

Shrinking Ecosystems: An Investigation into the Impact of Sea Level Rise on the Distribution of Coastal Marshes Situated on the Southern and Mid-Atlantic Coast of North America

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Abstract

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Coastal marshes are important habitats which provide many ecosystem services which benefit many, including acting as natural buffers to flooding and sea level rise and carbon sinks. These wetlands are dynamic and undergo various changes in characteristics as a response to changes in environmental conditions. This paper explores the impact that sea level rise has and continues to have on coastal marshes on the Southern Mid-Atlantic coast of North America. Coastal erosion and salt-water encroachment were two prominent drivers of change occurring in these ecosystems. The mechanisms of both aforementioned drivers are explained in the context of sea level rise and how they cause the fragmentation and redistribution of coastal marshes. Additionally, anthropogenic drivers of coastal change were considered, however, they were not the main focus of this paper. As many varying ecosystems continue to deteriorate, approach and even pass their tipping points, it is crucial to understand what contributes to the widespread observed change in characteristics such as their geographic extent.

Introduction

Coastal marshes cover around 40 million acres of the United States, with 81% situated in the southeast regions (U.S. Environmental Protection Agency, 2020). These are extremely complex and dynamic ecosystems, which support a wide range of species including migratory birds, fishes, vegetative, (Lang et al. 2024), and microbial species (Wilson et al. 2019). Additionally, coastal marshes provide several ecosystem services such as acting as natural buffers for communities subjected to flooding (Elsey-Quirk et al. 2022), as both vegetation and bathymetry of the marsh can dissipate wave energy and reduce wave height (Truong et al. 2015). Furthermore, coastal marshes are important sites of carbon storage, sequestering an estimated 53.65 Tg of carbon annually (Wang et al. 2020). One of the largest threats to these crucial habitats is amplified sea level rise due to climate change, causing widespread shifts in salt marsh distribution with the Southern Atlantic region experiencing 74,000 acres of wetland loss from 2009 to 2019 (Lang et al. 2024) (Figure 1). Mechanisms responsible for this change induced by sea-level rise include saltwater intrusion and coastal erosion, both of which are complex factors that can vary depending on the local environmental conditions. This paper aims to explore how the mechanisms of coastal erosion and changing salinity levels due to sea level rise act as drivers threatening coastal marshes through inducing fragmentation and changes in their distributions.

Coastal Erosion

Coastal erosion is one of the most influential drivers of changing marsh extent, with wave energy, swell, and wind fetch being the main contributor to erosion. Wave energy and power are strongly correlated with coastal marsh erosion rates (Schwimmer et al. 2001), with sediment breaking away from the bank as a result of the force generated from wave collisions (Marani et al. 2011). Therefore, they should be considered a strong contributor to changes in marsh distribution along shorelines. The following was found by Schwimmer et al. 2001; there are various mechanisms relating to wave action eroding marsh communities such converting the shoreline from its once relatively linear shape to one consisting of necks and clefts in the marsh (Figure 2). These necks in the marsh typically extend 3 meters with clefts experiencing elevated impacts of erosion, causing the eventual isolation and complete erosion of the resulting patches of marsh. Marshes can also be undercut by incoming waves, which results in the erosion of sediments underlying the marsh and produces overhangs of vegetation, up to 50 meters in length, which eventually collapses from the mainland.

Swell can be described as waves which are able to travel large distances from their wind source and upon interaction with the coast, can experience up to a 1.5 x increase in height (NOAA, 2023). Swell was found to fluctuate on a daily basis,

with energy changing based on proximity of storms and winds to a local area (Everett et al. 2017). This illustrates the strong variability in wave energy experienced by the coastal marsh. Wind fetch is another factor which can increase wave energy, defined as the distance wind can travel unobstructed over water (Rohweder et al. 2018). Losses in marsh extent can lead to increased wind fetch which in turn results in more loss in vegetation due to the increase in wind-generated wave size, and increased erosive forces present (Everett et al. 2017, Rohweder et al. 2018), illustrating a positive feedback loop. The synthesis of the concepts introduced above results in strong extents of erosion and induced fragmentation and redistribution of coastal marshes.

