AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL078056

Key Points:
- Seagrass loss increases bay-wide sediment concentrations
- Influence of seagrass decline on sediment budget in shallow bays
- Seagrass impact on sediment exchange between tidal flats and salt marsh

Supporting Information:
- Supporting Information S1

Correspondence to:
C. Donatelli,
carmine@liverpool.ac.uk

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

Received 27 MAR 2018
Accepted 24 APR 2018
Accepted article online 30 APR 2018
Published online 20 MAY 2018

Seagrass Impact on Sediment Exchange Between Tidal Flats and Salt Marsh, and The Sediment Budget of Shallow Bays

Carmine Donatelli[1], Neil Kamal Ganju[2], Sergio Fagherazzi[3], and Nicoletta Leonardi[1]

[1]Department of Geography and Planning, School of Environmental Sciences, Faculty of Science and Engineering, University of Liverpool, Liverpool, UK, [2]Woods Hole Coastal and Marine Science Center, U.S. Geological Survey, Woods Hole, MA, USA, [3]Department of Earth Sciences, Boston University, Boston, MA, USA

Abstract Seagrasses are marine flowering plants that strongly impact their physical and biological surroundings and are therefore frequently referred to as ecological engineers. The effect of seagrasses on coastal bay resilience and sediment transport dynamics is understudied. Here we use six historical maps of seagrass distribution in Barnegat Bay, USA, to investigate the role of these vegetated surfaces on the sediment storage capacity of shallow bays. Analyses are carried out by means of the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) numerical modeling framework. Results show that a decline in the extent of seagrass meadows reduces the sediment mass potentially stored within bay systems. The presence of seagrass reduces shear stress values across the entire bay, including unvegetated areas, and promotes sediment deposition on tidal flats. On the other hand, the presence of seagrasses decreases suspended sediment concentrations, which in turn reduces the delivery of sediment to marsh platforms. Results highlight the relevance of seagrasses for the long-term survival of coastal ecosystems, and the complex dynamics regulating the interaction between subtidal and intertidal landscapes.

Plain Language Summary Seagrasses influence the resilience of coastal wetlands to external agents, such as sea level rise, by altering the velocity field and sediment transport dynamics of coastal environments. In many areas worldwide seagrass habitats are declining. This paper studies how seagrasses influence the sediment budget of shallow bays using a computer model, and Barnegat Bay, New Jersey, as test case. Specifically, we used computer models to simulate velocity and sediment transport dynamics in Barnegat Bay with historical seagrass maps for the period 1968–2009. These maps show that for Barnegat Bay seagrasses have decreased in time. We found that seagrasses are important for the retention of sediments within bay systems, and when seagrasses are present less sediments are lost in the ocean, which is relevant for the long-term survival of coastal wetlands as an abundance of sediments generally corresponds to more resilient wetlands. The presence of seagrasses mainly increases the storage of sediments on tidal flats, while it decreases the delivery of sediments to the marsh platforms during high tide. Our results highlight the importance of seagrasses and are relevant for coastal communities and coastal managers worldwide as they could aid the design of coastal protection schemes.

1. Introduction

Seagrasses are marine flowering plants that provide important ecosystem services such as sediment stabilization, nutrient cycling, organic carbon production and export, and enhanced biodiversity (Koch, 2001; Moriarty & Boon, 1989; Waycott et al., 2009). Seagrasses act as ecological engineers, modifying the physical and ecological environment to promote their growth and reduce mortality. For instance, by reducing bed shear stress and sediment resuspension, seagrasses increase light penetration, and indirectly stimulate their own biomass production. By stabilizing sediments, seagrasses enhance their survival rate during extreme storm conditions (Cardoso et al., 2004; Madsen et al., 2001; Terrados & Duarte, 2000). The influence of seagrasses on suspended sediment concentrations (SSCs) can significantly vary during the year and can be maximum during summer; in fall and spring, SSC values over vegetated beds are similar, while during the winter SSCs within the less dense meadows can be higher as the finer particles settled during summer get easily resuspended (Hansen & Reidenbach, 2013).

Seagrasses are sensitive to external agents and can decline as a consequence of multiple stressors including eutrophication, overfishing, overgrazing, and temperature stress. Many studies have documented a decline in the extent of seagrasses for many areas worldwide (Cambridge et al., 1986; Campbell & McKenzie, 2004; Cardoso et al., 2004; Daby, 2003; Gonzalez et al., 2005; Hughes et al., 2004; Morris & Viknstein, 2004; Orth et al., 2006; Polte et al., 2005; Short & Burdick, 1996; Waycott et al., 2005). Seagrasses also impact system morphology due to their capacity to hold sediments and favor deposition (Ganthy et al., 2013; Harlin et al., 1982; Potouroglou et al., 2017). For instance, Ganthy et al. (2013) studied sediment transport dynamics in tidal flats in the Arcachon lagoon, measured centimeter-scale accretion rates over seagrass meadow, and found that these were correlated with seasonal growth rates. They found that during growth periods, particle trapping dominates, leading to accretion, while during senescence periods, erosion occurs, but less than in unvegetated areas. Massive seagrass losses have also been documented after storms and cyclones as a consequence of meadow uprooting, and burial caused by increased sediment loads (Koch, 1999; Preen et al., 1995).

Sediment convergence and divergence, and the ensuing erosional and depositional patterns, are largely influenced by changes in the velocity field as a consequence of flow deflection, and increased friction across seagrass meadows (Fonseca et al., 1982; Koch et al., 2006; Peterson et al., 2004). Large horizontal velocity gradients are generally present between the unvegetated seabed and vegetated meadows, and the vertical velocity profile presents significant discontinuities at the interface between the water column occupied by the meadow and the free flow over it (e.g., Gambi et al., 1990; Koch, 2001). The impact of submerged canopies on the hydrodynamic of surrounding bare beds has been documented in previous studies; for instance, within the context of patchy vegetation, it has been shown that a decrease in shear stress is observable before and after vegetation patches and that the aerial extent of the bare beds affected by vegetation depends on stem density (e.g., Souliotis & Prinos, 2011).

Numerous studies have investigated the role of submerged vegetation on hydrodynamics and sediment transport; however, many of these studies solely focus on vegetation-flow interactions at small scales and in uniform field and laboratory conditions (Dijkstra & Uittenbogaard, 2010; Nepf, 2012).

The role of seagrasses has rarely been quantified at the basin scale, or in terms of the estuary-wide sediment budget (Ganthy et al., 2013; Ward et al., 1984). In this manuscript we use a numerical model to investigate how variations in seagrass meadow coverage and density influence sediment trapping across an entire back-barrier estuary, and the exchange of sediments between marsh platforms and tidal flats.

Six historical seagrass coverage maps of Barnegat Bay Little-Egg Harbor Estuary for the period 1968–2009 have been used in combination with the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system (Warner et al., 2010), and associated flow-vegetation module (Beudin et al., 2016). To the best of our knowledge, there is a lack of studies presenting results about the impact of seagrasses on sediment transport dynamics at a decadal time scale and through the combined use of numerical models and multiple years' seagrass maps.

Results demonstrate that seagrasses can significantly impact the sediment budget of coastal environments, and also influence the dynamics between salt marshes and tidal flats. For instance, the presence of seagrass increases the storage of sediments within the bay but also reduces the amount of sediments in suspension decreasing thus the delivery of sediments to marsh platforms.

