Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services

Christopher Craft[1], Jonathan Clough[2], Jeff Ehman[3], Samantha Joye[4], Richard Park[5], Steve Pennings[6], Hongyu Guo[6], and Megan Machmuller[4]

We used field and laboratory measurements, geographic information systems, and simulation modeling to investigate the potential effects of accelerated sea-level rise on tidal marsh area and delivery of ecosystem services along the Georgia coast. Model simulations using the Intergovernmental Panel on Climate Change (IPCC) mean and maximum estimates of sea-level rise for the year 2100 suggest that salt marshes will decline in area by 20% and 45%, respectively. The area of tidal freshwater marshes will increase by 2% under the IPCC mean scenario, but will decline by 39% under the maximum scenario. Delivery of ecosystem services associated with productivity (macrophyte biomass) and waste treatment (nitrogen accumulation in soil, potential denitrification) will also decline. Our findings suggest that tidal marshes at the lower and upper salinity ranges, and their attendant delivery of ecosystem services, will be most affected by accelerated sea-level rise, unless geomorphic conditions (ie gradual increase in elevation) enable tidal freshwater marshes to migrate inland, or vertical accretion of salt marshes to increase, to compensate for accelerated sea-level rise.

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Tidal wetlands such as salt, brackish, and freshwater marshes provide essential ecosystem services to society. Such services include functions associated with regulation, habitat, and production (Daily *et al.* 1997; de Groot *et al.* 2002).

Positioned at the interface between land and sea, tidal marshes are uniquely suited to provide ecosystem services associated with waste treatment, biological productivity, and disturbance regulation. These services are especially important to the 53% of the US population that lives in the coastal zone (Boesch *et al.* 2000). Tidal marshes are susceptible to climate change, especially accelerated sea-level rise (SLR). Sea level is predicted to increase by 30–100 cm by 2100, based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES; Meehl *et al.* 2007). The vulnerability of tidal wetlands to accelerated SLR depends on geologic factors, such as tectonic uplift and glacial isostatic adjustment, which buffer shorelines from SLR, and subsidence, which accelerates it. Tide range also affects marsh vulnerability, as macro- (> 4 m) and meso-tidal (2–4 m) marshes are less susceptible to SLR than are micro-tidal (< 2 m) marshes (Stevenson and Kearney in press).

In some coastal areas, rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration, as salt marshes transgress landward and replace tidal freshwater and brackish marshes (Park *et al.* 1991). Declining tidal marsh area and habitat conversion may lead to changes in delivery of ecosystem services provided by these wetlands.

We used field and laboratory measurements, geographic information systems, and simulation modeling to predict the effects of accelerated SLR on tidal marsh area and delivery of select ecosystem services along the Georgia coast. Our goal was to predict how tidal marsh area and delivery of ecosystem services would respond to different scenarios of sea-level rise during the 21st century.

Methods

Ecosystem services related to production (macrophyte biomass) and waste treatment (nitrogen [N] accumulation in soil, potential denitrification) were measured in two salt marshes, two brackish marshes, and two tidal freshwater marshes on each of three rivers along the Georgia coast: the Ogeechee, the Altamaha, and the Satilla. Marshes were chosen for this study by examination of their dominant vegetation, which correlates strongly with salinity: on the southeastern and Gulf coasts of the US, *Spartina alterniflora* dominates in salt marshes (20–35 ppt [parts salt per thousand parts water]), *Juncus roemerianus* dominates in brackish marshes (5–20 ppt), and *Zizaniopsis mileacea* dominates in tidal freshwater marshes (< 0.5 ppt). *Spartina* spp and *Juncus* spp are also common genera of salt and brackish marshes, respectively, in the temperate zone.

Aboveground biomass of macrophytes was measured by harvesting vegetation from 0.25-m^2 quadrats (n = 12 per marsh) at the end of the season (October 2006). Nitrogen accumulation in soil was determined by collect-

[1]*School of Public and Environmental Affairs, Indiana University, Bloomington, IN* *(ccraft@indiana.edu); [2]*Warren Pinnacle Consulting Inc, Warren, VT;* [3]*Image Matters, Bloomington, IN;* [4]*Department of Marine Sciences, University of Georgia, Athens, GA;* [5]*Eco Modeling, Diamondhead, MS;* [6]*Department of Biology and Biochemistry, University of Houston, Houston, TX*

