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What controls marsh edge erosion?

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ABSTRACT

The survival of salt marshes depends on their ability to maintain vertical elevation and areal extent. In the lateral direction, marsh edges can expand laterally or undergo edge erosion through mass failure or continuous particle erosion through waves and tidal processes. In this study, we evaluate possible relationships between marsh shoreline type within the Great Marsh in Massachusetts and major geotechnical parameters along the marsh edge. We also explore if wave energy, using fetch as a proxy, affects the presence, type, and distribution of shoreline type. We mapped and classified the marsh into four categories: slumping, vertical and abrading, stable/accretionary, and bedrock or gravel, and sampled the marsh edge at 98 sites. Using over 450 measurements, we present typical ranges of values at these marsh edges for bulk density (0.10–1.43 g/cm^3), organic content (0.99–55.07%), belowground biomass (0.11–36.76%), and shear strength (4.04–136.49 kPa at 20 cm into the marsh bank, and 4.04–131.03 kPa at 40 cm into the bank). We show that there are no significant differences in fetch or geotechnical properties for the different marsh edge classes. Thus, none of these parameters explain or correlate with edge erosion, even though the majority of previous edge erosion studies focus on these parameters as determinants of edge erosion. We further emphasize the heterogeneity of the marsh, as edge erosion can occur in highly exposed or sheltered areas alike with no trends in geotechnical properties, and that complex interactions between parameters not generally studied may be responsible for edge erosion.

1. Introduction

Salt marshes are valuable ecosystems that sequester carbon (Duarte et al., 2013), protect the mainland from storms (Möller et al., 2014; Temmerman et al., 2013), exchange nutrients with the coastal ocean, and provide nursery grounds and habitat for fish and shellfish and other aquatic species (Barbier et al., 2011; Zedler and Kercher, 2005). They are dynamic systems that are constantly evolving vertically and laterally; in the lateral direction, marshes may retreat or expand onto tidal flats, changing their overall extent and morphology. Marsh retreat via edge erosion is a major contributor to marsh degradation and loss (Schwimmer, 2001; van de Koppel et al., 2005), and thus, reduction of key marsh ecosystem functions. Through the process of edge erosion material is removed from the marsh edge by continuous (particle by particle) erosion, and infrequent mass failures such as slumping (Bendoni et al., 2014; Francalanci et al., 2013). Previous studies have identified a number of factors directly impacting the edge, including local and storm wave climate (Day et al., 1998; Schwimmer, 2001; Marani et al., 2011; Leonardi et al., 2016b) vegetation characteristics and marsh bank geotechnical properties (van Eerdt, 1985; Feagin et al., 2009). Even though widespread marsh loss can occur without sea level rise (SLR) (Fagherazzi et al., 2013), rising water levels caused by climate change will increase edge erosion as water depths and wave heights increase (FitzGerald and Hughes, 2019).

Wave energy, and its effects on edge erosion, are impacted by tidal flat elevation and fetch (Möller et al., 2009; Mariotti and Fagherazzi, 2013). Along exposed, open-water marsh edges the incident wave energy is depth-limited, whereas in more protected inshore areas the wave energy is fetch-limited (Möller et al., 2009). McLoughlin et al. (2014) found that the relationship between wave energy and edge erosion rates in a microtidal salt marsh in Virginia, USA, was not significant for spatially-averaged shorelines, but did become significant when individual segments were considered. In addition, they found a relationship between marsh edge platform elevation and retreat rates. In Venice Lagoon, Italy, wave energy flux and edge erosion rates were correlated at the monthly time scale only when mass failure events were excluded, as these events are generally infrequent (Bendoni et al., 2016).

Wave erosion can create marsh edges with a vertical scarp morphology, but waves can also undercut the bank and exploit differences in bank strength caused by vegetation and rooting, creating overhangs that can slump into the channels and bays (Schwimmer, 2001). In microtidal settings, Tonelli et al. (2010) found that marsh edges located higher in the tidal range and infrequently submerged are less vulnerable to direct erosion through wave thrust. At these sites, edge erosion is caused mainly by bottom shear stresses undercutting the bank through ongoing erosion rather than removal of blocks (Tonelli et al., 2010). However, in the mesotidal Great Marsh spanning northern

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Massachusetts and southern New Hampshire, bank scarps are vertical and overhanging (cantilever) profiles are much less common. This morphology signifies that other processes dominate edge erosion.

Edge morphology can also reflect the rates of edge erosion and wave energy at a boundary. Leonardi et al. (2016a) showed that in Barnegat Bay, New Jersey, edge erosion rates are correlated with wave thrust, and that marsh edge morphology and the edge erosion rate are related. They showed that local heterogeneities affect the overall resistance of the edge to wave action, and lower rates of edge erosion result in irregular marsh edges. They also demonstrated that marsh edges experiencing low wave energy are most susceptible to infrequent, unpredictable failure from extreme events. Further, Leonardi et al. (2016b) identify, in fetch-limited, finite depth conditions, a linear relationship between relative wave energy and erosion. Additionally, they found that moderate storms are responsible for more edge erosion than large, infrequent storms. However, edge morphology may not reflect current edge erosion or instantaneous wave forcing; wave energy can create an unstable bank, but the edge may slump may not slump off until much later, even with low wave energy (Bendoni et al., 2016).

Whereas waves provide the energy to erode edges, vegetation and geotechnical properties of marsh edges control their strength and resistance to erosion (van Eerdt, 1985). Feagin et al. (2009) found that edge erosion of marshes in Galveston Bay are best predicted by bulk density, corroborating the findings of Bale et al. (2006) from marshes along the Tamar Estuary, UK. In contrast, Feagin et al. (2009) found no relationship between belowground biomass and edge erosion. Plant roots and rhizomes can directly modify the soil properties by incorporating detritus and finer-grained sediments through vertical accretion, making the soil finer, less dense, but stronger and more cohesive, thereby indirectly reducing edge erosion. Lab experiments have shown that the tensile strength of roots reduces the formation of tension cracks caused by tidal oscillation (Francalanci et al., 2013). In fact, although both vegetated and unvegetated banks can fail because of wave impact, the presence of vegetation can delay the occurrence of mass failures (Francalanci et al., 2013). Bendoni et al. (2016) found that the lower portion of the bank is more prone to erosion because of either roots in the upper part of the face increasing resistance to erosion or changes in water level impacting the wave field. Counterintuitively, this meant that vegetation did not always reduce the net edge erosion or the observed lateral retreat because the consequent cantilever profile promotes mass failure. However, these observations were made in the microtidal lagoon of Venice (Bendoni et al., 2016) and may not hold for a larger tidal range.