2. Study Site

The Barnegat Bay-Little Harbor Estuary is a shallow lagoon-type estuary located along the east coast of New Jersey, USA, between 39°41′N and 39°56′N latitude and 74°04′W and 74°12′W longitude. The system is a long and narrow water body extending approximately 70 km in the north-south direction. The lagoon is composed by three shallow bays (Barnegat Bay, Manahawkin Bay, and Little Egg Harbor) and is connected to the ocean through two inlets (Little Egg Inlet and Barnegat Inlet) and the Point Pleasant Canal. The total basin area is around 280 km^2 with a maximum depth of 5 m, mean depth of 1.5 m, and width ranging from 2.0 to 6.5 km (Hunchak-Kariouk, 1999). The composition of the seabed is a mixture of sand, silt, shells, and organic matter (Rogers, Golden and Halpern, 1990). Tides are mainly semidiurnal, with the M2 harmonic being the dominant constituent. The tidal range in the ocean is over 1 m, but the tidal signal within the

Bay is damped through the inlets and the range within the bay reduces to a minimum of 15–20 cm (Aretxabaleta et al., 2014). In Barnegat Bay-Little Harbor Estuary, the submerged aquatic vegetation (SAV) is characterized by two main species: *Zostera marina* and *Ruppia maritima*. As showed by recent studies (Bologna et al., 2000), the seagrass coverage has decreased by 62% over the last several decades; the central and northern parts of the bay have been the most affected by this decline (Lathrop & Bognar, 2001). The total loss can be estimated as 2,000–3,000 ha in 30 years (from 1960 to 1990). The main causes of the seagrass decline are related to the shading effect of phytoplankton blooms, increased growth of epiphytic algae, and wasting disease (Bologna et al., 2000; Kennish, 2001; Kennish, Bricker, et al., 2007).

The bathymetry of the model used in this study is based on the National Ocean Hydrographic Survey data (National Oceanic and Atmospheric Administration National Ocean Service, 2012) updated with field measurements (Miselis et al., 2012). Bathymetric data were collected by using a SWATHplus-H interferometric sonar, operating at a frequency of 468 kHz, with ±1 cm accuracy (Andrews et al., 2016). Since the 1940s there have been negligible bathymetric changes with exception of areas near the jetty (Defne & Ganju, 2014) and even Hurricane Sandy did not alter estuary's bathymetry (Miselis et al., 2015). The bathymetry of the study area and historical seagrass coverages are illustrated in Figure 1, with Figure 1h illustrating an idealized test case with no seagrass.

3. Methods

The hydrodynamics and sediment transport of the system have been simulated using the COAWST modeling framework (Warner et al., 2010). The ocean model used in COAWST is ROMS (Regional Ocean Modeling System), which currently incorporates a sediment transport module based on CSTMS (the Community Sediment Transport Modeling System; Shchepetkin & McWilliams, 2005; Warner et al., 2008). Details of model setup are presented in the supporting information.

For this study, one class of sediments is defined having a mass density of 2,650 kg/m^3, settling velocity of 0.5 mm/s, erodibility and critical shear stress equal to 0.0005 $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$, and 0.05 N/m^2, respectively; values were chosen based on sediment characteristics typical of a coastal embayment (Fagherazzi et al., 2013). The seabed is defined as one layer having an initial thickness of zero. The time frame of the analysis is 30 days. As initial condition, a uniform SSC is imposed for each water cell inside the bay; specifically, the sediment injection occurs at mean sea level, and during the first flood period. Three different initial SSCs have been tested, that is, 50, 100, and 200 mg/L. As the initial sediment thickness at the bottom is zero, sediment transport, as well as erosive or depositional fluxes, is solely related to the concentration imposed at the beginning of the simulation.

The flow-vegetation interaction is computed using the vegetation module recently implemented in COAWST (Beudin et al., 2016). The flow-vegetation module includes plant posture-dependent three-dimensional drag, in-canopy wave-induced streaming, and production of turbulent kinetic energy and enstrophy for the vertical mixing parameterization; the spatially averaged vegetation drag force is approximated using a quadratic drag law, and the effect of plant flexibility on drag is computed using the approach of Luhar and Nepf (2011). Apart from the mean flow velocity, vegetation also significantly impacts turbulence intensity and mixing. The selected turbulence model is the k-ε scheme, which accounts for extra dissipation and turbulence kinetic energy production due to vegetation (Uittenbogaard, 2003). The vertical discontinuity of the drag across the canopy interface generates turbulent shear stress, which peaks near the top of the seagrass (Ghisalberti & Nepf, 2002, 2006; Nepf et al., 2007), and provides efficient exchange between the canopy and the overlying flow. This effect is explicitly accounted in the k-ε model by expressing eddy viscosity and Reynolds stresses as a function of velocity variations along the vertical; the model calculates the velocity profile assuming extraction of momentum by the canopy, which is then fed into the turbulence model (Beudin et al., 2016).

Seagrass meadows in the model are defined as sparse (251 shoots/m^2), moderate (600 shoots/m^2), or dense (900 shoots/m^2), nominally selected using Kennish et al. (2013) for guidance. Seagrass canopy height is set equal to 20 cm. For salt marshes, canopy height is 50 cm, and stem density is equal to 248 stems/m^2 (U.S. Department of Agriculture, 2008). The typical mass density and Young's modulus of the seagrass *Zostera marina* vary in the range 700–900 kg/m^3 (Abdelrhman, 2007; Fonseca, 1998; Fonseca et al., 2007) and 0.4–2.4 GPa

