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A nonlinear relationship between marsh size and sediment trapping capacity compromises salt marshes' stability

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ABSTRACT

Global assessments predict the impact of sea-level rise on salt marshes with present-day levels of sediment supply from rivers and the coastal ocean. However, these assessments do not consider that variations in marsh extent and the related reconfiguration of intertidal area affect local sediment dynamics, ultimately controlling the fate of the marshes themselves. We conducted a meta-analysis of six bays along the United States East Coast to show that a reduction in the current salt marsh area decreases the sediment availability in estuarine systems through changes in regional-scale hydrodynamics. This positive feedback between marsh disappearance and the ability of coastal bays to retain sediments reduces the trapping capacity of the whole tidal system and jeopardizes the survival of the remaining marshes. We show that on marsh platforms, the sediment deposition per unit area decreases exponentially with marsh loss. Marsh erosion enlarges tidal prism values and enhances the tendency toward ebb dominance, thus decreasing the overall sediment availability of the system. Our findings highlight that marsh deterioration reduces the sediment stock in back-barrier basins and therefore compromises the resilience of salt marshes.

INTRODUCTION

Salt marshes provide critical ecosystem services (Costanza et al., 1997). In recent years, salt marshes have been the focus of many restoration plans built on the concept of "nature-based solutions" for flood defenses that aim to use vegetated surfaces to protect coastal communities from storms (Temmerman et al., 2013). The economic value of salt marsh ecosystem services has been estimated to be as much as US$5 million per square kilometer in the United States (Costanza et al., 2008), and £786 million per year for all United Kingdom marshes (Foster et al., 2013; Leonardi et al., 2017). Projections of salt marsh response to climate change are variable, with initial studies suggesting a 46%–59% reduction of the present-day area by 2100 CE under moderate sea-level rise (Spencer et al., 2016), and more refined studies estimating "coastal squeezing" of as much as 30% when accounting for landward migration (Schuerch et al., 2018). When allowed by the availability of accommodation space, the landward migration of fringing marshes supports the maintenance of marsh extent, but erosion at the seaward side remains a serious threat to areal preservation (Schwimmer and Pizzuto, 2000; Leonardi and Fagherazzi, 2014; Leonardi et al., 2016).

Apart from hydrodynamics, salt marsh resilience has been linked to the sediment budget of the marsh complex as a whole, including not only the vegetated surfaces, but surrounding tidal flats, seabed, and tidal channels (Ganju et al., 2013; Fagherazzi, 2014). Ganju et al. (2017) synthesized sediment budgets of eight micro-tidal salt marsh complexes and demonstrated the existence of a relationship between sediment budget and the unvegetated-vegetated marsh ratio (UVVR), indicating that sediment deficits are linked to conversion of vegetated marsh into open water. A positive sediment budget is indeed necessary to allow marshes and tidal flats to keep pace with sea-level rise (Mariotti and Fagherazzi, 2010).

Regional effects are crucial when evaluating coastal interventions under the management of multiple agencies. Though many studies have focused on local marsh dynamics, less attention has been paid to how changes in marsh areal extent might drive large-scale variations of hydrodynamic and sediment transport processes (Donatelli et al., 2018a; Zhang et al., 2018). Donatelli et al. (2018b) studied the influence of salt marsh deterioration on the sediment budget in Barnegat Bay–Little Egg Harbor estuary (New Jersey, USA) and showed the existence of a positive feedback between marsh erosion and the decrease in the trapping efficiency of the marsh and the whole tidal system.