Mariotti and Fagherazzi (2010) determined through numerical modeling that a scarp between the marsh edge and tidal flats signals marsh retreat, and that vegetation characteristics such as biomass, belowground production, and sediment trapping determine the rate of lateral marsh accretion or retreat. However, vertical scarps (and slumping) can be observed in sheltered areas of marshes and in small creeks with minimal fetch. For example, although multiple studies find close relationships between edge erosion and wind waves (Leonardi and Fagherazzi, 2015), failure of large peat blocks has also been observed in low wave energy conditions such as along small to moderately sized creeks and in small bays (FitzGerald and Hughes, 2019; Leonardi and Fagherazzi, 2015). In fact, despite banks in most tidal channels showing some evidence of slump events and erosion, lateral retreat rates can be very small and are certainly not a sure sign of net marsh loss (Gabet, 1998; Mariotti et al., 2016; Redfield, 1972). Redfield (1972) also noted that even in places where marsh banks have eroded by slumping, sediment was often found accumulating at the base of the scarp, behind the slump block. This facilitated revegetation with *Spartina*, extending the marsh laterally and creating a cyclic behavior of erosion and recovery. If modern erosion rates translated to constant retreat rates throughout the life of a marsh, many marshes would have disappeared (FitzGerald and Hughes, 2019). It would seem that edge erosion only signifies retreat in highly exposed areas of open water, where wave energy can cause considerable marsh loss and vegetation cannot recolonize eroded edges. Few studies have addressed the fact that areas with very different physical processes exhibit similar geomorphology (scarped marsh edge with slumping). Several studies have looked at erosion in either open bays or small channels, but have not investigated patterns of edge erosion throughout an entire marsh (Leonardi et al., 2016a; Mariotti et al., 2016; Mariotti and Fagherazzi, 2013). Additionally, although there have been many investigations into marsh edge erosion and lateral retreat in tandem, few have investigated the drivers of edge erosion itself and its relationship with geomorphology. The objective of this study is to determine the relationships among marsh edge type, geotechnical properties of marsh edges, fetch, and how these factors are related to marsh edge erosion.

2. Methods

2.1. Physical setting

The Great Marsh in northern Massachusetts, USA, is an expansive marsh system containing several estuaries within Plum Island Sound, including the Rowley, Parker, and Ipswich rivers (Fig. 1). These back-barrier systems consist of broad open water areas with intertidal sandy shoals surrounded by large platform salt marsh systems that are dissected by tidal channels and drainage ditches. In the early seventeenth century, settlers began ditching and haying the marsh and farming livestock in the area, but grazing, haying, and ditching of the marsh declined by the 1930s (Holden et al., 2013).

The tides have a range from 2.6 to 2.8 m across the system. The average rate of relative SLR in this region is 2.9 mm/yr (Boston tidal gauge station 8443970, based on 1921–2019 record).

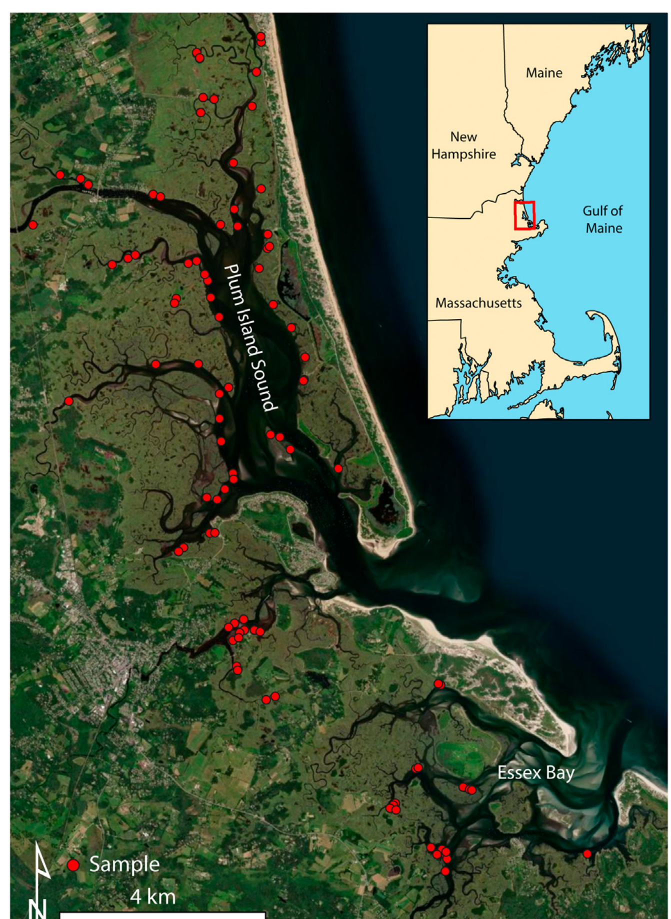

Fig. 1. Map of study site with locations of sampled marsh edge banks.

The prevailing winds are seasonal and come from the northerly quadrant from late fall through early spring switching to the southerly quadrant from late spring to early fall. Extratropical storms occur from late fall to early spring generating winds from the north-northeast and infrequently from the southwest (Portsmouth, NH station ID 44005, based on 1997–2006 data) (Fig. 2).

The Great Marsh comprises several relatively small estuaries with low suspended sediment input (Hopkinson et al., 2018). It has a north-south orientation and is fronted by Plum Island and Castle Neck barrier to the east, and a glaciated terrain to the west. The mean grain size distribution in the Great Marsh is approximately 24% sand, 58% silt, 17% clay (FitzGerald et al., 2020), with the majority of sand being very fine. This marsh system is dominated by high marsh environments vegetated by *Spartina patens* and *Distichlis spicata*, and smaller areas of low marsh dominated by *Spartina alterniflora*. Tall-form *S. alterniflora* lines the tidal creeks, and short-form *S. alterniflora* can be found on high marsh platforms in areas of poor drainage. In Plum Island Estuary, the low marsh platform lies between 0.2 and 1.2 m NAVD88 and occupies about 10% of the area, whereas the high marsh platform lies at elevations between 1.2 and 2 m NAVD88 and covers 75% of the area (Millette et al., 2010; Wilson et al., 2014). In Essex, low marsh sits between 0 and 1.1 m NAVD88 and high marsh between 1.1 and 1.7 m NAVD88 (based on our assessment of 2015 Lidar, comparing vegetation distribution to elevation). Studies in Plum Island Sound have observed and tracked edge erosion (Hopkinson et al., 2018), and modeling suggests shoreline erosion will increase because of accelerating SLR (Kirwan et al., 2010; McLoughlin et al., 2014) and increased storminess (Hayden and Hayden, 2003). This will be exacerbated by low suspended sediment input (Mariotti and Fagherazzi, 2013).

2.2. Marsh edge mapping

Shorelines throughout the Great Marsh were mapped in the field by foot at low tide and with a small-draft vessel during mid to lower tide levels. The boat was only used when the clarity of the water allowed the character of the edge to be confidently determined. The shoreline exhibits a range of morphologies similar to those described at other marshes (Francalanci et al., 2013; McLoughlin et al., 2014; Priestas et al., 2015; Bendoni et al., 2016), including vertical walls, sloping marsh edges that transition to muddy to sandy tidal flats, cantilevered edges, terraced edges, and shorelines containing gravel and bedrock exposures. The vertical edges can be divided into those that exhibit no evidence of erosion, occur in low-energy environments, and are commonly covered with a thick layer of algae. The second type can be further separated into those that have a fresh-looking face with no algae, and those that contain active slumping features including slump blocks, terracing, cracks and chasms in the adjacent marsh platform, and deteriorating peat blocks at the base of the marsh edge. Edge failure and slumping have been related to wave processes including undercutting (Schwimmer, 2001; Francalanci et al., 2013; Bendoni et al., 2014), and tensional forces (Schwimmer, 2001; Mariotti et al., 2016). Direct seasonal field observations indicate that vertical, clean (no algal covering) peat faces that exhibit no slumping features erode very slowly and likely through the dislodgement of particles by waves and tidal currents (Bendoni et al., 2016). Certain crab species such as *Uca pugnax* (fiddler crab) and *Sesarma reticulatum* (purple marsh crab) can contribute to edge erosion in some marsh systems by burrowing and resuspending sediment as well as herbivory (Wilson et al., 2012); however, in the Great Marsh green crabs have been historically dominant, and only recently were fiddler crabs documented, though they remain in low abundance (Johnson, 2014). We have been monitoring crab abundance, holes, and marsh erosion in this system since 2015 and have observed no relationships, suggesting that crabs do not impact sediment on the marsh face like in other marsh systems, but rather other mechanisms remove sediment. During winter, ice processes can also erode the marsh edge through sediment freezing to the ice, as well as ice-gouging during early thaw (Argow et al., 2011).

