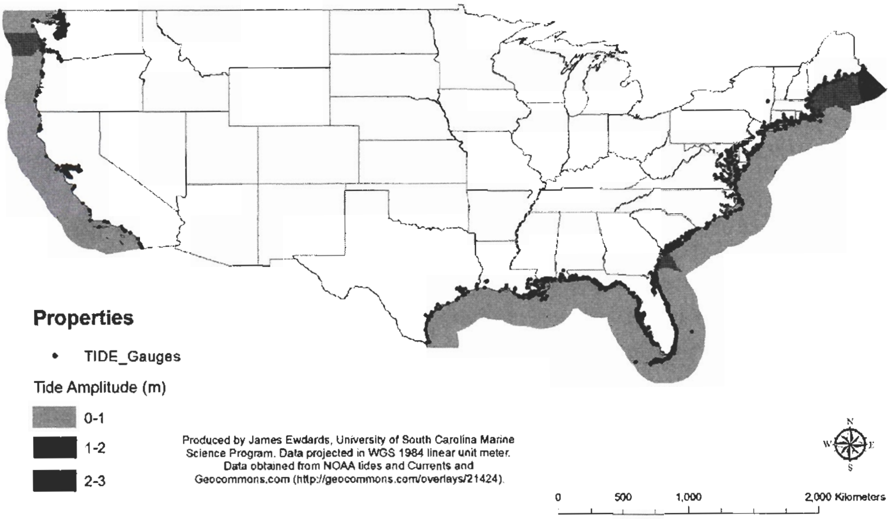
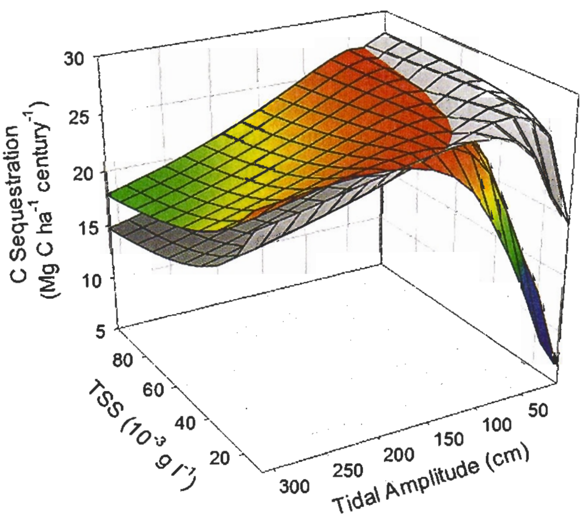


Fig. 24.1 Tidal amplitudes from the network of tide gages (gages are plotted as *dots*) mapped around the U.S. coastline

Fig. 24.2 Computed rate of carbon sequestration for coastal wetlands that are equilibrated to a contemporary rate of sea-level rise of 0.24 cm year^{-1} (*grey surface*), and following an accelerating rate of sea-level rise that reaches the 1 m elevation in a century (*color surface*)



(Fig. 24.2). Figures 24.2 and 24.3 each show two surfaces; the one in grey represents the equilibrium solution to different combinations of tidal amplitude and TSS for a constant rate of sea-level rise of 0.24 cm year^{-1}. The color surfaces show the non-equilibrium solutions when sea level was increased by 100 cm by the end of the twenty-first century.

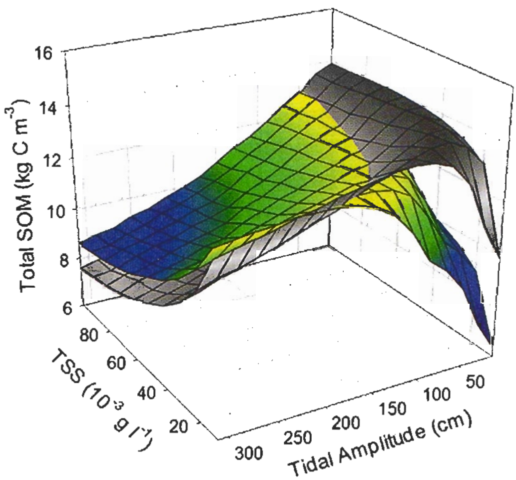


Fig. 24.3 Computed inventory of sediment organic matter in coastal wetlands that are equilibrated to a contemporary rate of sea-level rise of 0.24 cm year^{-1} (*grey surface*), and following an accelerating rate of sea-level rise that reaches the 1 m elevation in a century (*color surface*)