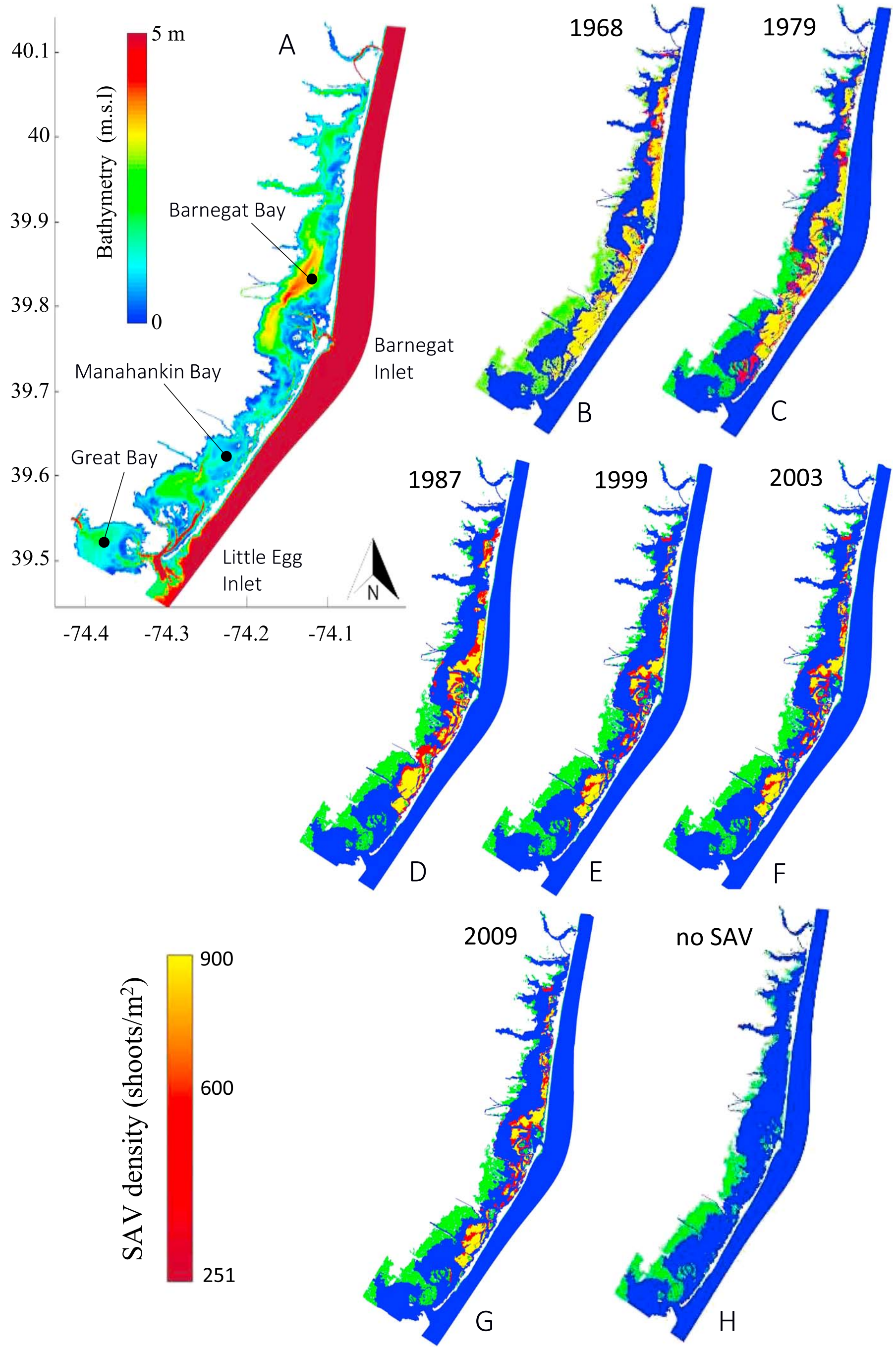

Figure 1. (a) Bathymetry and (b–g) seagrass coverages for different years, that is, 1968, 1979, 1987, 1999, 2003 and 2009; (h) base-case: no-SAV . For panels b–h the green areas are locations where salt marshes are present. The yellow to red shading indicates areas where seagrasses are present as sparse moderate or dense.

(Bradley & Houser, 2009), respectively. These values can also be used for *Spartina alerniflora* (Feagin et al., 2011). Therefore, mass density and elastic modulus are set equal to 700 kg/m^3 and 1 KN/mm^2, respectively. The dynamic frontal area is set equal to 1 cm, and the drag coefficient is set to 1. Salt marsh and seagrass coverage data came from the CRSSA's (Center for Remote Sensing and Spatial Analysis) geographic information systems database. Simulations are run implementing different seagrass distributions corresponding to the years 1968, 1979, 1987, 1999, 2003, and 2009, and for a test case where the meadow is completely

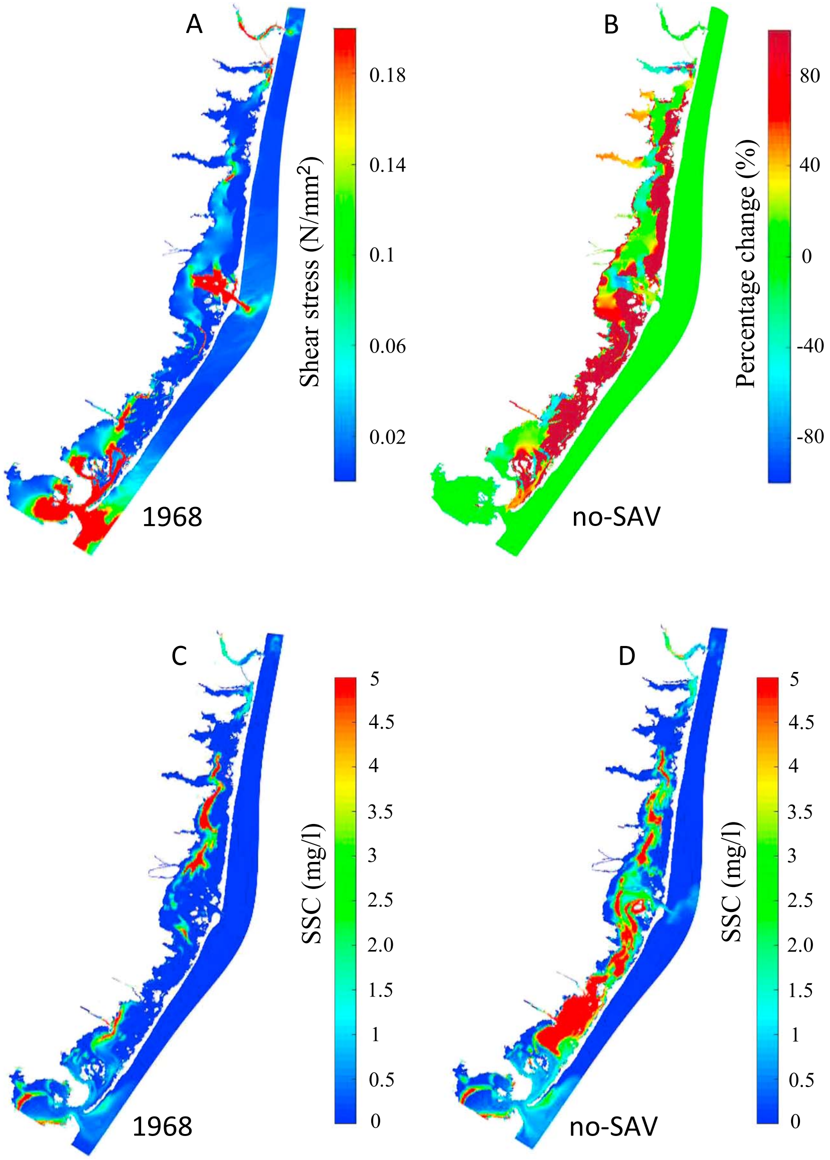

Figure 2. (a) Average shear stresses (Pa) at spring tide for the 1968 seagrass distribution case and (b) percentage change in shear stress after removal of the seagrass (no-SAV test case); average suspended sediment concentration (mg/L) during spring tide and after 27 simulated days for the (c) 1968 seagrass distribution case and for the (d) no-SAV test case.

removed (1968 map, U.S. Army Corps of Engineers, 1976; 1979 map, Macomber and Allen, 1979; 1987 map, Joseph et al., 1992; 1999 map, McClain and McHale, 1996; Bologna et al., 2000; and 2003 and 2009 maps, Lathrop and Haag, 2011).