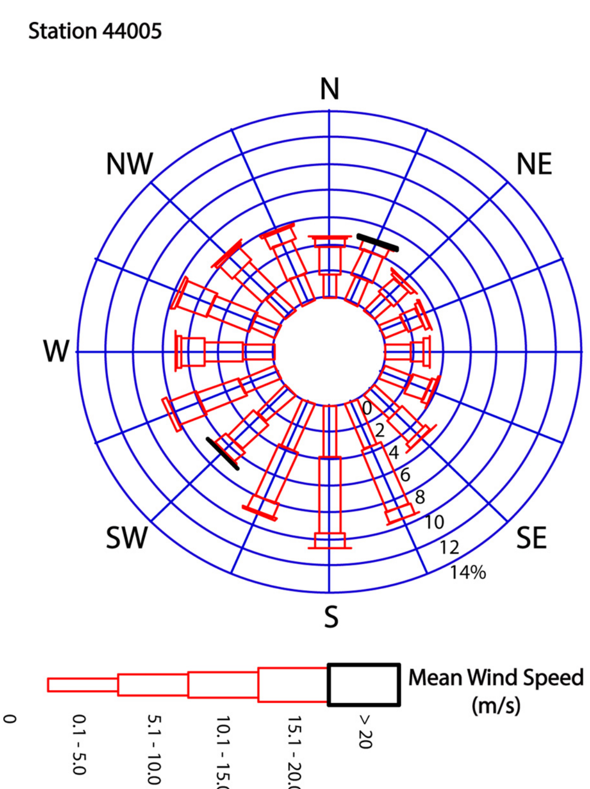

Fig. 2. Wind rose from station 44005.

Based on these morphodynamics, the Great Marsh shoreline is classified into four broad categories: 1. Slumping; 2. Vertical and abrading; 3. Bedrock-large gravel, and 4. Stable/accretionary (see SI Fig. 1 for photos). The broad nature of these types allowed long stretches of the shoreline to be defined by a single class, while still characterizing the overall state of the marsh shoreline. The slumping edge class is defined by 50% or more of the edge containing slump blocks. In addition to slump blocks, this shoreline type commonly contained surface cracks and deteriorated peat blocks at the base of the edge. The vertical and abrading class is defined as an eroding edge with a vertical bank, containing typically less than 10% slump blocks. The bedrock and boulder-cobble beaches are short segments of shore that frequently contain small pocket marshes (< 50 m long). The stable/accretionary class (sensu: McLoughlin et al., 2014) is defined as a gently sloping marsh shore that grades laterally onto a tidal flat. This class also includes a minor subclass (< 20%) consisting of more steeply to a vertical marsh edge, protected by a thick algae covering. These edges occur in sheltered environments (very limited fetches with weak tidal currents) and exhibit no slumping characteristics.

2.3. Geotechnical properties sampling and analysis

Previous studies have related vertical changes in bulk density, organic content, belowground biomass, and shear strength to the stability and erodibility of marsh edges (Chen et al., 2012; Feagin et al., 2009; Grabowski et al., 2011; Graham and Mendelssohn, 2014; Sapkota and White, 2019; van Eerdt, 1985). To evaluate how these properties pertain to our study area we obtained spatially-representative geotechnical measurements at 98 randomly-selected marsh edge sites throughout the Great Marsh (Fig. 1). Although human impacts from grazing, haying, and ditching declined in the 1930s, some ditches have remained as they slowly fill in; to ensure minimal impact from these features, 95% of the sample sites were located at least 5 m away from the nearest ditch.

Samples and measurements were taken at 20 cm intervals beginning at the marsh platform surface and extending to the bottom of the face, 80 to 200 cm below (SI Fig. 2). Two soil plugs were taken at each elevation using a 1 cm-diameter plastic cylinder. At each elevation, in situ shear strength measurements were also taken by inserting a Seiken hand vane horizontally into the face of the bank, at a distance of 20 cm into the bank, and then 40 cm into the bank. These measurements provide approximations of soil strength near the edge and deeper into the marsh.

Soil samples were dried and processed in the lab for bulk density, organic content, and belowground biomass. Bulk density (g/cm^3) was calculated by dividing the dry weight of the sample by the volume of the sample. Organic content (%) was determined using the loss on ignition (LOI) method, in which samples were ground up with a mortar and pestle, placed in ceramic crucibles, and burned in a furnace for 24 h at 500 °C. The % organic content was calculated by dividing the post-burn weight of the sample by the pre-burn weight of the sample (Rowell, 1994). Belowground biomass (%) was determined by rehydrating the samples, washing them through a 500 μm sieve to separate organic biomass from inorganics, removing and drying the organic material, and then weighing the organics and dividing it by the original dry sample weight. The in-situ shear vane torque measurements were converted to shear strength based on the diameter of the vane (New Zealand Geotechnical Society Inc., 2001).

Differences in soil strength at marsh edges may result from differences in sediment characteristics (Gillen et al., 2020) including the density and diversity in root structure, the degree of peat decomposition and compaction, mineral content and grain size. In addition to environmental factors, differences in operator speed can result in noisy data (Jafari et al., 2019). Hand-held shear vane measurements are therefore only able to provide trends in wetland strength with depth, and the accuracy of these vanes is considered too small to determine absolute changes.

Statistical significance (alpha = 0.05) of the analysis was determined using the Kruskal-Wallis and Wilcoxon signed-rank tests for these non-parametric data. Additionally, the geotechnical property variables (mean bulk density, organic content, belowground biomass, and shear strength for both 20 cm and 40 cm into the bank) were normalized along with the fetch and platform elevation data (see sections below) to perform a linear discriminant analysis. A linear discriminant analysis allows the edge classes to be optimally separated and reveals which variables provide the separation and best define the differences in edge classes (Tabachnick and Fidell, 1996). To remove redundancy, variables were excluded if their correlation with another variable was greater than |0.7|. In this case, mean organic content was removed because of its high correlation with mean bulk density (−0.8) and mean shear strength 40 cm into the bank was removed because of its high correlation with shear strength 20 cm into the bank (0.7). A canonical correlation analysis was also performed, comparing two groups of standardized data: geotechnical properties (mean organic content, bulk density, belowground biomass, shear strength 20 cm into the bank, and shear strength 40 cm into the bank) and fetch measured along the marsh edge (fetch in the S, NNE, and SW directions as well as longest fetch). Canonical correlation analysis computes the orthogonal linear combinations of the two sets of variables that are maximally correlated, and allows interpretation of which variables, in both sets, contribute the most to the correlation, and whether there is a strong correlation between multivariate sets of data (Tabachnick and Fidell, 1996).

2.4. Marsh platform elevations

Marsh platform elevation at the sampled sites were determined either from real-time kinematic (RTK) GPS or Lidar (OCM Partners, 2021). When Lidar was used, the elevation of the five points nearest the site (<5 m distance) were averaged. The marsh platform elevations were then used to convert the depths from scarp top, at which the geotechnical properties were measured, to elevations relative to NAVD88, and to Mean Sea Level (MSL) using the nearest geodetically surveyed tidal station (Boston; station ID 8443970). Statistical significance (alpha = 0.05) of the analysis was determined using the ANOVA and Tukey HSD tests for these parametric data.