Saltwater Intrusion

Rising sea levels have caused an observed increase in the infiltration of saltwater into brackish and freshwater systems (Baldwin et al., 1998, Charles et al., 2018). Saltwater intrusion can be defined as the encroachment of marine water composed of numerous salt forming ions, and has been found to occur through groundwater upwelling, tide, and storm surges (Wilson et al., 2019). This encroachment causes changes in the salinity levels of local ecosystems, which can cause alterations in habitats and the species which reside in them (Elsley-Quirk et al., 2022, McIver et al. 2023, Mitchell et al. 2017). These impacts can be amplified if the marsh has experienced recent disturbance, with flooding and increased salinity found to decrease species richness (Bladwin et al. 1998). Elevated rates of saltwater encroachment were associated with an increased change of freshwater delivery (Meeder et al. 2017). Vegetative species were found to vary in response to saltwater intrusion, with some better suited for elevated salinity levels (Bladwin et al. 1998). Increased salinity levels were correlated with decreases in root productivity and biomass with values of 70% and 37% respectively, leading to more root breakdown (Charles et al. 2018). The same study found that increased salinity can drive a decrease in soil organic carbon storage in brackish marshes, with previously sequestered carbon being released into the water column. Another study found that carbon dioxide and methane efflux from the soil increased by 52% and 98% respectively (Wilson et al. 2019). Additionally, saline encroachment can result in increased phosphorus deposition, and while this was seen to increase aboveground biomass, it had no impact or decreased belowground biomass (Charles et al. 2018, Wilson et al. 2019). Phosphorous was found to increase both gross ecosystem productivity and net ecosystem productivity, indicative of possible amelioration of habitat conditions. However, soil structure was negatively impacted by the accompanied salinity (Wilson et al. 2019). This tradeoff is likely to have a net negative impact on these marshes in the long term, with the reduction

in belowground biomass and consequently root structure likely to cause increased fragmentation.

Changes in Marsh Extent in Chesapeake and Delaware Bays

Chesapeake Bay is one of the largest estuaries in the United States, consisting of numerous contributing sub-estuaries and supporting vast coastal marsh communities. There have been numerous studies illustrating the ways in which salinity and erosion have caused changes in the distribution of marsh extent over varying temporal periods in Chesapeake Bay and surrounding regions (Beckett et al. 2016, Elsey-Quirk et al. 2022, Hong et al. 2012, Mitchell et al. 2017). In addition to erosion and salinity changes, the region is also undergoing subsidence of around 4.1 mm/year (Beckett et al. 2016), resulting in possible amplification of these drivers related to sea-level rise. Models have shown that Chesapeake Bay is projected to experience increased saline content in its waters, with saltwater intrusion extending as far as 7 km up the bay (Hong et al. 2012), acting as a driver of changing marsh extent in the region.

The York River Estuary has experienced significant loss in marsh coverage, losing 2,187,000 m² of wetlands over 40 years (Figure 3). Most of this can be attributed to edge erosion by wave energy. Some marshes experienced a complete loss, commonly fringing systems near developed shorelines causing the fragmentation and eventual loss of the marsh habitat (Mitchell et al. 2017). Migration was also observed in marsh communities during this study, shifting landward often towards low lying adjacent areas where there were even observed gains in marsh extent. However, migration was not possible in regions with stabilized and developed shorelines, resulting in an effective coastal squeeze of the community and limitations to sediment deposition (Mitchell et al. 2017). The impact of coastal squeeze can be detrimental to functioning of these populations. There are other ways in which marshes can counteract sea-level rise.

While marshes are able to migrate towards more favourable conditions, they are dynamic systems which can vary in elevation depending on their sediment accretion rates. A salt marsh in the Nanticoke Estuary, a tributary to Chesapeake Bay, showed accretion rates of 8.6 +/- 0.9 mm/year. However, when compared to the rate of subsidence in the marsh (-9.8 +/- 6.9 mm /year) combined with sea level rise (~3 mm/year), this accretion is not sufficient to keep up with current rates of marsh loss (Beckett et al. 2016). To further expand this concept, it was found that accretion rates also depend on soil composition. Marshes which contained higher density soil with mineral sediments were more efficient at accumulating matter and were more effective at increasing marsh elevation

compared to those soils that consisted mainly of organic matter (Elsley-Quirk et al. 2022).

In Delaware Bay, erosion rates of 1 km over 40 years were observed, with coastal salt marshes experiencing greater loss compared to freshwater tidal marshes. More specifically decrease in marsh extent was seen most in high salinity salt marshes with large accumulation rates of dead belowground biomass (roots) (Elsley-Quirk et al. 2022), which could be attributed to the weakening of soil structure, and result in increased vulnerability to wave erosion. The inundation of marine water is expected to occur in many of the marshes included in this review, causing negative ecosystem responses such as reduced plant growth, substrate degradation, and consequently more erosion (Beckett et al., 2016). For these reasons, there has already been and will continue to be an observed change in the distribution of coastal marsh communities in many subestuaries within Chesapeake Bay and Delaware Bay. This outcome can be generalized for many coastal marshes across the mid to southern Atlantic region of the United States, as the mechanisms of this change are constant over large areas.