4. Results

From 1968 until 2009, the extent of seagrass meadows within the Barnegat Bay-Little Egg Harbor system largely declined (Figures 1 and S1). The presence of seagrass decreases bed shear stress (Figures 2a and 2b), and SSCs (Figures 2c and 2d) across the entire bay, as demonstrated by the comparison between the 1968 and no-seagrass model results. In the presence of seagrass (Figures 2a and 2b), flow velocity decreases over the meadows, which in turn leads to lower SSCs in the water column and limited resuspension (Figures 2c and 2d). Changes in SSCs are observed across the entire bay. Numerical results show that seagrasses affect SSCs across 52% of the bare beds (Figures 2c and 2d), even if changes are more dramatic for previously

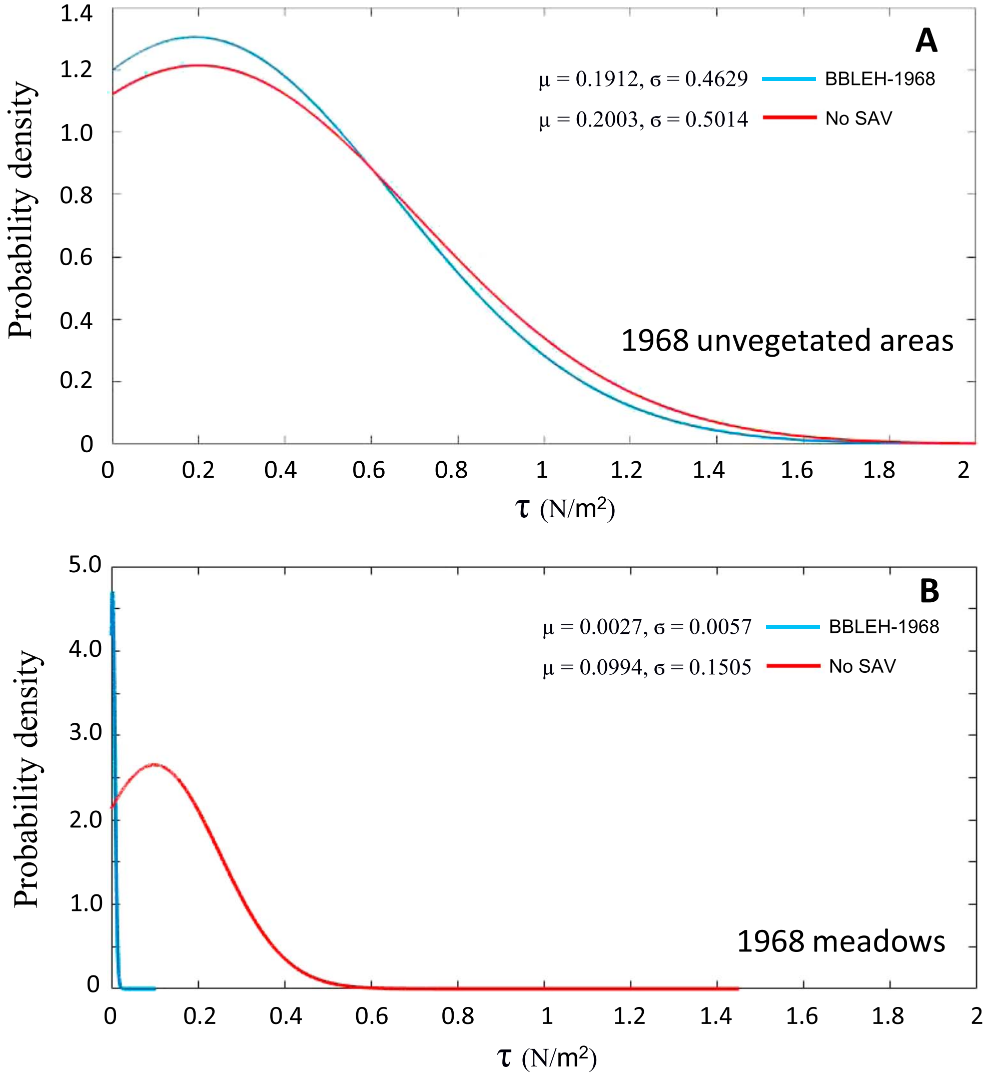

Figure 3. Probability density functions of average shear stress values (Pa) during spring tide given the 1968 seagrass distribution (blue lines), and for the test case with no seagrasses (red lines); the probability density functions refer to (a) areas with no seagrass in 1968 and (b) areas with seagrass in 1968.

vegetated beds (which for the 1968, constitute 31% of the entire estuary area) and nearby areas. Differences in the probability density function of bed shear stresses between the 1968 and the no-seagrass test case further highlight this trend (Figure 3). Specifically, as the seagrass is removed the mean shear stress increases for both unvegetated (Figure 3a) and vegetated areas (Figure 3b), even if differences in previously vegetated areas are more evident (Figure 3b). The probability distribution functions of shear stress within bare beds are slightly shifted, as the friction exerted by vegetation reduces the flow velocity next to the meadows as well. This effect also depends on plant density and tends to decrease for less dense meadows (Figure S4). To quantitatively evaluate the impact of seagrasses on the sediment budget, a series of simulations were conducted to relate changes in the extent of meadows with the amount of sediments stored within the bay after 30 days, given the same input concentration and sediment distribution. A uniformly distributed input sediment concentration represents potential riverine inputs during flood conditions, or large resuspension events during storms; such situations are the major contributors of inorganic sediments to salt marsh systems (e.g., Fagherazzi & Priestas, 2010; Falcini et al., 2012; Leonardi et al., 2016, 2017). The total sediment mass can be stored within the estuary in one of the following reservoirs: (i) suspended sediment in the water column, (ii) deposits on the bay seafloor, and (iii) deposits on the marsh platform. Suspended sediments are considered as a contribution to the sediment budget of the system because, even if not yet deposited, remain available for the potential storage on the seafloor and on the marsh platforms. Results are presented as a function of the ratio between vegetated seabed and basin area following the seagrass maps for the 1968–2009 period (Figure 4).

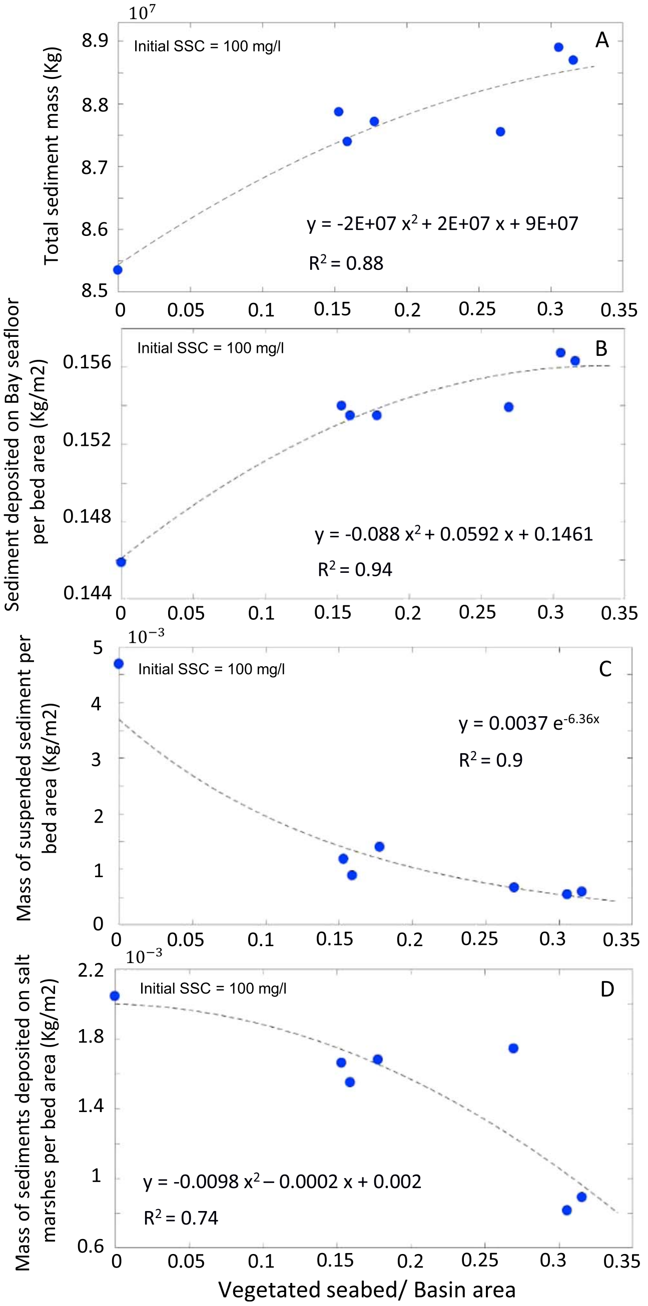

Figure 4. (a) Total sediment mass within the lagoon, mass of sediments per unit area: (b) deposited on the seafloor within the bay, (c) in suspension, and (d) deposited on salt marsh platforms. Data are presented after 30 simulated days, and as a function of the vegetated bed/basin area ratios obtained from the maps of Figure 1 and corresponding to different years.