2.5. Fetch

As discussed above, breaking and shoaling waves can remove sediment particle by particle from the edge face or they can undermine and compromise the integrity of the marsh edge causing slope failure and slumping (Schwimmer, 2001; Bendoni et al., 2014). Rates of erosion have been related to wave power (i.e., cumulative wave energy over time; e.g., Schwimmer, 2001; Marani et al., 2011; Leonardi et al., 2016a) and wave thrust (vertical wave-generated force) (e.g., Tonelli et al., 2010; Leonardi et al., 2016b). The bays of the Great Marsh are shallow water estuaries with average depths of between 1.4 and 5.7 m (Vallino and Hopkinson, 1998), a similar magnitude to the tidal range (~2.6 m). Most marsh edges are fronted by relatively uniform and similar intertidal areas. As a consequence, wind-generated waves throughout the study area are fetch-limited and the impact of waves along marsh shorelines is chiefly a function of exposure, wind velocity, and tidal elevation. The strongest winds are typically associated with extra-tropical storms that last for at least one or two tidal cycles. As wind velocity and water elevation are essentially spatially consistent over the storm, the relative wave energy flux along any marsh edge is largely a product of fetch with respect to the wind direction. Thus, we evaluate the impact of wave energy using fetch relative to north-northeast and southwest storm wind directions as a proxy. In addition, we also analyzed the longest fetch for each station and fetch for the prevailing southerly wind conditions. Fetch was measured in Google Earth every 200 m alongshore in Essex Bay and every 500 m along the longer shoreline of PIS.

Statistical significance (alpha = 0.05) of the analysis was determined using the ANOVA and Tukey HSD tests for these parametric data.

3. Results

3.1. Marsh edge mapping

Approximately 110 km of marsh edge were mapped in the Great Marsh with 65.7% of the marsh edge classified as eroding (38.5% as slumping and 27.2% as vertical and abrading), and 28.5% classified as stable/accretionary (Fig. 3). The remaining 5.8% of the shoreline consisted of bedrock and gravel beach exposures. When excluding the bedrock and gravel beach shoreline, because they were not sampled for geotechnical properties, the shoreline consists of 40.9% slumping edge, 28.9% vertical and abrading edge, and 30.2% stable/accretionary edge. Ninety-eight sites across the marsh were sampled, and over 450 measurements were taken for each geotechnical property (SI Table 1). In addition, a total of 1832 fetch lengths were measured for comparison to the slumping, vertical and abrading, and stable/accretionary edge categories. The majority (36%) of the fetch measurements were positioned at slumping edges, which corresponds well with the percentage of edge length mapped as slumping (38.5%).

3.2. Geotechnical properties

Overall, the randomly selected sites comprise 52.6% slumping edges ($N = 51$), 28.2% vertical and abrading edges ($N = 28$), and 19.2% of sites along stable/accretionary edges ($N = 19$). Although this distribution is not identical to the mapped percentages (because site selection was random), the uneven sample size does not impact the assumptions of

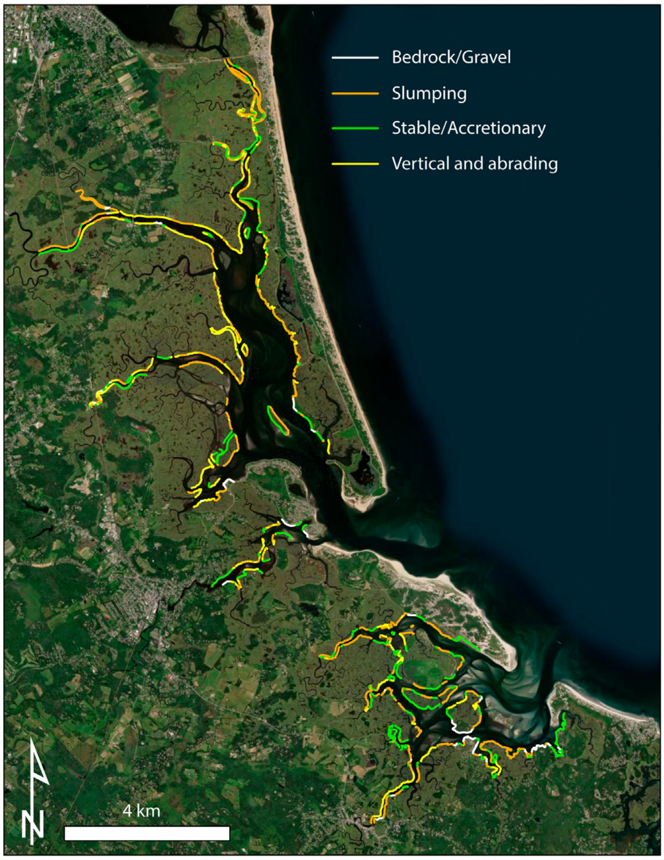

Fig. 3. Edge erosion map indicating mapped areas and their edge classification.

the Kruskal-Wallis test (Lowry, 2020). Bulk density and LOI data show a nonlinear, inverse relationship that corresponds well to the Morris et al. (2016) dataset (Fig. 4). Shear strength values 20 and 40 cm into the bank are positively correlated, but show no significant difference between measurements at 20 and 40 cm (*t*-test, *p*-value = 0.67). The other geotechnical properties have no correlation (SI Fig. 3).

The geotechnical property dataset ($n > 450$ for each characteristic) provide probability density functions that show a range of values for the Great Marsh: 0.99–55.07% for organic content (mean = 0.55%), 0.10–1.43 g/cm^3 for bulk density (mean = 15.50 g/cm^3), 0.11 to 36.76% for belowground biomass (mean = 6.41%), 4.04–136.49 kPa for shear strength 20 cm into the bank (mean = 23.44 kPa), and 4.04–131.03 kPa for shear strength 40 cm into the bank (mean = 23.91 kPa) (Fig. 5 and SI Table 1). These density functions indicate that marsh edges have no clear, specific values or tight range of values, but rather exhibit a wide range and considerable heterogeneity. None of the distributions are normal, however, bulk density is log-normal.

3.3. Marsh platform elevations

Elevation of the marsh platform at the sampled sites exhibits a log-normal trend for each of the edge classes (slumping; vertical and abrading; stable/accretionary), and the cumulative frequency plots show that overall, the stable/accretionary edges are lower in elevation than slumping edges, and the vertical and abrading edges have higher marsh platforms (Fig. 6). A statistical analysis shows that the stable/accretionary class is significantly lower in elevation compared to the vertical and abrading class (ANOVA, $p = 0.01$; Tukey HSD, p adj = 0.017), but exhibits no significant difference from the slumping class. The vertical and abrading class has marsh platform elevations that are significantly higher than the elevations in the slumping class (ANOVA, p = 0.01; Tukey HSD, p adj = 0.04). The platform elevations ranged from −1.02 to 1.60 m NAVD88 (mean = 0.48 m NAVD88) for slumping edges, −0.81 to 2.54 m NAVD88 (mean = 0.60 m NAVD88) for vertical and abrading edges, and −0.73 to 1.45 m NAVD88 (mean = 0.43 m NAVD88) for stable/accretionary edges. Marsh platform elevations exhibit geographical variability, with higher elevations occurring in the northern half of Plum Island Sound, decreasing to the south (SI Fig. 6).