We conducted a meta-analysis of high-resolution numerical modeling results for the hydrodynamics and sediment transport of six back-barrier estuaries along the United States Atlantic Coast, extending the results presented in Donatelli et al. (2018b) to five other systems. The sediment dynamics of these bays were simulated under different scenarios of salt marsh loss obtained by artificially changing the present-day bathymetries. The erosion of salt marshes was simulated by removing vegetation from the eroded marsh cells, and by matching the corresponding bathymetry values with the elevation of the surrounding tidal flats (Donatelli et al., 2018b). The Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) modeling system (Warner et al., 2010) and the computational fluid mechanics package Delft3D (https://oss.deltares.nl/web/delft3d; Lesser et al., 2004) were used to carry out a set of exploratory models (Murray, 2007; Zhou et al., 2017). The study sites are listed in Table 1, and the present-day salt marsh area is highlighted

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TABLE 1. STUDY SITES AND ASSOCIATED DATA

System	Location		Marsh/basin area ratio	Average water depth (m)	Mean tidal range (m)	Marsh elevation, MSL (m)	Tidal prism (m^3)	Numerical model
Plum Island Sound (PI), Massachusetts	42°45′N	70°47′W	0.6	3	2.6	0.4	6.4×10^7	Delft3D
Great South Bay (GSB), New York	40°68′N	73°11′W	0.16	1.2	0.25	0.45	5×10^8	COAWST
Jamaica Bay (JB),New York	40°60′N	73°87′W	0.07	4	1.5	0.35	1.4×10^8	COAWST
Barnegat Bay–Little Egg Harbor (BB-LEH), New Jersey	39°86′N	74°11′W	0.25	1.5	0.4	0.55	3.3×10^8	COAWST
Chincoteague Bay (CB), Maryland	38°02′N	75°30′W	0.13	1.4	0.25	0.25	2.1×10^8	COAWST
Virginia Coast Reserve (VCR), Virginia	37°41′N	75°68′W	0.32	1.35	1.2	0.4	7.8×10^8	Delft3D

Note: MSL—mean sea level. Delft3D [Lesser et al., 2004] is used to carry out numerical simulations for Plum Island Sound and Virginia Coast Reserve. COAWST [Warner et al., 2010] is used to carry out numerical simulations for Great South Bay, Jamaica Bay, Barnegat Bay-Little Egg Harbor and Chincoteague Bay.

in Figure 1. Details of the model setup can be found in the Supplemental Material[1].

RESULTS

For each bay, five simulations were run with different marsh loss percentages: 0% (present-day salt marsh distribution), 25%, 50%, 75%, and 100% (vegetated area completely eroded). Salt marsh erosion alters tidal prism values (Fig. S8 in the Supplemental Material) and consequently the inlet morphology (D'Alpaos et al., 2010). The tidal signal also changes across different portions of the basins. A comparison of tidal amplitude and phase lag (delay of high tide peak within the bay with respect to high tide peak in the ocean) values between the pre- and post-erosion salt marsh configurations suggests that changes in tidal amplitude depend on the increased filling time of the back-barrier bay due to post-erosion increases in intertidal storage volume of the estuary. Indeed, tidal water levels in back-barrier basins are controlled by the ratio between inlet cross-sectional area and basin planform area (Keulegan, 1967). High ratios mean that tidal water levels in the back-barrier basin adjust quickly to offshore water level fluctuations, and therefore the phase lag between the ocean and the lagoon tidal wave is small.

For those systems where marshes mainly fringe the mainland and barrier island boundary (Plum Island Sound, Jamaica Bay, and Barnegat Bay–Little Egg Harbor in our study; Fig. 1), the tidal phase lag between the ocean and the lagoon increases, leading to a reduction in tidal amplitude over the entire back-barrier bay. In contrast, in Great South Bay, Chincoteague Bay, and Virginia Coast Reserve, large marsh portions are

[1]Supplemental Material. Model validation and supplementary figures. Please visit https://doi.org/10.1130/GEOL.S.12417530 to access the supplemental material, and contact editing@geosociety.org with any questions. Data input files are available in the following repository: https://doi.org/10.5281/zenodo.3797263.