Fragmentation and Redistribution of Coastal Marshes

There has been a widespread increase in both fragmentation and redistribution observed among coastal marshes in response to increased erosion and saltwater intrusion due to sea-level rise. The fragmentation of coastal marshes causes the isolation and reduction of size of habitats for the plant and animal populations with which they support (Lang et al. 2024), effectively causing shifts in biodiversity (Mitchell et al. 2017). Along the Southern-Atlantic region, there was a net decrease of 31,000 acres of salt marsh, accompanied by the conversion of vegetated areas to marine deepwater habitats (65,000 acres) (Lang et al. 2024). Long term rates of shoreline change were found to range from -6.55 m/year to 0.39 m/year. (Smith et al. 2025). The same study found that 95% of marshes were migrating elsewhere, while the remaining 5% were subject to coastal squeeze due to industrial developments. Migration caused the conversion of around 8 km of upland habit to marshes, reducing marsh loss by 54%. Additionally, Smith et al. found that with every 1 km of marsh lost, there was a corresponding gain of 0.57 km in marsh coverage through upland migration from 1957-2022. While it is observed that marsh migration rates are somewhat able to offset loss due to erosion, the rates of habitat gain may not be sufficient to keep up with long-term sea-level rise. Increased salinity caused a loss of 0.8 cm of elevation and 47 g/m² of belowground biomass in brackish marshes (Charles et al. 2018). These two findings can result in increased fragmentation, with the combination of decreased

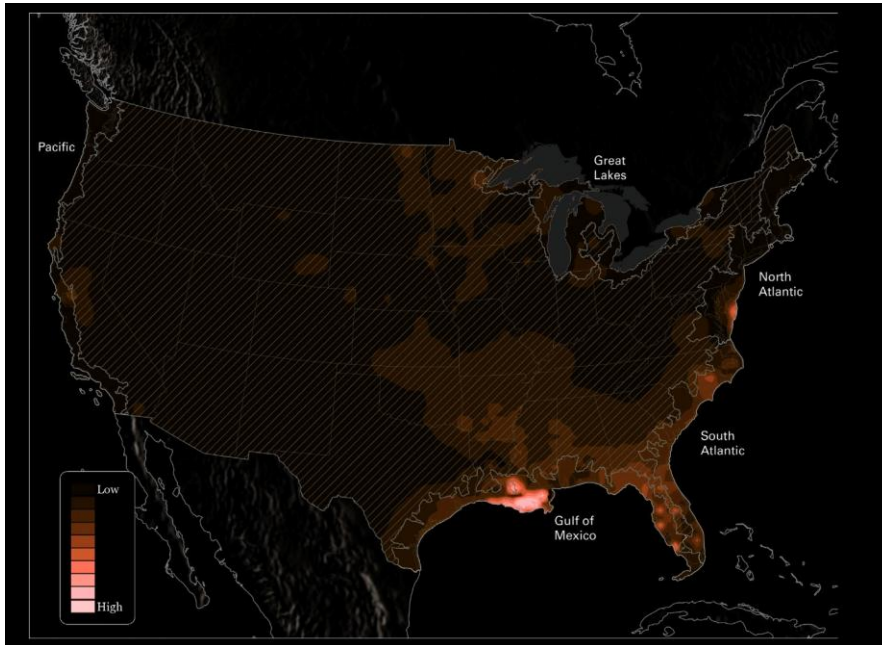
elevation and soil structure due to reduction in root biomass increasing the vulnerability of coastal marshes to erosion.

Conclusion

A review of relevant scientific literature has shown that coastal marshes are threatened by climate change, and sea-level rise is expected to drive changes in their distribution through coastal erosion and saltwater intrusion. There have been consistent results showing that drivers of erosion such as wave and swell energy show strong correlations with the loss of marsh coverage (Everett et al., 2017, Schwimmer et al. 2001). Additionally, increased marine water inundation was correlated with decreases in root productivity and biomass, net ecosystem productivity, soil structure, elevation, and storage of organic carbon (Charles et al. 2018, Baldwin et al. 1998, Wilson et al. 2019). These combined responses of coastal wetlands to increasing sea levels will lead to migration of communities to more favourable conditions. The fragmentation of coastal marsh ecosystems causes decreases in biodiversity and consequently ecosystem resilience (Mitchell et al. 2017), leading to the inability to counter the effects of sea level rise and the shrinking of habitats. Coastal marshes are also subject to anthropogenic stressors, further increasing fragmentation and redistribution (Smith et al. 2025). Mitchell et al. found that shorelines which have been more impacted by stabilization and hard structures exhibited increased levels of marsh loss compared to undisturbed marshes. Furthermore, Anthropogenic alterations of contributing watersheds can also have impacts on salinity levels within marshes, as diversion projects can decrease the freshwater delivery to marshes and lead to amplification of saltwater intrusion, decreasing the resiliency of the wetland (Charles et al. 2018). This increased saltwater intrusion has been linked to decreases in species richness, with remaining habitats favouring more salt-tolerant species (Baldwin et al. 1998).