Given the same sediment input, the total sediment mass stored within the bay increases as the area occupied by seagrasses increases (Figures 4a and S5). A time series of the decline in the total amount of suspended sediment within the bay system is provided in Figure S2, which also shows that 30 simulation days are sufficient to reach equilibrium conditions. Going into more detail, seagrasses mostly influence the deposition of sediment on the seafloor (Figures 4b, S6a, and S7a); however, the presence of seagrasses also reduces the sediment mass in suspension (Figures 4c, S6b, and S7b), and deposited on the marsh platform (Figures 4d, S6c, and S7c).

5. Discussion and Conclusions

Numerous studies have investigated the role of seagrasses as ecosystem engineers, and their contribution to the dissipation of flow energy (e.g., Duarte et al., 2013; Koch et al., 2006; Ondiviela et al., 2014). However, there is limited insight about the importance of seagrasses from a sediment storage point of view, and within the context of large-scale bay systems comprising salt marshes and unvegetated intertidal flats. The impact of SAV on the storage of sediments within enclosed bay systems is evaluated using the Barnegat Bay-Little Egg Harbor system as test case. The analyses are based on historical trends of seagrass distribution from 1968 to 2009; a scenario with no SAV is also included as a plausible system configuration in the near future (Figure S3).

In tidal landscapes, flow velocities are influenced by vegetation as plants exert a frictional effect and obstruct the flow (Temmerman et al., 2007). Our results also indicate that seagrasses are reducing flow velocity and bottom shear stresses within the canopy, in agreement with the field measurements of Hansen and Reidenbach (2012). While the presence of vegetation is generally associated with a decrease in flow velocity, in case of patchy emergent canopies, the deviation of the flow from vegetated to unvegetated areas can increase the shear stress, and erode the latter bare zones (Temmerman et al., 2007). Differently than for emergent canopies, our findings show that the presence of SAV lowers bottom shear stresses (Figures 2a and 2b) everywhere in the system, including unvegetated beds (Figure 3b), although flow concentrations are registered in small areas between meadows (Figure 2b). A comparison in terms of probability density function of the bed shear stress in bare beds shows that a reduction of the mean (from 0.2003 to 0.1912 N/m^2) and standard deviation (from 0.5014 to 0.4629 N/m^2) occurs when seagrasses are added to the model. Differences in shear stress across the bay between cases with and without seagrasses (e.g., 1968 compared to no-SAV test case) are significantly higher for areas that have transitioned from vegetated to unvegetated conditions (Figures 3 and S4).

Given an initial input of sediment, the presence of seagrasses promotes sediment storage within the bay, especially on the seabed. However, seagrasses also reduce the sediment mass in suspension, and the likelihood for sediments to be transported on marsh platforms during high tide. An increase in the areal extent of meadows reduces the deposited sediment mass on marsh platforms (Figure 4d). The areas experiencing the highest reduction in terms of deposition are salt marshes located in the proximity of seagrasses. Seagrasses also decrease the time that sediments remain in suspension (Figure S2), promoting a faster clearing of the water column and increasing the period of light availability for seagrass growth over the year (Carr et al., 2010). Conversely, as highlighted by our findings, the decline of seagrass meadows increases bay-wide sediment concentrations and therefore reduces light levels at the lagoon bottom. This causes a change from a state of favorable conditions for seagrass proliferation to a configuration with high water turbidity and light attenuation.

The influence of seagrasses on sediment trapping and on the erosive force of flowing water should be explored seasonally as seagrass aboveground biomass peaks during June–July and declines significantly during fall, when it becomes five times smaller (Farnsworth, 1998; Hansen & Reidenbach, 2013; Kennish, Haag, et al., 2007; Kennish et al., 2008; Koch et al., 2009). The lack of seasonal data in our study constitutes a significant gap in the understanding of how these ecosystems can affect erosion and sediment retention on a long-term basis. Furthermore, by using current salt marsh configurations, we are evaluating the impact of SAV under the worst-case scenario in terms of sediment budget. Indeed, as salt marshes migrate landward, the basin area and tidal prism increase, causing higher water exchanges with the ocean and higher sediment losses throughout a tidal cycle. Given that in Barnegat Bay salt marshes have been eroding, the decline in trapping capacity of the bay over the last decades could have been higher than the one predicted by our model due to the compound action of salt marsh erosion and seagrass decline.

These considerations are relevant considering that the survival of coastal wetlands depends on a delicate balance and interaction between processes regulating vertical and horizontal dynamics of the intertidal landscape. The survival of coastal wetlands has been interpreted as a sediment budget problem (e.g., Fagherazzi et al., 2013; Ganju et al., 2017); for instance, Ganju et al. (2017) synthesized the sediment budget of eight micro-tidal salt marsh complexes, demonstrating the link between sediment deficits and the conversion of salt marshes to open water. Apart from sediment availability, the ability of salt marshes to withstand different sea level rise values has been also related to the likelihood of sediments to be delivered on marsh surfaces during normal tidal conditions, as well as during storms (Kirwan et al., 2016; Schuerch et al., 2012). The mutual interaction between vegetated seagrass beds and salt marshes is thus complex, and incorporates processes promoting, or possibly obstructing the maintenance of salt marsh areas, that is, reduced delivery of sediments on the marsh surface under normal weather conditions. However, the increased deposition in front of marsh platforms in the presence of segrasses could (i) decrease tidal flats depth, which in turn decreases wind and current-induced shear stresses at the land interface; (ii) directly shelter marsh boundaries from erosive forces; and (iii) constitute an additional source of sediments that while not being resuspended during normal weather conditions, could be available for resuspension during storms, when surge occurrence can efficiently distribute sediments landward.

Acknowledgments
Data are available in the following repositories: Carmine, 2017a, 2017b, 2017c, and Carmine, 2018a, 2018b, 2018c, 2018d, 2018e, 2018f, 2018g, 2018h, 2018i, 2018j, 2018k, 2018l, 2018m, 2018n, 2018o, 2018p, 2018q, 2018r, 2018s, 2018t, 2018u. We thank the Editor, the two anonymous reviewers, and Julia M. Moriarty for critical revision of the manuscript.

References

Abdelrhman, M. A. (2007). Modeling coupling between eelgrass *Zostera marina* and water flow. *Marine Ecology Progress Series*, *338*, 81–96. https://doi.org/10.3354/meps338081

Andrews, B. D., Miselis, J. L., Danforth, W. W., Irwin, B. J., Worley, C. R., Bergeron, E. M., & Blackwood, D. S. (2016). Marine geophysical data collected in a shallow back-barrier estuary, Barnegat Bay, New Jersey (no. 937). US Geological Survey.