The response surfaces are complex and show that there are optimum combinations of TSS and tidal amplitude that maximize C sequestration and C stocks. Rising sea level will have a significant effect on C sequestration of existing wetlands. In some cases the effect of rising sea level will be positive while in others the effect will be negative. This occurs because in some cases (e.g., macrotidal estuaries) the marshes are initially in equilibrium at an elevation that is considerably greater than optimal for the vegetation, and a rapid rise in sea level will at first increase productivity. Other scenarios (e.g., microtidal estuaries) start with marshes equilibrated much closer to the optimum elevation. In general, the results indicate that C sequestration is greatest in mesotidal estuaries (Fig. 24.2).

The MEM predictions of C sequestration tend to fall around the lower end of empirical estimates that range from 18 to 1,713 g C m^{-2} year^{-1} or Mg C ha^{-1} century^{-1} (Chmura et al. 2003). Based on the C inventory of sediment cores and ^{14}C measurements, Choi and Wang (2004) reported C burial rates ranging from 18 to 193 g C m^{-2} year^{-1} in mid- to low-elevation salt marshes, but they also reported that these rates were considerably higher than long-term rates of C sequestration due to the slow but continuous decomposition of OM over time.

The permanent burial of C is equivalent to the product of the production of roots and rhizomes and the OM fraction resistant to decay. Figures 24.2 and 24.3 were generated using a 7% sequestration rate (the product of the resistant fraction and production), which is needed to fit the model to typical sediment SOM profiles from minerotrophic marshes typical of the southeast United States. Neither the quantity of labile C in sediment nor its addition to sediment contributes to C sequestration, unless the site is one that is being restored or newly colonized, in which case the increase in the inventory of labile C does contribute to sequestration. Labile C by definition will decay, but on a restoration site the addition of living root and rhizome biomass represents the *de novo* addition of C that remains approximately constant as long as the vegetation survives.

24.6 Unit Area Carbon Inventory

The current inventory or density of C in wetland sediments varies greatly. The C density varies primarily with the rate of relative sea-level rise, but tide range also has an effect (Fig. 24.3). This occurs because biomass production is a function of relative elevation, and the elevation is a function of the rate of sea-level rise. Tidal amplitude is also significant because it determines the vertical range over which with vegetation can grow, and the feasible growth range increases with increasing tidal amplitude. The C density in wetland sediments is largely a function of dilution by mineral sediment, which, like primary production, is a function of relative elevation. Peatlands widely occur in northern latitudes in the eastern United States. Interestingly, these are the regions with the greatest (2–3 m) tidal amplitude (Fig. 24.1), but they are also occur where isostatic rebound is important (Shipp et al. 1991). Isostatic rebound would have lowered the relative rate of sea-level rise for thousands of years, allowing the marshes to equilibrate at the top of the tidal frame. Thus, peat forms when the relative RSLR is very low and when a marsh equilibrates at the top of the tidal frame where the opportunity for mineral inputs is limited and where, at very low RSLR, the accretion of OM alone is sufficient to keep the marsh surface in equilibrium with MSL. Furthermore, there is probably a positive feedback between the concentration of soil organic carbon (SOC) and its preservation. As the C density rises, the concentration of phenolic compounds rises and helps to preserve OM (Freeman et al. 2004), further increasing the C density.