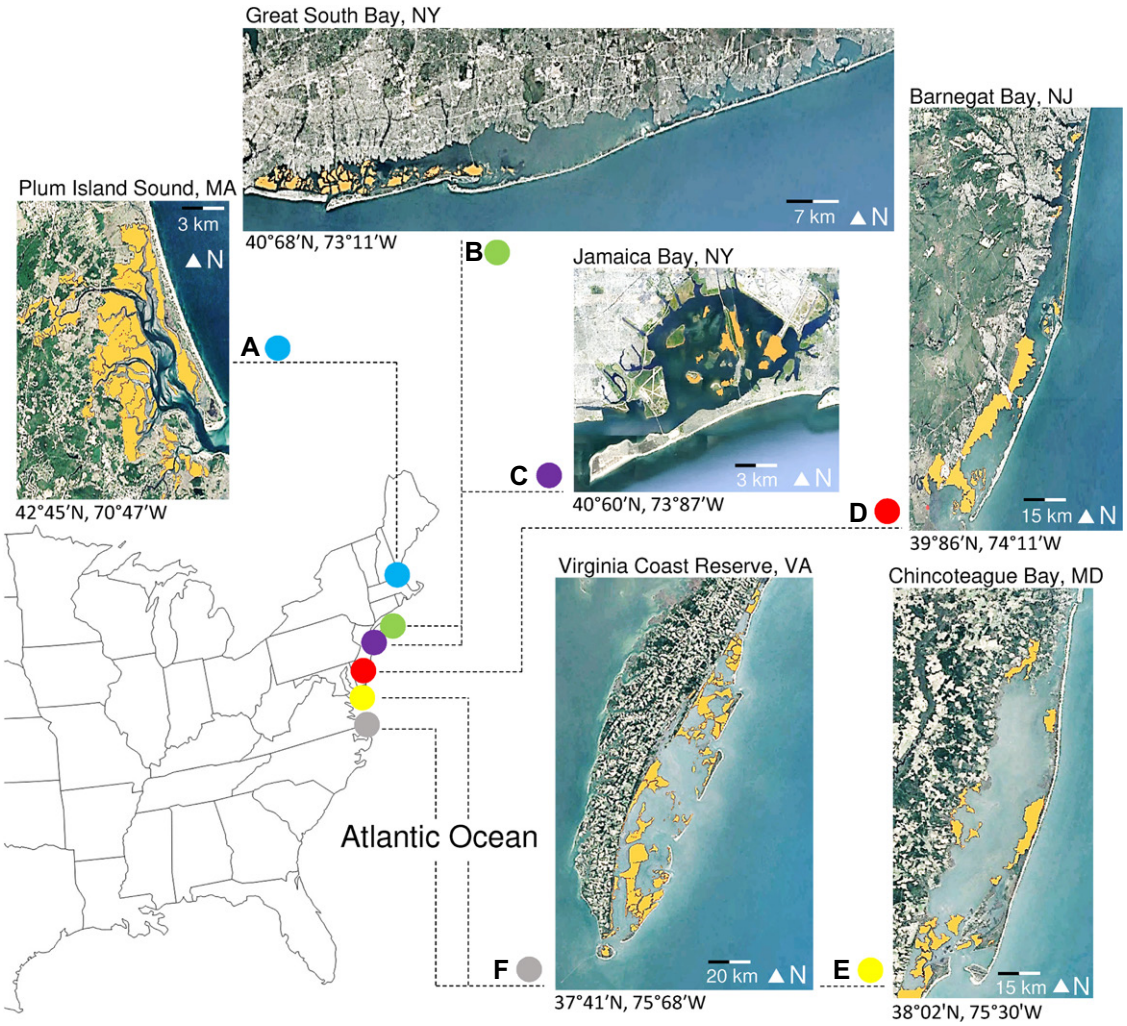

Figure 1. Satellite images of studied bays. All systems are located along Atlantic coast of United States: Plum Island Sound, Massachusetts (A); Great South Bay, New York (B); Jamaica Bay, New York (C); Barnegat Bay–Little Egg Harbor, New Jersey (D); Chincoteague Bay, Maryland (E); and Virginia Coast Reserve, Virginia (F). Satellite images were acquired from Google Earth™.

detached from the mainland, and different parts of the domain experience different variations in tidal amplitude. When salt marshes are detached from the mainland, the deterioration of the marshes produces an increase in tidal amplitude behind the eroded patches and a decrease in tidal amplitude between the eroded vegetated areas and the inlets. This suggests that locations near the mainland sheltered by marsh would be more affected by frictional reduction due to marsh disappearance than by the increase in filling time. The spatial distribution of tidal amplitude and phase lag before and after salt marsh removal for each bay are depicted in Figures 2A, 2B, 2E, and 2F (see also the Supplemental Material and Figs. S5F, S5G, S6F, S6G, S7F, S7G, S5O, and S5P).