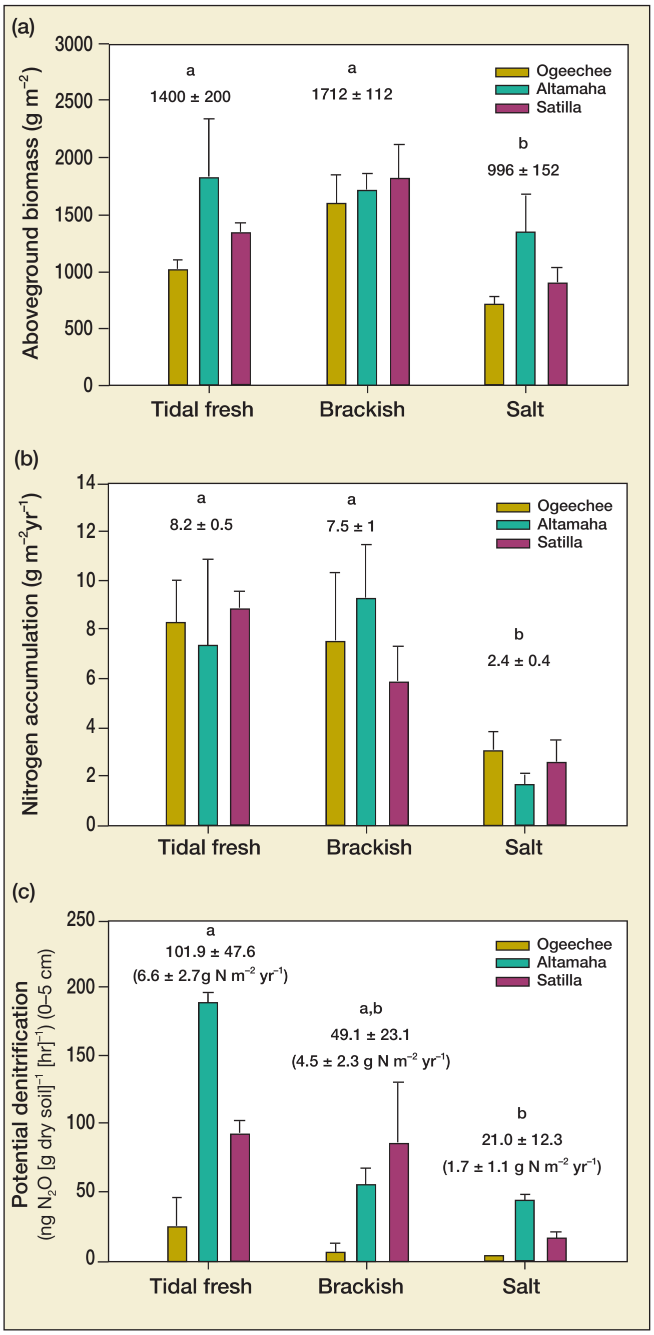

Figure 1. *(a) Aboveground biomass, (b) N accumulation in soil, and (c) potential denitrification in tidal fresh, brackish, and salt marshes of three Georgia river systems (Ogeechee, Altamaha, and Satilla). Means sharing the same letter are not significantly different according to the Ryan–Einot–Gabriel–Welsch multiple range test* ($p \leq 0.05$).

ing two soil cores (8.5-cm diameter by 50 cm deep) from each marsh. Cores were sectioned into 2-cm increments and each increment was analyzed for bulk density, N concentration, and cesium-137 (^{137}Cs; Craft 2007). Potential denitrification was measured in laboratory (sediment slurry) incubations of soil (*n* = 4 cores in each marsh, taken May 2007) as described by Joye and Paerl (1994).

Changes in tidal marsh area and habitat type in response to accelerated SLR were modeled using a "sea-level affects marshes model" (SLAMM version 5), which simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea-level rise (Park *et al.* 1989; www.warrenpinnacle.com/prof/SLAMM). SLAMM5 integrates elevation–submergence and wave action–erosion. SLAMM5 also incorporates a salinity algorithm, based on freshwater discharge and cross-sectional area of the estuary, to model saltwater intrusion in river-dominated estuaries of our study domain. Model inputs included the USGS National Elevation Dataset (NED; http://ned.usgs.gov), NOAA tidal data, and USFWS National Wetlands Inventory (NWI) data (http://wetlandsfws.er.usgs.gov). SLAMM5, a cell-based model, was run at 28-m resolution based on NED characteristics within the study region; however, it simulates finer-scaled spatial features, such as the tall *Spartina* marsh.