The depth of accreted sediment and C sequestered in a given wetland is dependent on time and rate of relative sea-level rise. Sediment depth for a given wetland in equilibrium with sea level is by definition equal to the rate of sea-level rise multiplied by its age. Assuming that existing wetlands have been in equilibrium with sea level during the late Holocene when rates of sea-level rise averaged <1 mm year^{-1}, then marshes must have sediments that range in depth from near zero, for those that have recently transgressed, to perhaps as much as 7 m for the oldest wetlands or those that are 7,000 years in age.

24.7 Potential, Future and Contemporary Coastal Wetland Area

Comparisons of NWI and SRTM-derived estimates of wetland areas were made for the eastern United States coastline known to support coastal wetlands and differing in tidal influence. The states of North Carolina, South Carolina, and Georgia have tidal amplitudes, averaged over all stations by state of 0.4, 0.77 and 1.03 m, respectively. Potential, topographically-derived wetland area in North Carolina (SRTM = 0 m) was 433 km^2, while the NWI E2EM area was 725 km^2 (Table 24.1). Here the topographic method underestimated NWI-wetland area by 40%. At the other end of the tidal spectrum, Georgia has a potential vegetated wetland area of 608 km^2 by the topographic method (SRTM = 0 + SRTM = 1), which was 54% lower than the NWI area of 1,337 km^2. In South Carolina the topographic method also underestimated NWI-wetland area (Table 24.1).

Table 24.1 Comparison of potential wetland areas computed using SRTM data with intertidal emergent marsh area derived from classified imagery (NWI data)

	Intertidal wetland area (km^2)[a]				
	North Carolina	South Carolina	Georgia	Subtotal	Total U.S.
NWI (E2EM)	725	1,398	1,337	3,460	18,372
SRTM −1 to 0 m zone	177	346	76	599	3,052
SRTM 0 to <1 m zone	433	1,078	278	1,789	14,722
SRTM 1 to <2 m zone	0	188	330	518	1,057
SRTM 2 to <3 m zone	0	0	0	0	4
SRTM subtotal 0 to <3 m	433	1,266	608	2,307	15,783

[a]Areas within each SRTM zone are assumed to be potential wetlands only if they are adjacent to a coast with tidal amplitude great enough to flood that contour. NWI wetland area is that defined as estuarine intertidal, vegetated area (Dahl 2011)

Based on this small sample size it is estimated that the topographic method of delineating wetlands using SRTM data on a regional level can be approximately 45–90% of the actual, contemporary coastal wetland area. There are several possible interpretations that explain the discrepancy, including that wetlands extend to elevations lower than the SRTM = 0 m contour. Indeed, inclusion of the SRTM −1 class in the national data results in a total wetland area of 18,834 km^2, which is in good agreement with the NWI data (Table 24.1). Another source of error occurs when tidal amplitudes approach the upper limit of the maximum SRTM bin size and wetlands extend to a higher elevation, as they do in much of South Carolina and Georgia. A higher resolution DEM should improve the results, but for the purposes of constructing a global budget, the SRTM data give a reasonable approximation of potential wetland area.

At a national level the current spatial distribution of intertidal areas and the potential for marsh transgression following a 1 m rise in MSL were addressed. The coastline of the conterminous United States is dominated by tides less than 1 m (Fig. 24.1) and the great majority of potentially vegetated intertidal area lies at elevations between 0 and 1 m. Specifically, 73% of the U.S. coastline had tidal amplitudes of 1 m or less, and 24% had tidal amplitudes of 1–2 m. Of the total intertidal area, 93% lies within 0–1 m (Table 24.2). When broken down by tidal amplitude, intertidal areas along coastlines with 1–2 m tidal amplitudes were 43% and 57% within the 0–1 and 1–2 m elevations, respectively (Table 24.4). Coastlines with 2–3 m tidal amplitudes were distributed between 27% and 45% across elevation bins (Table 24.5).

