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 deltarex.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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CITATION: Donatelli, C., et al., 2020. A nonlinear relationship between marsh size and sediment trapping capacity compromises salt marshes’ stability: Geology, v. 48, p. 966–970, https://doi.org/10.1130/G47131.1
 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

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

### 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 x 10^7       | Delft3D         |
| Great South Bay (GSB), New York             | 40°68'N 73°11'W | 0.16                   | 1.2                     | 0.25                 | 0.45                   | 5 x 10^6         | COAWST          |
| Jamaica Bay (JB), New York                  | 40°60'N 73°87'W | 0.07                   | 4                       | 1.5                  | 0.35                   | 1.4 x 10^6       | COAWST          |
| Barnegat Bay–Little Egg Harbor (BB-LEH), New Jersey | 39°38'N 74°11'W | 0.25                   | 1.5                     | 0.4                  | 0.55                   | 3.3 x 10^6       | COAWST          |
| Chincoteague Bay (CB), Maryland             | 38°02'N 75°30'W | 0.13                   | 1.4                     | 0.25                 | 0.25                   | 2.1 x 10^6       | COAWST          |
| Virginia Coast Reserve (VCR), Virginia      | 37°41'N 75°68'W | 0.22                   | 1.35                    | 1.2                  | 0.4                    | 7.8 x 10^6       | 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.

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### 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.
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 overlap ping 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 \( M_2 \) shallow water overtide of principal lunar constituent) on the normal \( M_2 \), lunar semidiurnal constituent) tidal shape. Changes in the \( M_2 \) to \( M_4 \) water-level amplitude ratio and the phase difference between \( M_2 \) and \( M_4 \) were calculated for each scenario. The relative phase shift is computed as \( 2\phi_2 - \phi_4 \), where \( \phi_2 \) is the \( M_2 \) phase and \( \phi_4 \) 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 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.

**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...
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).

ACKNOWLEDGMENTS

Support was provided by the U.S. Department of the Interior Hurricane Sandy Recovery program G16AC00455 and associated award to the University of Liverpool (UK). Zhang and Fagherazzi were also funded by U.S. National Science Foundation awards 1832221 (Virginia Coast Reserve Long-Term Ecological Research [VCR LTER]) and 1637630 (Plum Island LTER) and the China Scholarship Council (201606140044). We thank the editor, Philip Orton, and two anonymous reviewers for critical revision of the manuscript.

REFERENCES CITED

Barbier, D.G., and Speer, P.E., 1985. A study of nonlinear tidal propagation in shallow inlet estuarine systems, Part I: Observations: Estuarine, Coastal and Shelf Science, v. 21, p. 185–205, https://doi.org/10.1016/0272-7714(85)90096-4.

Barbier, E.B., 2008, Ecosystems as natural assets: Foundations and Trends in Microeconomics, v. 4, p. 611–681, https://doi.org/10.1561/0700000031.

Costanza, R., et al., 1997, The value of the world’s ecosystem services and natural capital: Nature, v. 387, p. 253–260, https://doi.org/10.1038/387253a0.

Costanza, R., Pérez-Maquéo, O., Martín, M.L., Sutton, P., Anderson, S.J., and Mulder, K., 2008, The value of coastal wetlands for hurricane protection: Ambio, v. 37, p. 241–248, https://doi.org/10.1579/0044-7447(2008)37[241:VOCWFO]2.0.CO;2.

Donatelli, C., Ganju, N.K., Fagherazzi, S., and Leonard, N., 2018a, Seagrass impact on sediment exchange between tidal flats and salt marsh, and the sediment budget of shallow bays: Geophysical Research Letters, v. 45, p. 4933–4943, https://doi.org/10.1029/2018GL078056.

Donatelli, C., Ganju, N.K., Zhang, X., Fagherazzi, S., and Leonard, N., 2018b, Salt marsh loss affects tides and the sediment budget of shallow bays: Journal of Geophysical Research: Earth Surface, v. 123, p. 2647–2662, https://doi.org/10.1029/2018JF004617.

Fagherazzi, S., 2014, Storm-proofing with marshes: Nature Geoscience, v. 7, p. 701–702, https://doi.org/10.1038/NGEO2262.

Fitz Gerald, D.M., Buynevich, I., and Argow, B., 2006, Model of tidal inlet and barrier island dynamics in a regime of accelerated sea-level rise: Journal of Coastal Research, Special Issue 39, p. 789–795.

Foster, N.M., Hudson, M.D., Bray, S., and Nicholls, R.J., 2013, Intertidal mudflat and salt marsh conservation and sustainable use in the UK: A review: Journal of Environmental Management, v. 126, p. 96–104, https://doi.org/10.1016/j.jenvman.2013.04.015.