Aretxabaleta, A. L., Butman, B., & Ganju, N. K. (2014). Water level response in back-barrier bays unchanged following Hurricane Sandy. *Geophysical Research Letters*, *41*, 3163–3171. https://doi.org/10.1002/2014GL059957

Beudin, A., Kalra, T. S., Ganju, N. K., & Warner, J. C. (2016). Development of a coupled wave-flow vegetation interaction model. *Computers & Geosciences*, *100*, 76–86.

Bologna, P., Lathrop, R., Bowers, P., & Able, K. (2000). Assessment of submerged aquatic vegetation in Little Egg Harbor, New Jersey. Technical Report 2000–11, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

Bradley, K., & Houser, C. (2009). Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments. *Journal of Geophysical Research*, *114*, F01004. https://doi.org/10.1029/2007JF000951

Cambridge, M. L., Chiffings, A. W., Brittan, C., Moore, L., & McComb, A. J. (1986). The loss of seagrass in Cockburn Sound western Australia II: Possible causes of seagrass decline. *Aquatic Botany*, *24*(3), 269–285. https://doi.org/10.1016/0304-3770(86)90062-8

Campbell, S. J., & McKenzie, L. J. (2004). Flood related loss and recovery of intertidal seagrass meadows in southern Queensland, Australia. *Estuarine, Coastal and Shelf Science*, *60*(3), 477–490. https://doi.org/10.1016/j.ecss.2004.02.007

Cardoso, P. G., Pardal, M. A., Lillebo, A. I., Ferreira, S. M., Raffaelli, D., & Marques, J. C. (2004). Dynamic changes in seagrass assemblages under eutrophication and implications for recovery. *Journal of Experimental Marine Biology and Ecology*, *302*(2), 233–248. https://doi.org/10.1016/j.jembe.2003.10.014

Carr, J., D'Odorico, P. D., McGlathery, K., & Wiberg, P. (2010). Stability and bistability of seagrass ecosystems in shallow coastal lagoons: Role of feedbacks with sediment resuspension and light attenuation. *Journal of Geophysical Research*, *115*, G03011. https://doi.org/10.1029/2009JG001103

Daby, D. (2003). Effects of seagrass bed removal for tourism purposes in a Mauritian bay. *Environmental Pollution*, *125*(3), 313–324. https://doi.org/10.1016/S0269-7491(03)00125-8

Defne, Z., & Ganju, N. (2014). Quantifying the residence time and flushing characteristics of a shallow, back-barrier estuary: Application of hydrodynamic and particle tracking models. *Estuaries and Coasts*, *38*(5), 1719–1734. https://doi.org/10.1007/s12237-014-9885-3

Dijkstra, J., & Uittenbogaard, R. (2010). Modeling the interaction between flow and highly flexible aquatic vegetation. *Water Resources Research*, *46*, W12547.

Donatelli Carmine (2017a). bbleh_1968. https://doi.org/10.5281/zenodo.1133529

Donatelli Carmine (2017b). bbleh_1999. https://doi.org/10.5281/zenodo.1134239

Donatelli Carmine (2017c). no SAV. https://doi.org/10.5281/zenodo.1133987

Donatelli Carmine (2018a). bblehveg_c50. https://doi.org/10.5281/zenodo.1172994

Donatelli Carmine (2018b). bbleh_1968_c50. https://doi.org/10.5281/zenodo.1172589

Donatelli Carmine (2018c). bbleh_1968_c200. https://doi.org/10.5281/zenodo.1173037

Donatelli Carmine (2018d). bbleh_1968_251_run1. https://doi.org/10.5281/zenodo.1206007

Donatelli Carmine (2018e). bbleh_1968_600_run2. https://doi.org/10.5281/zenodo.1206009

Donatelli Carmine (2018f). bbleh_1968_900_run3. https://doi.org/10.5281/zenodo.1206013

Donatelli Carmine (2018g). bbleh_1979. https://doi.org/10.5281/zenodo.1137582

Donatelli Carmine (2018h). bbleh_1979_c50. https://doi.org/10.5281/zenodo.1172949

Donatelli Carmine (2018i). bbleh_1979_c200. https://doi.org/10.5281/zenodo.1173039

Donatelli Carmine (2018j). bbleh_1987. https://doi.org/10.5281/zenodo.1137801

Donatelli Carmine (2018k). bbleh_1987_c50. https://doi.org/10.5281/zenodo.1172951

Donatelli Carmine (2018l). bbleh_1987_c200. https://doi.org/10.5281/zenodo.1173041

Donatelli Carmine (2018m). bbleh_noSAV_c200. https://doi.org/10.5281/zenodo.1173051

Donatelli Carmine (2018n). bbleh_1999_c50. https://doi.org/10.5281/zenodo.1172953

Donatelli Carmine (2018o). bbleh_1999_c200. https://doi.org/10.5281/zenodo.1173047

Donatelli Carmine (2018p). bbleh_2003. https://doi.org/10.5281/zenodo.1134427

Donatelli Carmine (2018q). bbleh_2003_c50. https://doi.org/10.5281/zenodo.1172955

Donatelli Carmine (2018r). bbleh_2003_c200. https://doi.org/10.5281/zenodo.1173045

Donatelli Carmine (2018s). bbleh_2009. https://doi.org/10.5281/zenodo.1134588

Donatelli Carmine (2018t). bbleh_2009_c50. https://doi.org/10.5281/zenodo.1172992

Donatelli Carmine (2018u). bbleh_2009_c200. https://doi.org/10.5281/zenodo.1175835

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, *3*(11), 961–968. https://doi.org/10.1038/nclimate1970

Fagherazzi, S., & Priestas, A. M. (2010). Sediments and water fluxes in a muddy coastline: Interplay between waves and tidal channel hydrodynamics. *Earth Surface Processes and Landforms*, *35*(3), 284–293. https://doi.org/10.1002/esp.1909

Fagherazzi, S., Wiberg, P. L., Temmerman, S., Struyf, E., Zhao, Y., & Raymond, P. A. (2013). Fluxes of water, sediments, and biogeochemical compounds in salt marshes. *Ecological Processes*, *2*(1), 3.

Falcini, F., Khan, N. S., Macelloni, L., Horton, B. P., Lutken, C. B., McKee, K. L., et al. (2012). Linking the historic 2011 Mississippi River flood to coastal wetland sedimentation. *Nature Geoscience*, *5*(11), 803–807. https://doi.org/10.1038/ngeo1615

Farnsworth, E. (1998). Issues of spatial, taxonomic and temporal scale in delineating links between mangrove diversity and ecosystem function. *Global Ecology and Biogeography*, *7*(1), 15–25. https://doi.org/10.2307/2997694

Feagin, R. A., Irish, J. L., Möller, I., Williams, A. M., Colón-Rivera, R. J., & Mousavi, M. E. (2011). Short communication: Engineering properties of wetland plants with application to wave attenuation. *Coastal Engineering*, *58*(3), 251–255. https://doi.org/10.1016/j.coastaleng.2010.10.003

Fonseca, M. S. (1998). Exploring the basis of pattern expression in seagrass landscapes (PhD thesis). Berkeley: University of California.