We isolated the effect of salt marsh location from the effect of tidal wave interaction coming from multiple inlets by artificially transforming the estuaries into systems with a single entrance (Figs. S9–S11). For coastal bays with multiple inlets, water levels are controlled by overlapping waves propagating from each inlet, and changes in estuary morphology can alter their relative phase and amplitude. Additional simulations were conducted to verify that increases and decreases in tidal amplitude were caused by changes in salt marsh area rather than by the interference of multiple tidal constituents (Figs. S9–S11).

Salt marsh erosion also influences tidal asymmetry. Asymmetric tides are important for the transport and deposition of sediment in shallow estuaries (Aubrey and Speer, 1985; Gerkema, 2019). When asymmetry occurs, the distortion of the tidal wave is generally described by superposing a shorter-period overtide (M_4, shallow water overtide of principal lunar constituent) on the normal (M_2, lunar semidiurnal constituent) tidal shape. Changes in the M_4 to M_2 water-level amplitude ratio and the phase difference between M_4 and M_2 were calculated for each scenario. The relative phase shift is computed as $2\varphi_2 - \varphi_4$, where φ_2 is the M_2 phase and φ_4 is the M_4 phase, as per Friedrichs and Aubrey (1988). In this formulation, a relative phase between 0° and 180° means that the tidal wave has a shorter flood duration (flood dominance, stronger flood currents), while for a relative phase between 180° and 360°, the tidal wave has a shorter ebb duration (ebb dominance, stronger ebb currents). The maximum flood and ebb dominance occur for a relative phase of 90° and 270° respectively. For all test cases, the estuaries remained flood dominated, even though marsh loss raised the tendency toward ebb dominance in some systems (Figs. 2C, 2D, 2G, 2H; Figs. S13C, S13D, S13G, S13H, S14C, S14D, S14G, and S14H); the magnitude of the nonlinear distortion increases with marsh removal (Figs. S12, S13A, S13B, S13E, S13F, S14A, S14B, S14E, and S14). These results are consistent with previous one-dimensional numerical investigations (Friedrichs and Aubrey, 1988). Recent two-dimensional numerical studies suggest that these findings might be also depend on the choice of friction for small ratios of tidal amplitude to mean water depth (Zhou et al., 2018).

To quantitatively evaluate how changes in tidal dynamics impact the sediment budget of the systems, we quantified sediment trapping efficiency before and after the removal of the marsh. Sediment trapping was evaluated by releasing a fixed amount of sediment in the bay, and then computing the fraction stored in the marshes, tidal flats, and channels. We stopped the simulations after 30 d because the deposited volume did not change significantly after this period. The sediment deposit was sampled in the last day of simulation. Results are presented as a function of the ratio between marsh extent and basin area (Fig. 3). The fraction of sediment potentially stored in channels and tidal flats per unit area decreases exponentially as the ratio between marsh and basin area becomes smaller (Fig. 3A); similarly, the fraction of sediment per unit area trapped by salt marshes drops exponentially (Fig. 3B). Excluding Jamaica Bay, the exponential decay in sediment trapping as a function of marsh loss is relatively similar in each bay and close to the overall trend.