If MSL increases by 1 m and no contemporary vegetated surface lower than 1 m survives, then there will be a 22% loss of total potential wetland area (SRTM-derived wetland area) from 15,783 to 12,264 km^2 (Table 24.2). That is, the topography of the landscape over which the marsh will transgress is limited in area even when all anthropogenic barriers are removed or prevented. Alternatively, assuming 100% survival of surfaces in the 0 m elevation class (i.e., 1 cm year^{-1} accretion), as much as a 71% increase in intertidal area is possible. Note that both of these projections assume that transgression inland is limited only by elevation and not by barriers

Table 24.2 Contemporary and projected, cumulative intertidal areas by topographic zone (intertidal elevation) along the coastline of the conterminous United States

Current intertidal elevation (m)	Current area (km^2) within each zone	Area (km^2) following a 1 m rise, no survival	Area (km^2) following a 1 m rise, 100% survival[a]
0–1 (SRTM contour)	14,722 (93%)	0	0
1–2	1,057 (7%)	11,224 (92%)	25,946 (96%)
2–3	4 (<0.5%)	1,035 (8%)	1,035 (4%)
3–4	0	5 (<0.5%)	5 (<0.5%)
Totals	15,783 (100%)	12,264 (100%)	26,986 (100%)

[a]Assumes all contemporary marshes survive and gain 1 m in elevation

Table 24.3 Contemporary and projected, intertidal areas by topographic zone (intertidal elevation) along coastlines with a 0–1 m tidal amplitude

Current intertidal elevation (m)	Current area (km^2) within each zone	Area (km^2) following a 1 m rise, no survival	Area (km^2) following a 1 m rise, 100% survival
0–1 (SRTM contour)	13,911	0	0
1–2	0	10,168	24,079
Totals	13,911	10,168	24,079

Table 24.4 Contemporary and projected, intertidal areas by topographic zone (intertidal elevation) along coastlines with a 1–2 m tidal amplitude

Current intertidal elevation (m)	Current area (km^2) within each contour	Area (km^2) following a 1 m rise, no survival	Area (km^2) following a 1 m rise, 100% survival
0–1 (SRTM contour)	804 (43%)	0	0
1–2	1,053 (57%)	1,053 (51%)	1,857 (64%)
2–3	0	1,031 (49%)	1,031 (36%)
Totals	1,857 (100%)	2,084 (100%)	2,888 (100%)

Table 24.5 Contemporary and projected, intertidal areas by topographic zone (intertidal elevation) along coastlines with a 2–3 m tidal amplitude

Current intertidal elevation relative to MSL (m)	Current area (km^2) within each zone	Area (km^2) following a 1 m rise, no survival	Area (km^2) following a 1 m rise, 100% survival
0–1 (SRTM contour)	6 (45%)	0	0
1–2	4 (27%)	4 (29%)	10 (53%)
2–3	4 (28%)	4 (31%)	4 (21%)
3–4	0	5 (40%)	5 (27%)
Totals	14 (100%)	13 (100%)	19 (100%)

such as sea walls. Thus, the future C sequestration of coastal wetlands depends on barriers to upland migration and accretion rates sufficient to maintain elevation relative to MSL (Table 24.2).

24.8 Spatially Integrated Rates of Carbon Sequestration

Salt marsh coverture at either the national or global level is subject to variable accuracy (Mitra et al. 2005). In the United States, the estimates of coastal wetland area range from the present SRTM-derived estimate of 15,783 km^2 (this chapter) to the current NWI estimate of 18,372 km^2 (Dahl 2011). For this range of wetland areas the contemporary rates of C sequestration weighted by tide range, and the effect of a 1 m rise in sea-level over the next century was computed. One of the variables affecting unit area C sequestration is the TSS concentration, for which there are no national or global data bases. However, a majority of estuaries reported by (Kirwan et al. 2010) had TSS concentrations ranging from 20 to 80 mg l^{-1}. For marshes in equilibrium with a constant rate of sea-level rise of 0.24 cm $year^{-1}$, TSS concentration of 20×10^{-3} g l^{-1}, and tidal amplitudes of 50–250 cm, the MEM-derived, unit C sequestration (Fig. 24.2) ranged from 28 to 22 Mg C ha^{-1} $century^{-1}$. At a TSS of 80×10^{-3} g l^{-1} the MEM-derived, unit C sequestration ranged from 26 to 17 Mg C ha^{-1} $century^{-1}$ for tides ranging from 50 to 250 cm.