Fonseca, M. S., Fisher, J. S., Zieman, J. C., & Thayer, G. W. (1982). Influence of the seagrass *Zostera marina* on current flow. *Estuarine, Coastal and Shelf Science*, *15*(4), 351–364. https://doi.org/10.1016/0272-7714(82)90046-4

Fonseca, M. S., Koehl, M. A. R., & Kopp, B. S. (2007). Biomechanical factors contributing to self-organization in seagrass landscapes. *Journal of Experimental Marine Biology and Ecology*, *340*(2), 227–246. https://doi.org/10.1016/j.jembe.2006.09.015

Gambi, M. C., Nowell, A. R. M., & Jumars, P. A. (1990). Flume observations on flow dynamics in *Zostera marina* eelgrass beds. *Marine Ecology Progress Series*, *61*, 159–169. https://doi.org/10.3354/meps061159

Ganju, N. K., Defne, Z., Kirwan, M. L., Fagherazzi, S., D'Alpaos, A., & Carniello, L. (2017). Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. *Nature Communications*, *8*, 14156.

Ganthy, F., Sottolichio, A., & Verney, R. (2013). Seasonal modification of tidal flat sediment dynamics by seagrass meadows of *Zostera noltii* (Bassin d'Arcachon, France). *Journal of Marine Systems*, *109–110*, S233–S240.

Ghisalberti, M., & Nepf, H. M. (2002). Mixing layers and coherent structures in vegetated aquatic flows. *Journal of Geophysical Research*, *107*(C2), 3011. https://doi.org/10.1029/2001JC000871

Ghisalberti, M., & Nepf, H. M. (2006). The structure of shear layers in flows over rigid and flexible canopies. *Environmental Fluid Mechanics*, *6*(3), 277–301. https://doi.org/10.1007/s10652-006-0002-4

Gonzalez, C. J. M., Bayle, J. T., Sanchez-Lizaso, J. L., Valle, C., Sanchez-Jerez, P., & Ruiz, J. M. (2005). Recovery of deep *Posidonia oceanica* meadows degraded by trawling. *Journal of Experimental Marine Biology and Ecology*, *320*(1), 65–76. https://doi.org/10.1016/j.jembe.2004.12.032

Hansen, J. C., & Reidenbach, M. A. (2012). Wave and tidally driven flows in eelgrass beds and their effect on sediment suspension. *Marine Ecology Progress Series*, *448*, 271–287. https://doi.org/10.3354/meps09225

Hansen, J. C., & Reidenbach, M. A. (2013). Seasonal growth and senescence of a *Zostera marina* seagrass meadow alters wave-dominated flow and sediment suspension within a coastal bay. *Estuaries and Coasts*, *36*(6), 1099–1114. https://doi.org/10.1007/s12237-013-9620-5

Harlin, M. M., Thorne-Miller, B., & Boothroyd, J. C. (1982). Seagrass-sediment dynamics of a flood-tidal delta in Rhode Island (USA). *Aquatic Botany*, *14*, 127–138.

Hughes, A. R., Bando, K. J., Rodriguez, L. F., & Williams, S. L. (2004). Relative effects of grazers and nutrients on seagrasses: A meta-analysis approach. *Marine Ecology Progress Series*, *282*, 87–99. https://doi.org/10.3354/meps282087

Hunchak-Kariouk, K. (1999). Relation of water quality to land use in the drainage basins of four tributaries to the Toms River, New Jersey, 1994--1995. No. PB-99-149098/XAB; USGS/WRI--99-4001. Geological Survey, Water Resources Div., West Trenton, NJ (United States); New Jersey Dept. Of Environmental Protection, Trenton, NJ (United States).

Joseph, J., Purdy, K., & Figley, B. (1992). *The influence of water depth and bottom sediment on the occurrence of eelgrass in Barnegat, Manahawkin and Little Egg Harbor bays*. Nacote Creek, NJ: Marine Fisheries Administration, New Jersey Department of Environmental Protection and Energy.

Kennish, M., Haag, S., & Sakowicz, G. (2008). Seagrass demographic and spatial habitat characterization in Little Egg Harbor, New Jersey, using fixed transects. *Journal of Coastal Research Special Issue*, *55*, 148–170.

Kennish, M. J. (2001). State of the estuary and watershed: An overview. *Journal of Coastal Research Special Issue*, *32*, 243–273.

Kennish, M. J., Bricker, S. B., Dennison, W. C., Glibert, P. M., Livingston, R. J., Moore, K. A., et al. (2007). Barnegat Bay-Little Egg Harbor Estuary: Case study of a highly eutrophic Coastal Bay system. *Ecological Applications*, *17*, S3–S16. https://doi.org/10.1890/05-0800.1

Kennish, M. J., Fertig, B. M., & Sakowicz, G. P. (2013). In situ Surveys of Seagrass Habitat in the Northern Segment of the Barnegat Bay-Little Egg Harbor Estuary: Eutrophication Assessment, Final report to the Barnegat Bay Partnership (bbp.ocean.edu/Reports/ 2011Northernseagrasssurvey. Pdf)

Kennish, M. J., Haag, S., & Sakowicz, G. (2007). Demographic investigation of SAV in the Barnegat Bay-Little Egg Harbor Estuary with assessment of potential impacts of benthic macroalgae and brown tides (Technical Report 107–15, 47). Institutes of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey. pp. 366.

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016). Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, *6*(3), 253–260. https://doi.org/10.1038/nclimate2909

Koch, E. W. (1999). Sediment resuspension in a shallow Thalassia testudinum banks ex König bed. *Aquatic Botany*, *65*(1-4), 269–280. https://doi.org/10.1016/S0304-3770(99)00045-5

Koch, E. W. (2001). Beyond light: Physical, geological, and geochemical parameters as possible submersed aquatic vegetation habit requirements. *Estuaries*, *24*(1), 17.

Koch, E. W., Barbier, E. B., Silliman, B. R., Reed, D. J., Perillo, G. M. E., Hacker, S. D., et al. (2009). Non-linearity in ecosystem services: Temporal and spatial variability in coastal protection. *Frontiers in Ecology and the Environment*, *7*(1), 29–37. https://doi.org/10.1890/080126

Koch, E. W., Sanford, L. P., Chen, S.-N., Shafer, D. J., & Smith, J. M. (2006). *Waves in seagrass systems: Review and technical recommendations*. Washington, DC: U.S. Army Corps of Engineers.

Lathrop, R. G. Jr., & Bognar, J. A. (2001). Habitat loss and alteration in the Barnegat Bay region. *Journal of Coastal Research*, 212–228. https://doi.org/10.2307/25736235

Lathrop, R. G., & Haag, S. (2011). Assessment of seagrass status in the Barnegat Bay-Little Egg Harbor Estuary: 2003 and 2009. CRSSA Technical Report#2011-01. Rutgers University, grant F. Walton Center for Remote Sensing and Spatial Analysis, New Brunswick, NJ.

Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N. K., Plater, A. J., Schuerch, M., & Temmerman, S. (2017). Dynamic interactions between coastal storms and salt marshes: A review. *Geomorphology*, *301*, 92–107.

Leonardi, N., Defne, Z., Ganju, N. K., & Fagherazzi, S. (2016). Salt marsh erosion rates and boundary features in a shallow bay. *Journal of Geophysical Research: Earth Surface*, *121*, 1861–1875. https://doi.org/10.1002/2016JF003975

Luhar, M., & Nepf, H. M. (2011). Flow-induced reconfiguration of buoyant and flexible aquatic vegetation drag. Adv. *Water Research*, *51*, 305–316.

Macomber, R. T., & Allen, D. (1979). *The New Jersey submerged aquatic vegetation distribution atlas final report*. Washington, DC: Earth Satellite Corporation.