While these results can be discouraging, there have been proposed mitigation strategies in order to reduce the impact of sea-level rise on these vulnerable ecosystems. For example, the addition of thin sediment layers which promote belowground plant productivity can increase resiliency to wave inundation, due to increased consolidation of soils (Elsey-Quirk et al. 2022). Additionally, restoration efforts to increase freshwater delivery to coastal marshes can provide increased resiliency to saltwater intrusion through stabilizing elevation change and increasing carbon sequestration, both results of increased root development (Charles et al. 2018). Conservation efforts such as the ones mentioned above are crucial and must be initiated immediately, with coastal marsh ecosystems rapidly approaching a tipping point in their ability to counter sea level rise. The passing of such a tipping point would result in widespread loss of these ecologically

important habitats and the services they provide, increasing vulnerability of surrounding ecosystems to sea-level rise and other climate change-induced threats.



Figures

Figure 1: Map showing relative density of net vegetative wetland decrease in the United States from 2009-2019 (Lang et al. 2024).

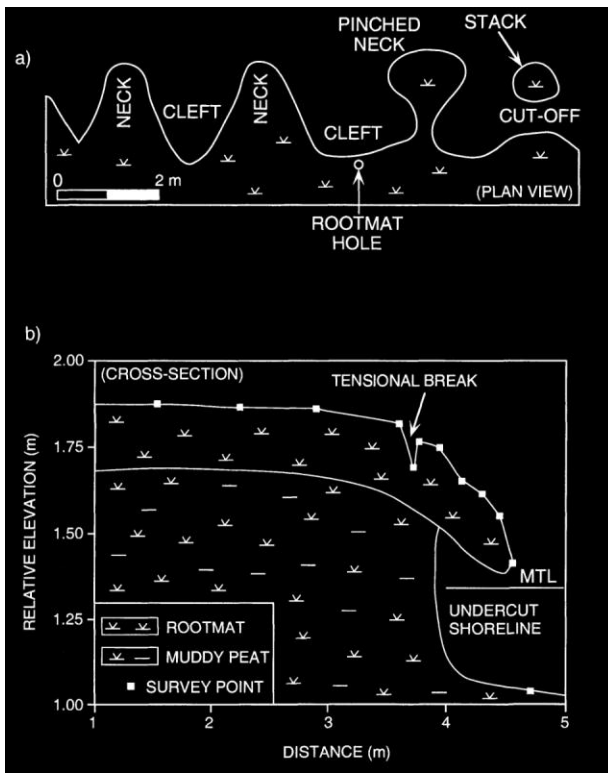


Figure 2: Illustration of mechanisms of coastal erosion due to wave energy (Schwimmer et al. 2001). a) depicts the formation of marsh clefts and necks due to erosion b) depicts the formation of overhangs because of wave action eroding the

extensive marsh. MTL: Estimated Mean Tide Level

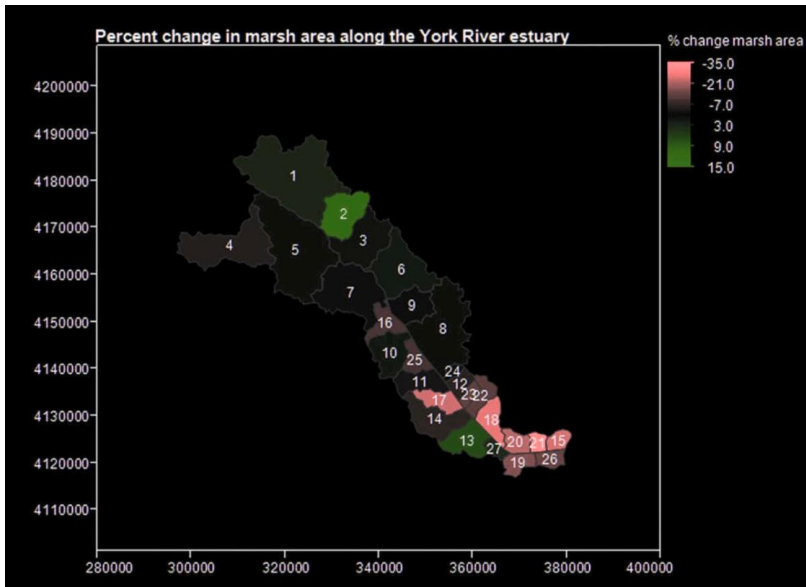


Figure 3: % change in marsh area by distance from the mouth of York River Estuary subwatersheds (numbered regions). Negative values represent marsh loss and positive values represent gain. X and Y coordinates are UTM eastings and northings (Mitchell et al. 2017).

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