The MEM-derived contemporary rate of C sequestration for the conterminous United States is 0.44 Tg C $year^{-1}$ at a TSS of 20×10^{-3} g l^{-1}. At a TSS of 80×10^{-3} g l^{-1} the rate is only 10% lower. The arithmetic mean C sequestration of 210 g m^{-2} $year^{-1}$ from the meta-analysis of Chmura et al. (2003) gave an integrated rate of 5 Tg C $year^{-1}$ for the conterminous U.S. Using their data, a geometric mean rate of 115 g C m^{-2} $year^{-1}$ was calculated, which would halve their integrated rate, but that is still greater than the MEM estimate. Thus, this discrepancy may be a function of the inclusion of labile C in the empirical measurements of total organic C density in sediment cores. The estimate in this study is more consistent with the radiocarbon technique used by Choi and Wang (2004).

As sea-level rise accelerates this century, the change in C sequestration by coastal wetlands will depend on how successfully the existing marsh surfaces maintain a relative elevation that continues to support the vegetation. For marshes in equilibrium with an initial rate of sea-level rise of 0.24 cm $year^{-1}$, and with sea level rising 1 m in 100 years, the MEM-derived, unit C sequestration (Fig. 24.2) ranged from 22 to 25 Mg C ha^{-1} $century^{-1}$ for tidal amplitudes of 50 and 250 cm, with a maximum of 27 Mg C ha^{-1} $century^{-1}$ for the 150 cm tidal amplitude at TSS of 20×10^{-3} g l^{-1}. Note that the rate of C sequestration in the case of accelerating sea-level rise is not constant, which is the rationale for computing a rate that is integrated over a century. The corresponding, spatially integrated rates for the conterminous United States, with no survival of marshes at current elevations less than 1 m, are 0.27 and 0.33 Tg C $year^{-1}$ at TSS of 20 and 80×10^{-3} g l^{-1}, respectively. This is a significant reduction below the contemporary rate (0.44 Tg C $year^{-1}$), even when transgression was assumed to be unimpeded by anthropogenic barriers. However, with 100% survival of existing wetland surfaces less than 1 m in elevation, rates of C sequestration rise to 0.58 and 0.73 Tg C $year^{-1}$ at TSS of 20 and 80×10^{-3} g l^{-1}, respectively, or 32–66% higher than the contemporary rate.

MEM simulations predict that most of these 1 m sea-level rise scenarios are survivable for 100 years when the *in silico* marshes were started at elevations equilibrated with a rate of SLR of 0.24 cm $year^{-1}$. The exceptions are those marshes in regions of low tidal amplitude. Marshes with tidal amplitude of ≤ 50 cm and $TSS \leq 20 \times 10^{-3}$ g l^{-1} will not survive. Nevertheless, before those marshes drown, toward the end of the century, they will continue to sequester C. Not simulated here was the fate of marshes with starting elevations of 50, 150 and 250 cm, which are the elevations corresponding to the SRTM bin sizes.

On a global scale, MEM estimates of coastal wetland C sequestration range from 4.5 to 15.4 Tg C $year^{-1}$. These estimates are small in comparison to global fossil fuel emissions of 8 Pg C $year^{-1}$ (Canadell et al. 2007), i.e., 0.05–0.2%, but unlike other natural ecosystems that approach a C equilibrium at maturity, coastal wetlands will continue to sequester C, because they are depositional environments.

Another large uncertainty in the global C sequestration of coastal wetlands is the estimated areal extent of mangrove and salt marsh wetland types. It ranges from 159,760 to 552,361 km^2 (Mcleod et al. 2011), a range that is unacceptably large and points to the need for an alternative means of quantification, such as satellite altimetry. The global coverage provided by SRTM is a good starting point.