Model simulations were based on the SRES A1B mean (39 cm) and maximum (69 cm) increase in SLR over the next 100 years, with a time step of 25 years. Because the measured rate of SLR is greater along the Georgian coast (2.5 mm per year) and the southeastern coast of the US in general, relative to the global average of 1.8 mm per year (Church *et al.* 2001; Peltier 2001), our simulations are based on mean and maximum increases of 52 cm and 82 cm, respectively, by 2100. The SRES A1 scenario assumes rapid economic growth, low population growth, and rapid introduction of new and more efficient technology (Church *et al.* 2001; Meehl *et al.* 2007). The SRES A2 scenario, which assumes a lower rate of economic growth and fewer technological advances, but greater population growth, predicts a similar increase in sea-level rise during the next century (Church *et al.* 2001).

Delivery of ecosystem services was scaled up by multiplying the habitat-specific, plot-based measurements (ie amount of macrophyte biomass, N accumulation in soil, or potential denitrification per unit area for tidal freshwater, brackish, or salt marsh) by the total area of the habitat types predicted by the model. Changes in a particular service are the difference between the totals for two different times (ie initial condition versus 2100 for the scenarios simulated).

Results

Ecosystem services of tidal freshwater, brackish, and salt marshes

The various habitats of tidal marshes provide different quantities of ecosystem services. For example, aboveground biomass was 40–70% greater in tidal freshwater and brackish marshes than in salt marshes (Figure 1). Biomass quality, based on leaf C:N, was also greater in the tidal freshwater marsh (34.5 ± 2.8) than in the brackish marsh (40.9 ± 1.3) and salt marsh (36.4 ± 1.8). Reduced aboveground biomass in salt marshes is linked to greater