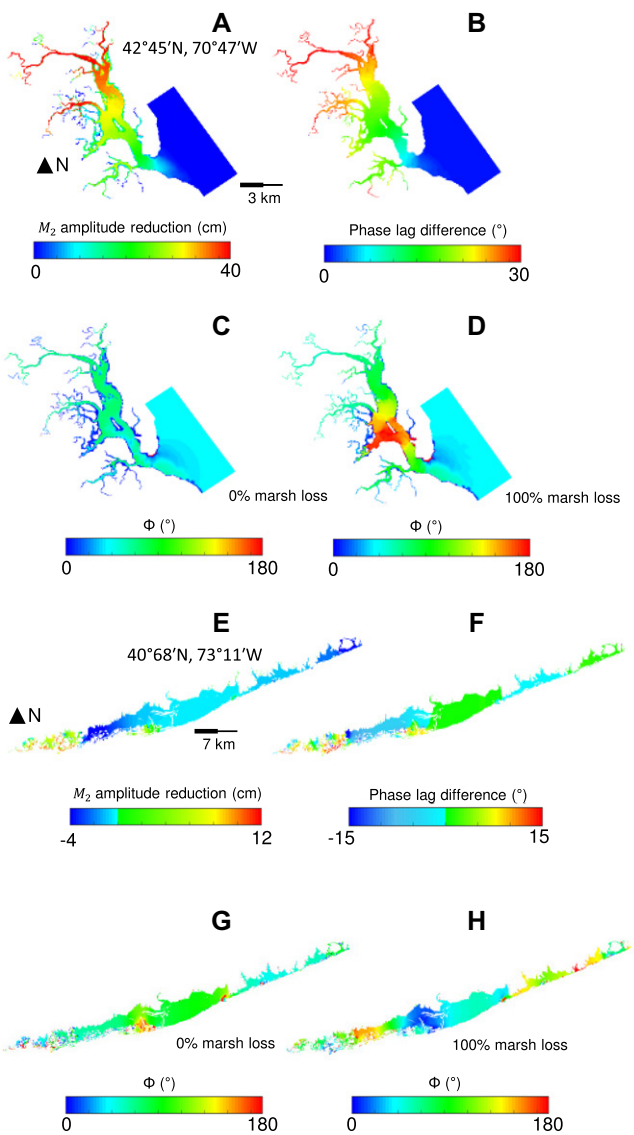

Figure 2. Changes in tidal dynamics induced by marsh loss in Plum Island Sound (Massachusetts; A–D) and Great South Bay (New York; E–H) on the Atlantic coast of the United States. Shown are the reduction in M_2 (lunar semidiurnal tidal constituent) amplitude and the increase in phase lag after removal of the entire marsh surface (A–B, E–F) and the sea-surface phase of M_4 (shallow water overtide of the principal lunar constituent) relative to M_2 (ϕ) for the current marsh distribution (C, G) and a marsh completely eroded (D, H).

DISCUSSION AND CONCLUSIONS

Our findings in relation to the sediment budget are relevant for the long-term resilience of the systems because the sediment budget is an integrated metric of ecosystem stability (Ganju et al., 2017). More specifically, our model results demonstrate that variations in marsh extent affect the sediment storage capacity of back-barrier estuaries in both vegetated and unvegetated areas. Here, we extend the results of Donatelli et al. (2018b) for Barnegat Bay–Little Egg Harbor estuary to the other five back-barrier bays, and we argue that the effect of marsh loss on the stability of the remaining salt marshes depends on the extent of the eroded marsh area with respect to the basin size. This study shows