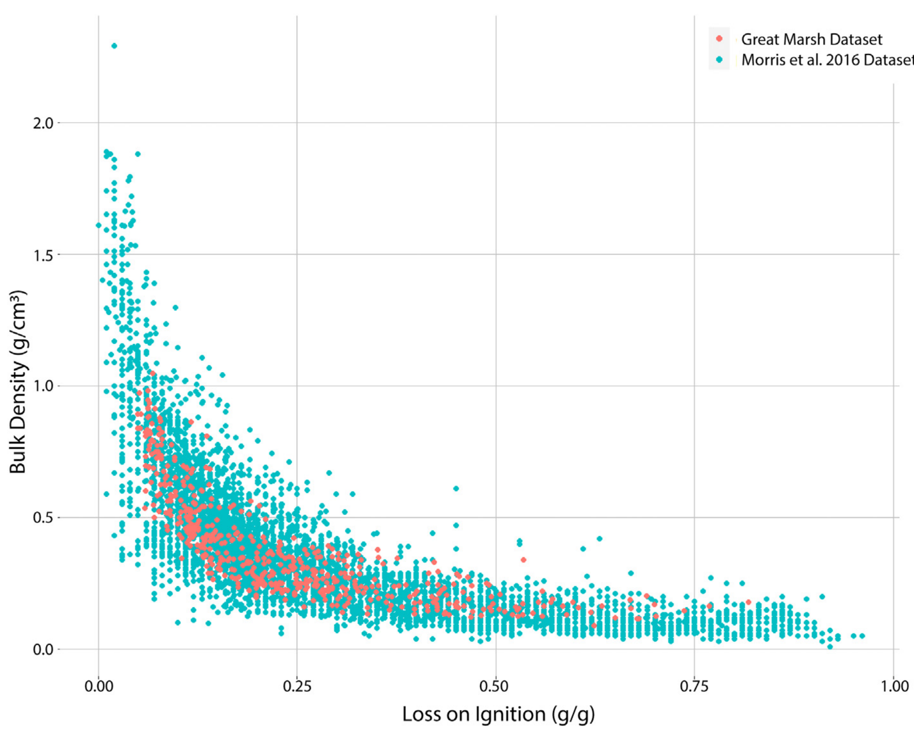

Fig. 4. Bulk density versus loss on ignition (organic matter) data from Morris et al. (2016) overlain by this study's Great Marsh measurements, sampled in Plum Island Sound and Essex Bay.

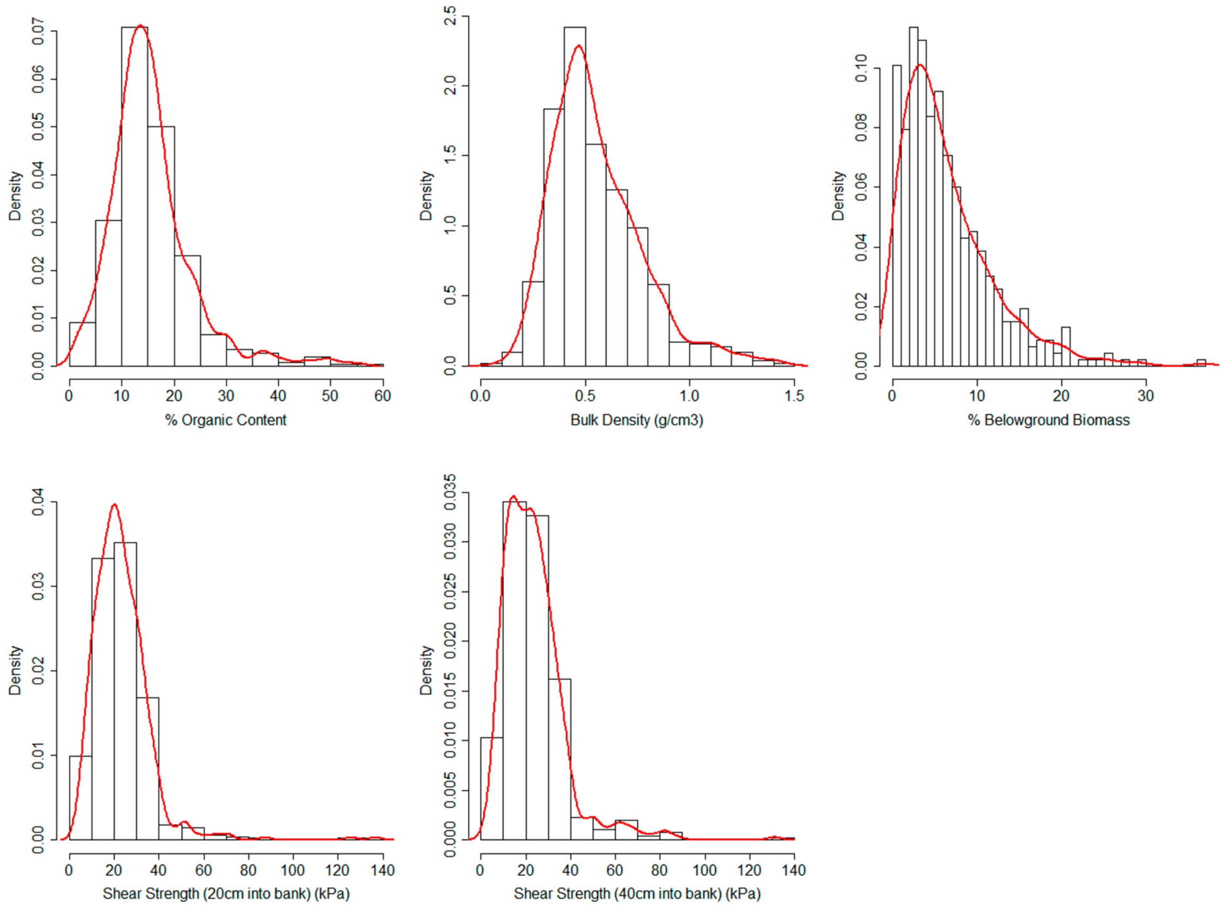

Fig. 5. Probability density distributions for each of the geotechnical properties.

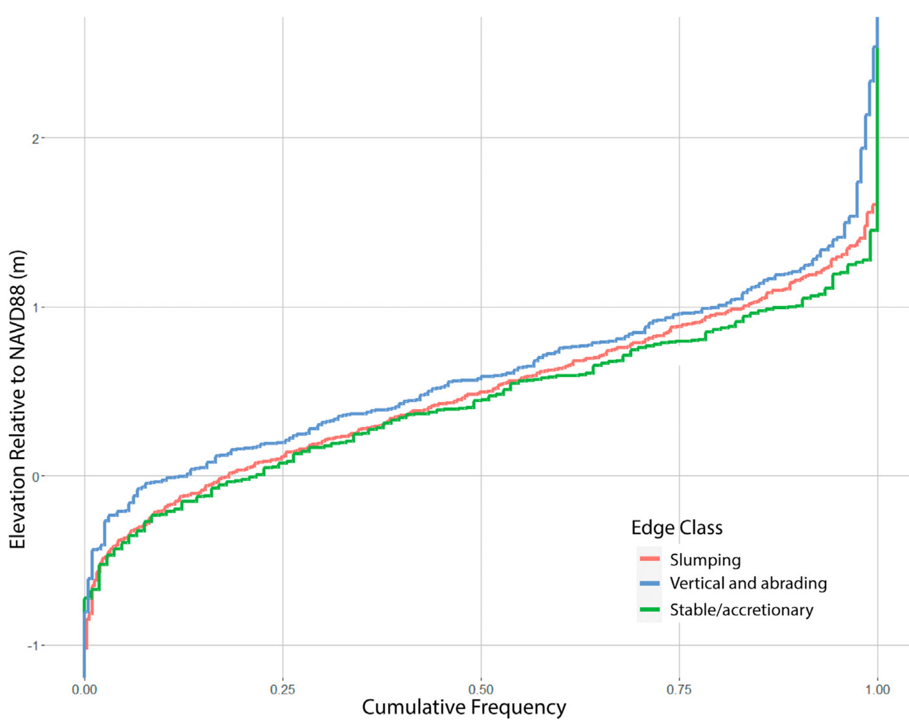

Fig. 6. Cumulative frequency plot of marsh platform elevations at the sampled marsh edge sites, separated by edge class.