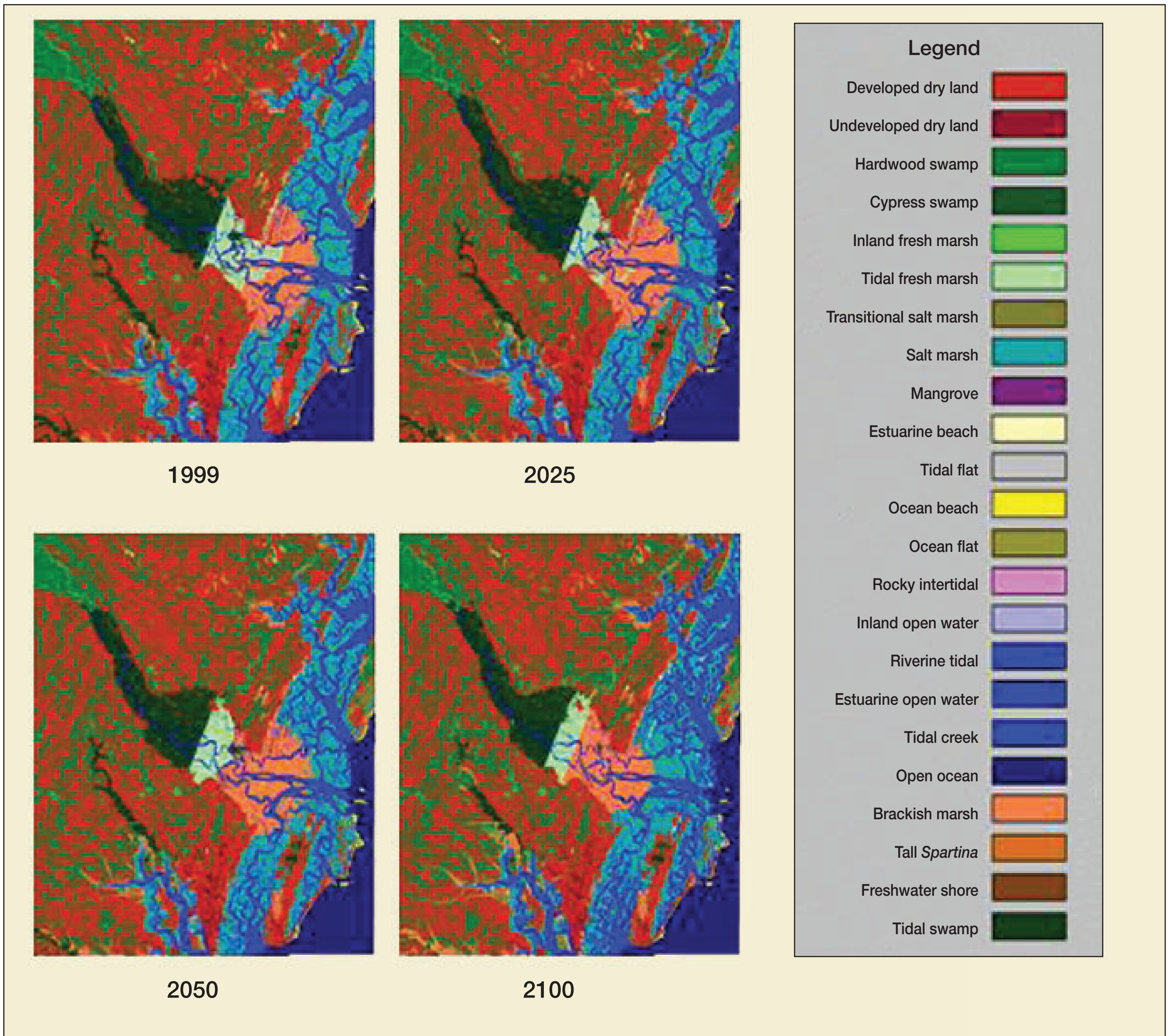

Figure 2. *SLAMM simulation of effects of accelerated SLR on tidal marshes of the Altamaha River, Georgia. The simulation was run using the SRES A1B scenario that assumes a 52-cm increase in sea level by 2100. The coarse vertical resolution of the NED dataset results in the linear pattern (ie striping) of wetland migration observed during the simulation.*

salinity and sulfide stress, which inhibits N uptake and reduces plant growth (Odum 1988; Mendelssohn and Morris 2000).

Tidal freshwater and brackish marshes also provided greater waste treatment per unit area than did salt marshes (Figure 1). These marshes sequestered three times more N in soil and supported two to three times greater potential denitrification than salt marshes. Greater N accumulation and potential denitrification in tidal freshwater and brackish marsh soils is linked to low levels of salinity. In tidal marsh soils, decomposition is positively related to salinity, such that organic matter and N accumulation are reduced in salt marsh soils relative to brackish and tidal freshwater marshes (Craft 2007). Salinity also hinders denitrification by inhibiting nitrifying bacteria that convert ammonium to nitrate (Joye and Hollibaugh 1995) and by favoring sulfate-reducing bacteria that may outcompete denitrifiers for available labile carbon substrates (Weston *et al.* 2006).

Effect of accelerated SLR on tidal marsh area and ecosystem services

Simulation modeling predicts that a 52-cm increase in sea level will lead to a decline in tidal marsh area and delivery of ecosystem services along the Georgia coast during this century. To illustrate, Figure 2 depicts SLAMM simulation results for the Altamaha River. For this river system, the model predicts a large decline in area of tidal freshwater marsh (–38%) and swamp (–24%), a smaller decline of salt marsh (–8%), and a small increase in brackish marsh habitat (+4%). A corre-

Table 1. Predicted change in area (km^2) of selected land-cover types along the Georgia coast, in response to the A1B SRES sea-level rise scenario, as modeled by SLAMM

	A1B mean = 52 cm			*A1B max = 82 cm*		
	1999	*2100*	*% change*	*1999*	*2100*	*% change*
Dry land	5008	4385	–12	5006	4265	–15
Non-tidal swamp	1838	2089	+14	1837	2106	+15
Tidal swamp	413	316	–24	407	267	–34
Inland fresh marsh	64	65	+2	64	63	–2
Tidal fresh marsh	79	80	+1	82	50	–39
Brackish marsh	417	458	+10	416	412	–1
Salt marsh	1116	890	–20	1106	610	–45
Transitional salt marsh[1]	32	254	+694	34	306	+800
Tidal flat	11	26	+136	11	177	+1510
Estuarine open water	742	1091	+47	756	1401	+85

Notes: The simulation was run assuming the mean (52 cm) and maximum (82 cm) increase in sea level between 1999 and 2100. Differences in the initial areas of land-cover types between the A1B mean and max simulations are the result of using IPCC projections that begin in 1990 and, thus, lead to small differences in the initial conditions based on the scenario (mean versus max) chosen. [1]High marsh shrub vegetation flooded only during spring tides and storm tides.

sponding increase in transitional salt marsh (+780%, from 8 to 68 km^2), tidal flat (+400%, from 1 to 5 km^2), and estuarine open water (+52%, from 176 to 268 km^2) also occurs as sea level rises (Figure 2).