The prospect for recarbonization through wetland restoration is significant on the basis of percentage change, but not in terms of global fluxes. The 51% conversion of coastal wetlands to other land uses in China (He and Zhang 2001; An et al. 2007) is probably typical of global patterns and is consistent with figures reported earlier (Armentano and Menges 1986). There are, therefore, opportunities for mitigation of greenhouse gas (GHG) emissions on a local scale. Moreover, saline wetlands have an advantage over freshwater wetlands in terms of net sequestration of short-lived GHGs in that they emit little or no methane (Bridgham et al. 2006).

24.9 Conclusions

Simulations were made of the unit area carbon sequestration potential of contemporary coastal wetlands at different rates of sea-level rise, for various concentrations of TSS and tidal amplitudes. Salt marsh vegetation occupies approximately the upper half of the tidal frame, and biomass density varies within this range from minima at the extremes to a maximum where the elevation is optimal for growth. Understanding this is key to forecasting how carbon sequestration will change with sea-level. Computed rates of sequestration typically fell between 0.2 and 0.3 Mg C ha^{-1} $year^{-1}$. Rates generally decline when TSS is high, because marshes equilibrate at higher elevations within the tidal frame where productivity is lower. When sea level was accelerated to 1 m over the next century, sequestration rates declined at low tidal amplitudes, but increased at high tidal amplitudes. At low tidal amplitude, the marsh surface transitions quickly to a suboptimal elevation for primary production, while at high tidal amplitude marshes are able to maintain an elevation favorable to primary production for a longer time than that possible in microtidal estuaries.

Spatially integrated rates of carbon sequestration depend largely on tidal amplitude and the projected rate of sea-level rise. Tidal amplitude and local topography determine the areal extent of intertidal habitat suitable for marsh development. These variables also interact to determine how the areal extent of marsh habitat will change following a rise in sea level. The great majority of the coastline of the United States is dominated by tidal amplitudes less than 1 m. The area of coastal wetlands will decrease following a 1 m rise in sea level if existing wetland surfaces <1 m fail to maintain elevation relative to mean sea level, i.e. expansion by transgression will be limited by topography. On the other hand, if the existing vegetated surfaces survive, coastal wetland area could expand by 71%, provided there are no anthropogenic barriers to migration. The model-derived contemporary rate of carbon sequestration for the conterminous United States was estimated to be 0.44 Tg C $year^{-1}$, which is at the low end of earlier accounts. With 100% survival of existing wetland surfaces following a 1 m rise in sea level, rates of carbon sequestration rise to 0.58 and 0.73 Tg C $year^{-1}$ at TSS = 20 and 80 mg l^{-1}, respectively, or 32–66% higher than the contemporary rate. Globally, carbon sequestration by coastal wetlands is a small fraction of other global fluxes. It represents probably less than 0.2% of the annual fossil fuel emission. However, the opportunity for restoration is significant locally considering large losses of wetland habitat that have been caused by wetland conversion to other land uses.

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References

An S, Li H, Guan B et al (2007) China's natural wetlands: past problems, current status, and future challenges. Ambio 36:335–342

Armentano TV, Menges ES (1986) Patterns of changes in the carbon balance of organic soil-wetlands of the temperate zone. J Ecol 74:755–774

Bridgham SD, Megonigal JP, Keller JK et al (2006) The carbon balance of North American wetlands. Wetlands 26:889–916

Canadell JG, Pataki D, Gifford R et al (2007) Saturation of the terrestrial C sinks, Chapter 6. In: Canadell JG, Pataki D, Pitelka L (eds) Terrestrial ecosystems in a changing world, The IGBP series. Springer, Berlin

Chmura GL, Anisfeld SC, Cahoon DR et al (2003) Global carbon sequestration in tidal, saline wetland soils. Glob Biogeochem Cycle 17. doi:10.1029/2002GB00197