3.4. Geotechnical property vertical transects

No clear geotechnical trends versus elevation were found along the marsh face, and there is considerable overlap for the values in each edge class. Overall, organic content appears to follow a U-shaped trend in which it increases with decreasing elevation up to a point, and then decreases (Fig. 7a). However, organic content does not significantly change with elevation (Kruskal-Wallis test, p-value $= 0.13$). Inversely, bulk density tends to decrease and then increases with decreasing elevation (Kruskal-Wallis test, p-value = 0.02); this trend is statistically significant (Wilcoxon signed-rank test, p-value <0.05) for only a few pairwise elevation combinations, such as (0.7, 0.8 m) NAVD88 compared to (−0.7, −0.6 m) NAVD88 (Fig. 7b). The below-ground biomass data are noisy (with large standard errors), but tend to follow a pattern similar to that of organic content of general increasing values with elevation (Fig. 7c). Belowground biomass values are only statistically different for a few pairwise elevation combinations (Kruskal-Wallis test, p-value = 0.04). The trends for shear strength are less clear, and shear strength 20 cm into the bank does not change with elevation (Kruskal-Wallis test, p-value = 0.194) (Fig. 7d); values for shear strength 40 cm into the bank are significantly different between some elevations (Kruskal-Wallis test, p-value = 0.03) (Fig. 7e). It is worth noting that although these statistical tests suggest there is significant difference in some geotechnical properties at certain elevations, they do not show whether increases or decreases with elevation, or any other vertical trend, are significant. The Wilcoxon rank-sum test showed significant relationships among elevation and the geotechnical properties, but no patterns were observed. In addition, none of these geotechnical properties vary significantly with edge class (SI Fig. 4), except for shear strength 40 cm into the bank, which had overall lower values for the stable/accretionary edges when compared to the vertical and abrading edges (Kruskal-Wallis test, p-value = 0.01615; pairwise Wilcoxon signed-rank test, p-value = 0.026). The organic content for stable/accretionary edges tend to have lower values than vertical and abrading edges, but the differences are not statistically significant (Wilcoxon signed-rank test, p-value = 0.62).

Plots of the geotechnical properties at each site for a specific edge class show the considerable heterogeneity in the site-specific values of geotechnical properties (SI Fig. 5). Several sites are statistically different from each other even within the same edge class, though they are not statistically different with elevation. Additionally, geotechnical properties exhibit spatial heterogeneity, with no trends or distinction between edges exposed to open water and edges in narrow channels (SI Fig. 6).

3.5. Fetch and statistics

The fetch values for the Great Marsh study area are normally distributed, and there is no significant difference between fetch among the edge classes, nor throughout the Great Marsh study area (ANOVA, $p > 0.1$) (Fig. 8).

Linear discriminant analysis of the normalized data reveals poor separation of the groups, which is consistent with the Kruskal-Wallis tests

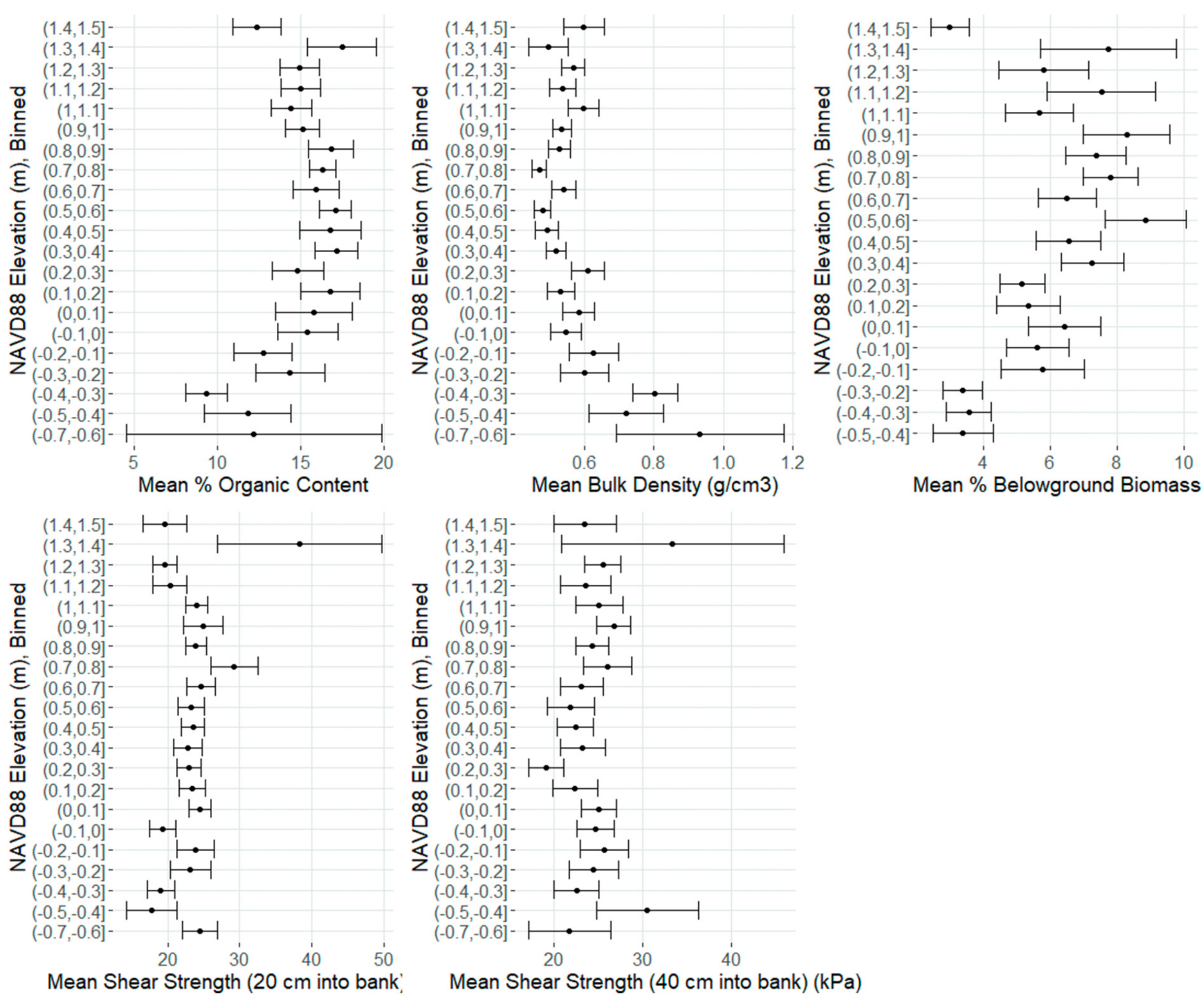

Fig. 7. Geotechnical properties with elevation; a) organic content versus elevation, b) bulk density versus elevation, c) belowground biomass versus elevation, d) shear strength (taken 20 cm into the marsh bank) versus elevation, and e) shear strength (taken 40 cm into the marsh bank) versus elevation. Points represent means and error bars represent standard errors.