For the entire Georgia coast, a 52-cm increase in sea level causes overall reduction in salt marsh (–20%), along with a small increase in tidal freshwater marsh (+1%) and a larger increase in brackish marsh (+10%; Table 1). The decline in salt marsh is attributed to submergence and replacement by tidal flats and estuarine open water (Table 1). The increase in tidal freshwater marsh and brackish marsh occurs at the expense of tidal swamp, which declines by 24% as these marshes migrate up-river in response to sea-level rise and saltwater intrusion. Overall, there is a net loss of tidal marsh habitat (184 km^2), as salt marsh habitat declines by 226 km^2, while brackish marsh and tidal freshwater marsh increase by 41 km^2 and 1 km^2, respectively (Table 2).

By combining measurements of ecosystem services with the change in tidal marsh habitat, we can predict how delivery of ecosystem services is affected by accelerated SLR. As tidal marsh habitat declines, delivery of ecosystem services related to productivity and N retention and removal are reduced. Aboveground biomass of macrophytes is reduced by more than 150 000 metric tons (t) per year under the A1B mean scenario (Table 2). Nitrogen sequestration in soil is reduced by 227 t per year, whereas potential denitrification is reduced by 193 t per year. The cumulative reduction in delivery of ecosystem services is attributed mostly to loss of salt marsh habitat, even though tidal freshwater marsh and brackish marsh provide greater delivery of ecosystem services than do salt marshes on a per-unit-area basis.

An 82-cm increase in sea level, predicted by the A1B maximum scenario, leads to even greater reduction in tidal marsh area and delivery of ecosystem services. Based on this scenario, tidal freshwater, brackish, and salt marshes decline by 39%, 1%, and 45%, respectively, by 2100. Delivery of ecosystem services is also dramatically reduced under the A1B maximum scenario, as macrophyte biomass

Table 2. Predicted change in tidal marsh area and delivery of select ecosystem services along the Georgia coast between 1999 and 2100 in response to a 52-cm and 82-cm increase in sea level

	Habitat change (km^2)		*Macrophyte biomass ($t\ yr^{-1}$)*		*N sequestration in soil ($t\ yr^{-1}$)*		*Potential denitrification ($t\ yr^{-1}$)*	
	52 cm	*82 cm*	*52 cm*	*82 cm*	*52 cm*	*82 cm*	*52 cm*	*82 cm*
Tidal fresh marsh	+1	–32	+1400	–44 800	+8	–262	+7	–211
Brackish marsh	+41	–4	+70 200	–6800	+307	–30	+184	–18
Salt marsh	–226	–496	–225 100	–494 000	–542	–1188	–384	–843
Cumulative (km^2)	–184	–532	–153 500	–545 600	–227	–1480	–193	–1072
Cumulative (%)	–11%	–33%	–8%	–28%	–4%	–23%	–4%	–25%

Notes: Change in delivery of ecosystem services was calculated by multiplying the change in habitat area by the mean ecosystem service values for each marsh type in Figure 1. Negative values denote a reduction in marsh area and delivery of ecosystem services.

decreases by nearly 550 000 t per year, N accumulation in soil decreases by 1482 t N per year, and potential denitrification declines by 1072 t N per year (Table 2).

Under the A1B mean and maximum SLR scenarios, cumulative tidal marsh area declines by 11% and 33%, respectively, while cumulative reduction in delivery of ecosystem services is 4–28% lower (Table 2). Delivery of ecosystem services is less affected by accelerated SLR than is tidal marsh area, because brackish marsh area, which has high delivery of services per unit area, does not change substantially (–1% to +10%) relative to salt marshes that decline in area by 20–45%. This result highlights an unappreciated value of brackish marshes: because they support high levels of ecosystem services and do not decline as much as other tidal marsh types, they may buffer some of the negative impacts of SLR.

Sensitivity analysis of model parameters

We conducted a sensitivity analysis by varying model parameters, historic rate of SLR, site-specific accretion rates for salt marsh, brackish marsh, and tidal freshwater marsh, and erosion rates for tidal flat and salt marsh by plus or minus 15%, to determine which parameters most affect model output when comparing results after 69 cm of eustatic (worldwide) SLR (82 cm for Georgia). Model results were most sensitive to changes in the historic rate of local SLR, which affects long-term projections of local SLR. Increasing this parameter by 15% decreased salt marsh and tidal freshwater marsh area by 7.3% and 13%, respectively, and tidal flat area increased by 12%. Model output was less sensitive to site-specific accretion and erosion rates. Decreasing accretion rates by 15% resulted in a 7% decrease in salt marsh area and a 5% decrease each in brackish marsh and tidal freshwater marsh area. Increasing tidal flat erosion rate by 15% resulted in an 18% decrease in this habitat type.