Friedrichs, C.T., and Aubrey, D.G., 1988, Non-linear tidal distortion in shallow well-mixed estuaries:
A synthesis: Estuarine, Coastal and Shelf Science, v. 27, p. 521–545, https://doi.org/10.1016/0272-7714(88)90082-0.
Friedrichs, C.T., Aubrey, D.G., and Speer, P.E., 1990, Impacts of relative sea-level rise on evolution of shallow estuaries, in Cheng, R.T., ed., Residual Currents and Long-Term Transport: American Geophysical Union Coastal and Estuarine Studies 38, p. 105–122.
Ganju, N.K., Nidzieko, N.J., and Kirwan, M.L., 2013, Inferring tidal wetland stability from channel sediment fluxes: Observations and a conceptual model, Journal of Geophysical Research: Earth Surface, v. 118, p. 2045–2058, https://doi.org/10.1002/jgrf.20143.
Ganju, N.K., Defne, Z., Kirwan, M.L., Fagherazzi, S., D’Alpaos, A., and Carniello, L., 2017, Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes: Nature Communications, v. 8, 14156, https://doi.org/10.1038/ncomms14156.
Gerkema, T., 2019, An Introduction to Tides: Cambridge, UK, Cambridge University Press, 214 p., https://doi.org/10.1017/9781316998879.
Keulegan, G.H., 1967, Tidal flow in entrances: Water-level fluctuations in basins in communication with seas: U.S. Army Corps of Engineers Committee on Tidal Hydraulics Technical Bulletin 14, 100 p.
Leonardi, N., and Fagherazzi, S., 2014, How waves shape salt marshes: Geology, v. 42, p. 887–890, https://doi.org/10.1130/G35751.1.
Leonardi, N., Ganju, N.K., and Fagherazzi, S., 2016, A linear relationship between wave power and erosion determines salt-marin resilience to violent storms and hurricanes: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 64–68, https://doi.org/10.1073/pnas.1510095112.
Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N.K., Plater, A.J., Schuerm, M., and Temmerman, S., 2017, Dynamic interactions between coastal storms and salt marshes: A review: Geomorphology, v. 301, p. 92–107, https://doi.org/10.1016/j.geomorph.2017.11.001.
Lesser, G.R., Roelvink, J.A., van Kester, J.A.T.M., and Stelling, G.S., 2004, Development and validation of a three-dimensional morphological model: Coastal Engineering, v. 51, p. 883–915, https://doi.org/10.1016/j.coasteng.2004.07.014.
Mariotti, G., and Carr, J., 2014, Dual role of salt marsh retreat: Long-term loss and short-term resilience: Water Resources Research, v. 50, p. 2963–2974, https://doi.org/10.1002/2013WR014676.
Mariotti, G., and Fagherazzi, S., 2010, A numerical model for the coupled long-term evolution of salt marshes and tidal flats: Journal of Geophysical Research, v. 115, F01004, https://doi.org/10.1029/2009JF001326.
Mariotti, G., and Fagherazzi, S., 2013, Critical width of tidal flats triggers marsh collapse in the absence of sea-level rise: Proceedings of the National Academy of Sciences of the United States of America, v. 110, p. 5353–5356, https://doi.org/10.1073/pnas.1219600110.
Murray, A.B., 2007, Reducing model complexity for explanation and prediction: Geomorphology, v. 90, p. 178–191, https://doi.org/10.1016/j.geomorph.2006.10.020.
Schuerm, M., et al., 2018, Future response of global coastal wetlands to sea-level rise: Nature, v. 561, p. 231–234, https://doi.org/10.1038/s41586-018-0476-5.
Schwimmer, R.A., and Pizzuto, J.E., 2000, A model for the evolution of marsh shorelines: Journal of Sedimentary Research, v. 70, p. 1026–1035, https://doi.org/10.1306/030400701026.
Spencer, T., Schuerm, M., Nicholls, R.J., Hinkel, J., Lincke, D., Vafeidis, A.T., Reef, R., McFadden, L., and Brown, S., 2016, Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model: Global and Planetary Change, v. 139, p. 15–30, https://doi.org/10.1016/j.gloplacha.2015.12.018.
Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., and De Vriend, H.J., 2013, Ecosystem-based coastal defence in the face of global change: Nature, v. 504, p. 79–83, https://doi.org/10.1038/nature12859.
Walters, D., Moore, L.J., Duran Vinient, O., Fagherazzi, S., and Mariotti, G., 2014, Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: Insights from a coupled model: Journal of Geophysical Research: Earth Surface, v. 119, p. 2013–2031, https://doi.org/10.1002/2014JF003091.
Warner, J.C., Armstrong, B., He, R., and Zambon, J.B., 2010, Development of a Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) Modeling System: Ocean Modeling, v. 35, p. 230–244, https://doi.org/10.1016/j.omc.2010.07.010.
Zhang, X., Fagherazzi, S., Leonardi, N., and Li, J., 2018, A positive feedback between sediment deposition and tidal prism may affect the morphodynamic evolution of tidal deltas: Journal of Geophysical Research: Earth Surface, v. 123, p. 2767–2783, https://doi.org/10.1002/2018JF004639.
Zhou, Z., et al., 2017, Is “morphodynamic equilibrium” an oxymoron?: Earth-Science Reviews, v. 165, p. 257–267, https://doi.org/10.1016/j.earscirev.2016.12.002.
Zhou, Z., Chen, L.Y., Townend, I., Coco, G., Friedrichs, C., and Zhang, C.K., 2018, Revisiting the relationship between tidal asymmetry and basin morphology: A comparison between 1D and 2D models: Journal of Coastal Research, Special Issue 85, p. 151–155.

Printed in USA