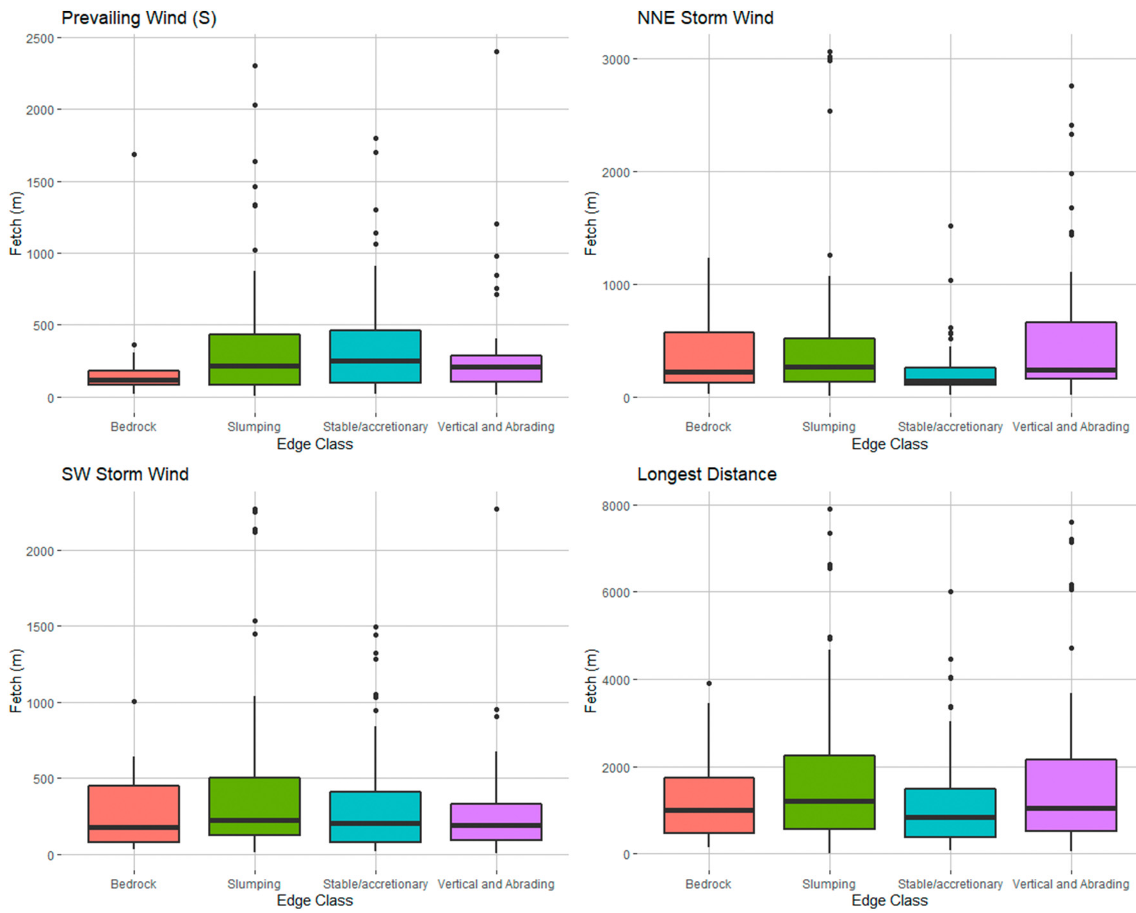

Fig. 8. Fetch distance for each of the measured directions (S, NNE, SW, and longest distance fetch) in the Great Marsh, separated by edge classification.

comparing each geotechnical property with edge class (SI Fig. 7). The linear discriminant functions produced account for 88.71 and 11.29% of the variability, respectively. Based on the coefficients of linear discriminants in the first linear discriminant function, the main variable that provides the separation between edge classes is platform elevation and the variable that contributes the least is fetch in the SW direction (with coefficients of approximately −6.57 and 0.26, respectively) (SI Table 2). However, a multivariate ANOVA test indicates that the mean vectors for the geotechnical properties of the different edge classes are not significantly different ($p = 0.41$).

The canonical correlation analysis between the standardized geotechnical property dataset and the standardized fetch dataset show low canonical correlations (0.39 for the first canonical factors and 0.25 for the second canonical factors), even though the correlation between the two datasets was maximized (SI Fig. 8). The coefficients of the linear combinations to get these canonical factors show that organic content and shear strength in the geotechnical properties' dataset, and longest distance and SW fetches in the fetch dataset contribute the most to the correlation between the two datasets (SI Table 3). However, because the canonical correlation is low, the geotechnical properties at the marsh edges are not closely related to the fetch at these marsh edges.

4. Discussion

This study examined the Great Marsh in Massachusetts, a typical northern Atlantic salt marsh, and the relationships among geotechnical properties, fetch, and edge erosion. The geotechnical properties' values found in this study, and trends or lack thereof, highlight the complexity of marsh systems and the drivers of edge erosion. Our study shows that the relationships among vegetation, sediment characteristics, and fetch are not as clear-cut as past studies observed, and care must be taken when developing assumptions of these relationships in modeling investigations.

4.1. Trends in geotechnical properties and bank stability

Several past studies have investigated geotechnical properties and their influence on edge erosion. van Eerdt (1985) and recent studies such as Feagin et al. (2009) found that vegetation and geotechnical properties, such as bulk density, determine the edge's susceptibility to erosion.

Our bulk density and organic content datasets correspond well with the relationship defined by Morris et al. (2016), suggesting our data represent a typical salt marsh like those studied previously. However, this study shows that most of the measured geotechnical properties do not vary significantly between stable/accretionary edges and eroding (slumping, or vertical and abrading) edges. The only significant relationship was found for shear strength 40 cm into the bank, in which shear strength values at stable/accretionary edges are significantly lower than at vertical and abrading edges; an eroding edge class may actually have higher shear strengths than a stable or accretionary edge, which is explained by the fact that stable/accretionary sites are either areas that are prograding and colonized by relatively new and less densely vegetation or the edge is relatively old and root structures have decomposed (Graham and Mendelssohn, 2014). This observation is different from previous claims that edges erode because of weaker soil strengths (Chen et al., 2012; Day et al., 2018). The lower shear strengths in stable/accretionary edges could be a sign that these edges are less compacted compared to older, higher elevation sites. Shear strength measurements are also often correlated with other soil properties such as belowground biomass (Jafari et al., 2019), and these correlations were not observed in our data. A laterally accreting marsh edge is expected to have higher bulk densities and lower organic content and belowground biomass because prograding tidal flats are still being colonized by vegetation, and thus dominated by inorganic sediment. However, the geotechnical properties show no significant relationship with the developing or eroding morphology of the marsh edge.

It cannot be assumed that eroding edges are solely related to instabilities caused by vertical changes in soil strength or with elevation. No strong trends were observed in the geotechnical properties with elevation; the significant difference with elevation found for bulk density, belowground biomass, and shear strength 40 cm into the bank only show differences for a few pairwise elevation comparisons and not for the overall trend with elevation. The lack of trends with depth and elevation differs from previous results, such as the trends in bulk density reported by Sapkota and White (2019) and shear strength found by Chen et al. (2012) and Graham and Mendelssohn (2014). Our data suggest that the measured geotechnical properties do not change appreciably with elevation and thus, do not produce an unstable vertical profile that promotes bank failure or undercutting (Bendoni et al., 2016; Chen et al., 2012; van Eerdt, 1985). Preliminary data from Louisiana found that shear strength decreased from the marsh edge to the interior of the marsh (Jafari et al., 2019), while in the York River Estuary, Virginia, the opposite was observed (Gillen et al., 2020). Interestingly, there is no significant difference in shear strength between 20 and 40 cm into the bank. Therefore, the edges could not be eroding simply because of lateral differences in soil strength.