Choi Y, Wang Y (2004) Dynamics of carbon sequestration in a coastal wetland using radiocarbon measurements. Glob Biogeochem Cycle 18, GB4016. doi:10.1029/2004GB002261

Dahl TE (2011) Status and trends of wetlands in the conterminous United States 2004 to 2009. Fish and Wildlife Service, Washington, DC

Donato DC, Kauffman JB, Murdiyarso D et al (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4:293–297

Farr TG, Rosen PA, Caro E et al (2007) The shuttle radar topography mission. Rev Geophys 45. RG2004 1:33

Freeman C, Ostle N, Hojeong K (2001) An enzymic 'latch' on a global carbon store. Nature 409:149

Freeman C, Ostle NJ, Fenner N et al (2004) A regulatory role for phenol oxidase during decomposition in peatlands. Soil Biol Biochem 36:1663–1667

Friedrichs C, Perry J (2001) Tidal salt marsh morphodynamics. J Coast Res Special Issue 27:7–37
Gehrels WR, Horton BP, Kemp AC et al (2011) Sivan Sea-level records of the last 2000 years hold the key to understanding contemporary and future sea-level change. EOS Trans Am Geophys Union 92:289–29
Harrison AF, Bocock KL (1981) Estimation of soil bulk-density from loss-on-ignition value. J Appl Ecol 18:919–927
He Y, Zhang MX (2001) Study on wetland loss and its reasons in China. Chin Geogr Sci 11:241–245
Hedges JI, Hu FS, Devol AH et al (1999) Sedimentary organic matter preservation: a test for selective degradation under oxic conditions. Am J Sci 299:529–555
Jeffrey DW (1970) A note on the use of ignition loss as a means for the approximate estimation of soil bulk density. J Ecol 58:297–299
Kirwan ML, Guntenspergen GR, D'Alpaos A et al (2010) Limits on the adaptability of coastal marshes to rising sea level. Geophys Res Lett 37:L23401. doi:10.1029/2010GL045489
Krone RB (1985) Simulation of marsh growth under rising sea levels. In: Waldrop WR (ed) Hydraulics and hydrology in the small computer age. Hydraulics Division of the ASCE, Lake Buena Vista
McKee KL, Patrick WH Jr (1988) The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums: a review. Estuaries 11:143–151
Mcleod E, Chmura GL, Bouillon S et al (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front Ecol Environ 9:552–560
Mitra S, Wassmann R, Vlek PLG (2005) An appraisal of global wetland area and its organic carbon stock. Curr Sci 88:25–35
Morris JT (2007) Estimating net primary production of salt-marsh macrophytes, Chapter 7. In: Fahey TJ, Knapp AK (eds) Principles and standards for measuring primary production. Oxford University Press
Morris JT, Sundareshwar PV, Nietch CT et al (2002) Responses of coastal wetlands to rising sea level. Ecology 83:2869–2877
Redfield AC, Rubin M (1962) The age of salt marsh peat and its relation to recent changes in sea level at Barnstable Massachusetts. Proc Natl Acad Sci USA 48:1728–1734
Reed DJ (1995) The response of coastal marshes to sea-level rise: survival or submergence? Earth Surf Process Landf 20:39–48
Rodriguez E, Morris CS, Belz JE (2006) Global assessment of the SRTM performance. Photogramm Eng Remote Sens 72:249–260
Shipp RC, Belknap DF, Kelley JT (1991) Seismic-stratigraphic and geomorphic evidence for a post-glacial sea-level lowstand in the northern Gulf of Maine. J Coast Res 7:341–364
Turner RE, Swenson EM, Milan CS (2001) Organic and inorganic contributions to vertical accretion in salt marsh sediments. In: Weinstein MP, Kreeger DA (eds) Concepts and controversies in tidal marsh ecology. Springer, New York
Yang S, Chen J (1995) Coastal salt marsh and mangrove swamps in China. Chin J Oceanogr Limnol 13:318–324