Discussion

Limitations of the approach

Several caveats associated with the tools and approaches we used deserve mention. First, uncertainties exist with scaling results from laboratory and plot measurements to the landscape level. Second, there are limitations associated with the data inputs used in the SLAMM5 SLR simulations. For example, NED elevation data covering the entire coast have only moderate resolution. Third, the SLAMM5 model lacks feedback mechanisms that may come into play as SLR accelerates. For example, increasing inundation of salt marshes may increase macrophyte production and lead to increased vertical accretion (Morris *et al.* 2002). Conversely, increasing saltwater intrusion into tidal freshwater marshes may accelerate decomposition (Weston *et al.* 2006), leading to reduced vertical accretion. Despite these caveats, our approach provides important insights into how accelerated SLR may affect tidal marshes and their delivery of ecosystem services in the future.

Beyond the southeast coast

Although our simulation focuses on the Georgia coast, we speculate that, elsewhere, tidal freshwater and salt marshes will also be most affected by SLR. Tidal freshwater marshes will decline in area as saltwater intrudes and brackish marshes migrate inland to replace them. Salt marshes will convert to open water because their low rate of vertical accretion relative to brackish and tidal freshwater marshes (Craft 2007) may prevent them from keeping pace with accelerated SLR.

Declining area of tidal freshwater wetlands, marshes, and swamp forests (Table 1) may be problematic for the American alligator (*Alligator mississippiensis*), wood stork (*Mycteria americana*), and other species that depend on freshwater aquatic habitats. On a per-unit-area basis, tidal freshwater wetlands provide higher levels of ecosystem services than do salt marshes, so their decline will lead to a disproportionate decrease in delivery of ecosystem services. In the 21st century, these problems will probably be compounded by reduced river discharge caused by the greater climate variability (eg droughts) that will accompany global warming (Meehl *et al.* 2007), and by increased demand for freshwater by a growing human population. At the same time, declining area of salt marsh may lead to reduced shoreline protection and habitat support for marsh nekton (free swimming aquatic animals; Kneib 2000), although increasing marsh edge may enhance nekton access to the remaining marsh (Zimmerman *et al.* 2000).

Our predictions of the effects of accelerated SLR on the delivery of tidal marsh ecosystem services of the Georgia coast should be viewed with caution, because the drivers of climate change, greenhouse gases (and temperature), will also increase. Increasing CO_2 and temperature over the next century may alter plant physiological processes that affect the distribution and productivity of plant communities. For example, increasing CO_2 may favor increased productivity and water-use efficiency, especially by C_3 vegetation, which may lead to changes in plant community composition and productivity (Körner 2006). Nitrogen accumulation in soil may be altered by increased temperature and lower N demand from vegetation as a result of higher CO_2 (Curtis *et al.* 1990).

Forecasted changes in tidal marsh area and delivery of ecosystem services are applicable to other temperate areas, where tidal marshes experience meso-tidal inundation and where rates of SLR are comparable (ie 2–3 mm per year). Some coastal regions experience tectonic uplift and there, tidal marshes are not as vulnerable. Worldwide, there is evidence that tidal marshes in flood-dominated estuaries, or those that receive high sediment loads, may be better buffered against SLR than marshes in ebb-dominated or low sediment supply estuaries (Morris *et al.* 2002; Stevenson and Kearny in press). In regions where subsidence is occurring, tidal marshes are at greater risk. Marshes exposed to micro-tidal (< 2 m) inundation are also likely to suffer greater declines in area and delivery of ecosystem services than are meso-tidal (2–4 m inundation) marshes, because they rely more on organic matter accumulation to support vertical accretion and, thus, may not be able to compensate for accelerated SLR (Stevenson and Kearney in press). On a positive note, Georgia's tidal marshes experience meso-tidal inundation (tide range = 2.3 m), which buffers them against moderate increases in sea level, as they may be able to increase their rate of vertical accretion to compensate (Morris *et al.* 2002). Thus, the decline in salt marsh habitat may not be as great as predicted by our model simulations.

In summary, our results suggest that salt, brackish, and tidal freshwater marshes of the Georgia coast will respond differently to a 52-cm increase in SLR, with fresh and salt marshes suffering greater losses than brackish marshes. Because brackish marshes provide ecosystem services at a rate greater than that of other marsh types, and because brackish marshes are predicted to undergo less precipitous declines in area than other marsh types, the predicted loss of ecosystem services along the Georgia coast is less than would be forecast based solely on losses in total marsh area.

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