Madsen, J. D., Chambers, P. A., James, W. F., Koch, E. W., & Westlake, D. F. (2001). The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*, *444*(1/3), 71–84. https://doi.org/10.1023/A:1017520800568

McCLain, P., & McHale, M. (1996). Barnegat Bay eelgrass investigations 1995–1996. In G. Flimlin & M. Kennish (Eds.), *Proceedings of the Barnegat Bay EcosystemWorkshop* (pp. 165–172). Toms River, New Jersey: Rutgers Cooperative Extension.

Miselis J., Andrews, B., Baker, R., Danforth, W., DePaul, V., Defne, Z., et al. (2012). Characterizing physical, chemical, and biological conditions and processes in the Barnegat Bay-Little Egg Harbor Estuary, New Jersey. 2012 Barnegat Bay Researchers Workshop, Bordentown Township, NJ.

Miselis, J. L., Andrews, B. D., Nicholson, R. S., Defne, Z., Ganju, N. K., & Navoy, A. (2015). Evolution of mid-Atlantic coastal and back-barrier estuary environments in response to a hurricane: Implications for barrier-estuary connectivity. *Estuaries and Coasts*, *39*(4), 916–934. https://doi.org/10.1007/s12237-015-0057-x

Moriarty, D. J. W., & Boon, P. I. (1989). Interactions of seagrass with sediment and water. In A. W. D. Larkum & S. A. Sheppard (Eds.), *Biology of Seagrasses* (pp. 500–535). Amsterdam: Elsevier.

Morris, L. J., & Viknstein, R. W. (2004). The demise and recovery of seagrass in the northern Indian River Lagoon, Florida. *Estuaries*, *27*(6), 915–922. https://doi.org/10.1007/BF02803418

Nepf, H. (2012). Flow and transport in regions with aquatic vegetation. *Annual Review of Fluid Mechanics*, *44*(1), 123–142. https://doi.org/10.1146/annurev-fluid-120710-101048

Nepf, H. M., Ghisalberti, M., White, B., & Murphy, E. (2007). Retention time and dispersion associated with submerged aquatic canopies. *Water Resources Research*, *43*, W04422. https://doi.org/10.1029/2006WR005362

National Oceanic and Atmospheric Administration National Ocean Service (2012). National Ocean Service Hydrographic Survey data, National Oceanic and Atmospheric Administration. Retrieved from http://www.ngdc.noaa.gov/mgg/bathymetry/hydo.html. Accessed 2012

Ondiviela, B., Losada, I. J., Lara, J. L., Maza, M., Galván, C., Bouma, T. J., & van Belzen, J. (2014). The role of seagrasses in coastal protection in a changing climate. *Coastal Engineering*, *87*, 158–168. https://doi.org/10.1016/j.coastaleng.2013.11.005doi:10.1016/j.coastaleng.2013.11.005

Orth, R. J., Luckenbach, M. L., Marion, S. R., Moore, K. A., & Wilcox, D. J. (2006). Seagrass recovery in the Delmarva Coastal Bays, USA. *Aquatic Botany*, *84*(1), 26–36. https://doi.org/10.1016/j.aquabot.2005.07.007

Peterson, C. H., Luettich, R. A., Micheli, F., & Skilleter, G. A. (2004). Attenuation of water flow inside seagrass canopies of differing structure. *Marine Ecology Progress Series*, *268*, 81–92. https://doi.org/10.3354/meps268081

Polte, P., Schanz, A., & Asmus, H. (2005). The contribution of seagrass beds (*Zostera noltii*) to the function of tidal flats as a juvenile habit for dominant, mobile epibenthos in the Wadden Sea. *Marine Biology*, *147*(3), 813–822. https://doi.org/10.1007/s00227-005-1583-z

Potouroglou, M., Bull, J. C., Krauss, K. W., Kennedy, H. A., Fusi, M., Daffonchio, D., et al. (2017). Measuring the role of seagrasses in regulating sediment surface elevation. *Scientific Reports*, *7*(1), 11917. https://doi.org/10.1038/s41598-017-12354-y

Preen, A. R., Long, W.-J. L., & Coles, R. G. (1995). Flood and cyclone related loss, and partial recovery, of more than 1000 km2 of seagrass in Hervey Bay. Queens-land, Australia. *Aquatic Botany*, *52*(1-2), 3–17. https://doi.org/10.1016/0304-3770(95)00491-H

Rogers, Golden and Halpern (1990). Profile of the Barnegat Bay. Final report for the Barnegat Bay Study Group, New Jersey Department of Environmental Protection and Energy, Trenton, New Jersey.

Schuerch, M., Rapaglia, J., Liebetrau, V., Vafeidis, A., & Reise, K. (2012). Salt marsh accretion and storm tide variation: An example from a Barrier Island in the North Sea. *Estuaries and Coasts*, *35*(2), 486–500. https://doi.org/10.1007/s12237-011-9461-z

Shchepetkin, A. F., & McWilliams, J. C. (2005). The Regional Ocean Modeling System: A split-explicit, free-surface, topography following coordinates ocean model. *Ocean Modelling*, *9*(4), 347–404. https://doi.org/10.1016/j.ocemod.2004.08.002

Short, F. T., & Burdick, D. B. (1996). Quantifying eelgrass habit loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. *Estuaries*, *19*(3), 730–739. https://doi.org/10.2307/1352532

Souliotis, D., & Prinos, P. (2011). Effect of a vegetation patch on turbulent channel flow. *Journal of Hydraulic Research*, *49*(2), 157–167. https://doi.org/10.1080/00221686.2011.557258

Temmerman, S., Bouma, T. J., Van de Koppel, J., Van der Wal, D., De Vries, M. B., & Herman, P. M. J. (2007). Vegetation causes channel erosion in a tidal landscape. *Geology*, *35*(7), 631–634. https://doi.org/10.1130/G23502A.1

Terrados, J., & Duarte, C. M. (2000). Experimental evidence of reduced particle resuspension within a seagrass (*Posidonia oceanica* L.) meadow. *Journal of Experimental Marine Biology and Ecology*, *243*(1), 45–53. https://doi.org/10.1016/S0022-0981(99)00110-0

U.S. Army Corps of Engineers (1976). Aquatic plant control project for the state of New Jersey: Design memorandum no. 1. Philadelphia District, Philadelphia, Pennsylvania.

U.S. Department of Agriculture (2008). Plants database. Natural Resources Conservation Service. Retrieved from http://plants.usda.gov

Uittenbogaard, R. (2003). Modelling turbulence in vegetated aquatic flows. International workshop on Riparian Forest vegetated channels: Hydraulic, morphological and ecological aspects, Trento, Italy, 20–22 February 2003.

Ward, L., Kemp, W., & Boyton, W. (1984). The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Marine Geology*, *59*(1-4), 85–103. https://doi.org/10.1016/0025-3227(84)90089-6

Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. (2010). Development of a coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system. *Ocean Modelling*, *35*(3), 230–244. https://doi.org/10.1016/j.ocemod.2010.07.010

Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C., & Arango, H. G. (2008). Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. *Computers and Geosciences*, *34*(10), 1284–1306. https://doi.org/10.1016/j.cageo.2008.02.012

Waycott, M., Duarte, C. M., Carruthers, T. J. B., Orth, R. J., Dennison, W. C., Olyarnik, S., et al. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(30), 12,377–12,381. https://doi.org/10.1073/pnas.0905620106

Waycott, M., Longstaff, B. J., & Mellors, J. (2005). Seagrass population dynamics and water quality in the Great Barrier Reef region: A review and future research directions. *Marine Pollution Bulletin*, *51*(1-4), 343–350. https://doi.org/10.1016/j.marpolbul.2005.01.017