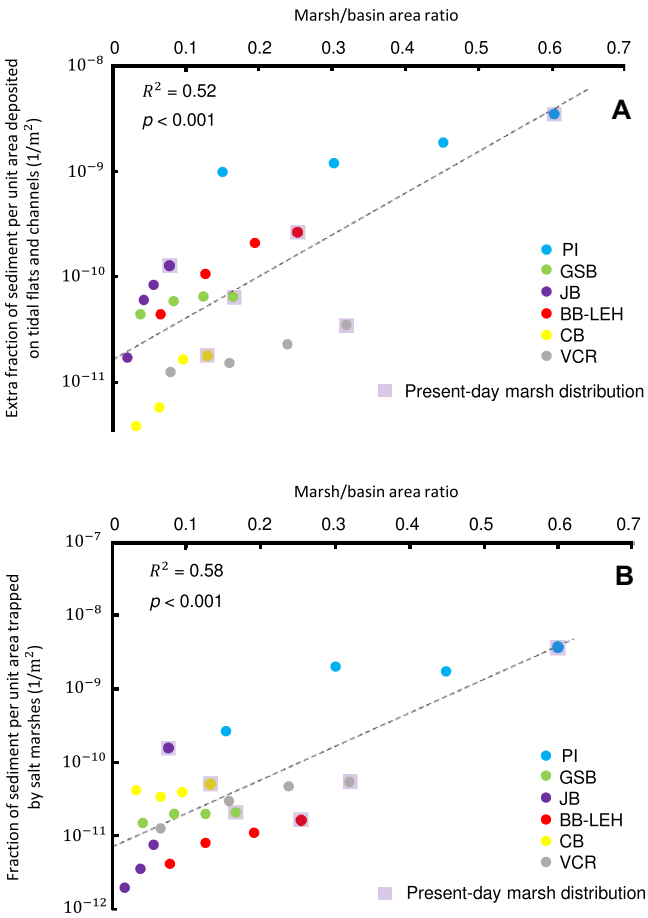

Figure 3. Effect of marsh extent on the ability of tidal flats, channels, and salt marshes to trap sediment inputs. (A) Fraction of sediment per unit area deposited on tidal flats and channels directly related to marsh presence as a function of marsh area normalized by basin area. Extra fraction of sediment is with respect to the case with salt marshes completely removed. (B) Fraction of sediment per unit area trapped on marshes as a function of normalized marsh area. Four values for each location are the four quartiles tested (0%, 25%, 50%, and 75%). See Table 1 for definitions of study area abbreviations.

that marsh resilience to negative stressors might be compromised even by small percentages of marsh lateral erosion, because the relationship between marsh areal extent and marsh sediment trapping capacity is strongly nonlinear. Changes in marsh extent due to erosion or restoration projects would cause changes in the amount of sediments trapped within the entire estuarine system. This might in turn promote further establishment or erosion of salt marshes. A decrease in salt marsh area causes a decrease in sediment trapping of the system, which could in turn promote further marsh deterioration. Given the assumption that the net sediment budget is the driving factor for marsh stability, the nonlinear relationship further suggests that any restoration project increasing salt marsh areas would trigger a positive feedback increasing sediment retention.

A shortcoming of this modeling framework is related to the choice to remove all of the sediments deriving from marsh erosion. In reality, the sediment generated by marsh deterioration could contribute to salt marsh survival (Mariotti and Carr, 2014), or might be distributed in the basin, modifying the hydrodynamic field and mitigating the sediment loss. Furthermore, the sediment injected into each system to evaluate the sediment stock after 30 d represents a fictitious input, and therefore we neglect that sediment released in the basin by rivers might be trapped with a different efficiency with respect to sediment coming from offshore.

Under scenarios of future sea-level rise, further tidal prism enlargements and additional fragmentation of the barrier islands might be expected, and these could potentially compromise the survival of entire lagoon ecosystems (Fitz Gerald et al., 2006). Even if increasing hydraulic depth would reinforce existing tidal asymmetries (Friedrichs et al., 1990) and enlarge the mean tidal range of the estuary, with insufficient sediment supply, the system would not be able to keep pace with sea-level rise. In the long term, a reduced sediment trapping capacity might also control the lateral extension of salt marshes. A simple model proposed by Mariotti and Fagherazzi (2013) shows that the ratio between marsh and open water area in a bay is controlled by sediment availability (and sediment concentration). Similarly, the long-term modeling framework of Walters et al. (2014) indicates that marsh extension in back-barrier areas is a function of sediment supply; more sediment flushing and less trapping would therefore lead to a reduced marsh extension in these models.

Our study highlights the efficacy of coastal restoration interventions, which should target coastal erosion before the vegetated surface becomes too small compared to the basin area in order to maximize the large-scale efficiency of the interventions. Our findings further show the necessity of accounting for the nonlinearity of ecosystem response to changes in habitat size. A simplified approach that assumes that ecosystem services provided by coastal habitats change linearly with their size would lead to a misrepresentation of the true economic value of salt marshes in terms of coastline resilience (Barbier, 2008).

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