4.2. Fetch and erosion distribution

Numerous studies have shown relationships between wind waves and edge erosion, and wave-related metrics are often used to explain observed or modeled erosion rates (Day et al., 1998; Leonardi et al., 2016b; Marani et al., 2011; Schwimmer, 2001; van de Koppel et al., 2005). Fetch and water depth, which is largely a function of tidal flat elevation at the marsh edge as well as tidal elevation, control wave energy impact (Möller et al., 2009). Valentine and Mariotti (2019) found spatial variability in wind patterns and waves in Barataria Bay, LA, which explained local variability in edge erosion. However, in the smaller system of the Great Marsh fetch had no apparent influence on the distribution of eroding and stable or accretionary edges; there is no distinct relationship between fetch in any of the measured wind directions (the prevailing wind direction, the two major storm directions, and the longest fetch possible at the marsh edge) and type and distribution of edge morphology. This study also found that there is no strong canonical correlation between soil properties and fetch in the different directions, implying that the marsh soil properties are not related to or significantly affected by fetch.

4.3. Marsh platform elevation and marsh evolution

The only clear measured difference between the edge classes was marsh platform elevation, which was spatially heterogeneous and ranged from 0.678 to 2.628 m above MSL. Although previous studies found that hydroperiod differences related to marsh platform elevation controls plant species presence, and thus controls certain soil properties and erodibility (Silvestri et al., 2005), vegetation type did not vary appreciably throughout the Great Marsh. In Louisiana, high marsh elevation is associated with changes in drainage and therefore plant productivity and belowground biomass (Reed and Cahoon, 1992). This study noted that vertical and abrading edges have significantly higher marsh platform elevations compared to slumping and stable/accretionary edges. However, we found no associated differences in soil properties or vegetation. These elevation differences may be attributed simply to the geometry of the edge classes, in which a stable/accretionary edge is gently sloping into the channels as the marsh is just starting to colonize and has not fully begun to accrete vertically, while the vertical and abrading edges have accreted vertically and reached higher platform elevations. However, we found no significant difference in marsh platform elevation between the stable/accretionary class and the eroding class, showing that platform elevation cannot distinguish between eroding and non-eroding edges; the marsh platform elevation may not determine whether an edge is eroding, but rather is descriptive of the geomorphology. The modeling study by Tonelli et al. (2010) reported that marshes higher in elevation with larger tidal ranges are more susceptible to erosion because of bottom shear stresses and undercutting. However, this morphology and implied erosive process do not appear active in the high-elevation vertical and abrading edges in the Great Marsh. These edges are usually almost vertical and show no sign of cantilever failure, but rather abrade and gradually erode through continuous, particle by particle erosion. Thus, the edge classes associated with the different platform elevations cannot be explained by differences in wave energy impacting marsh edges having different platform elevations.

4.4. Marsh heterogeneity

A constant trend across all measured variables is heterogeneity. McLoughlin et al. (2014) found little variability in sediment characteristics in the Virginia Coast Reserve marshes and could not explain the within-site heterogeneity in shoreline erosion rates. Priestas et al. (2015) suggested that the spatial variability in erosion rates in Hog Island Bay, VA, was caused by spatial variations in geotechnical properties and morphologies, as there was only a weak relationship between the spatial distribution of erosion rates and wave energy. In the Great Marsh, significant variability in geotechnical properties was observed, but it was not associated with the spatial distribution of edge types. The geotechnical properties and morphologies are spatially heterogeneous and follow no clear trends, even when comparing open water areas to narrow tidal creeks with little wave action. The heterogeneity exists not only on the large-scale marsh, but also in the small-scale comparisons between individual sites; when separating the geotechnical properties by edge class, many sample sites are statistically different from each other, and some sites even have statistically different values with elevation and depth. Significant heterogeneity exists among the different edge classes, and geotechnical properties and fetch measurements do not capture the mechanisms at play that determine whether a marsh edge is eroding or not and where this process occurs. This variability in geotechnical and sediment properties is found throughout the Great Marsh, not only at marsh edges but also in transects along channels, demonstrating that the marsh is much more complex than hydrodynamic models assume (Fitzgerald et al., 2020).

Although the relationship between geotechnical properties, fetch, and edge erosion are not as clear-cut as previously observed (Bale et al., 2006; Francalanci et al., 2013; Bendoni et al., 2016) and likely do not explain the presence or absence of edge erosion, these data show a range of values for the Great Marsh, which has a similar physical setting to other Northeastern (US) marshes (FitzGerald and Hughes, 2019; FitzGerald et al., in review). For example, Morris et al. (2016) have shown that northern marshes have similar bulk density-LOI ratios. The data clearly depict that marsh edges exhibit heterogeneity and a single attribute does not capture the small or large-scale variability in a marsh. Defining the range in geotechnical values is useful for better representing the heterogeneous nature of marshes, e.g., in models.

Eroding edges and stable or accretionary edges alike experience the same average fetch distance and have similar soil properties, and so they cannot be the main underlying mechanisms behind edge erosion. Many studies equate edge erosion with long-term edge retreat, and consequently look for the determinants of edge erosion to determine rates of retreat (Bendoni et al., 2016; Hopkinson et al., 2018). However, variables commonly measured to investigate edge erosion, such as those herein, do not clearly relate to or predict edge erosion, and the relationship with lateral retreat is even more tenuous. Excepting those that are prograding, the vertical nature and slumping character of marsh edges suggest that they are inherently dynamic and in a constant state of flux (Mariotti and Fagherazzi, 2013; Fagherazzi et al., 2013), with lateral erosion and expansion occurring simultaneously in different areas. These combined interactions determine whether the marsh is experiencing net retreat, stability, or progradation. Most marsh retreat caused by erosion occurs at the highly exposed seaward boundary where wave energy can cause retreat and eroded edges cannot re-establish themselves (Leonardi et al., 2016b). The mapping in this study shows that erosion can occur anywhere, including in small channels where the marsh is not retreating nor is the channel actively meandering. In the smaller channels, edges may be eroding but not causing retreat related to processes such as creep (Mariotti et al., 2016) or slump blocks buttressing and re-establishing edges (Gabet, 1998). Processes such as creep (Mariotti et al., 2016) help explain why slump blocks are observed in small channels that do not widen, and this process may also be active at more exposed sites with high platform elevations in which the unbuttressed edge gradually move towards the water. As a result, edge erosion does not always equal marsh retreat, and geotechnical properties and fetch do not explain retreat nor the presence or absence of erosion.

Even though some studies have related morphology to an erosion mechanism (Fagherazzi et al., 2006; Priestas and Fagherazzi, 2011; McLoughlin et al., 2014), it cannot always be assumed that a certain geomorphology, such as a slumping edge, is a result of a certain process or set of processes. Thus, a distinct edge morphology can be related to different drivers in different settings. For example, although Leonardi and Fagherazzi (2015) have related slumping to wave energy in Plum Island Sound, Mariotti et al. (2016) have suggested that soil creep explains slumping in other regions within the sound. Alternatively, other parameters that are often overlooked may instead play a more important role in causing edge erosion, such as variation in tidal currents that act upon marsh edges (Gabet, 1998), including in small creeks, or winter processes such as freezing and thawing cycles (Argow and FitzGerald, 2006).

Perhaps it is also not possible to predict erosion using parameters measured at one point in time. Sea level rise, increasing temperatures, and precipitation (Intergovernmental Panel on Climate Change, 2013) suggest that marshes will be in a constant flux and perhaps marsh edge morphologies reflect a certain stage in an erosional cycle or evolutionary process. Instead of being caused by changes in geotechnical properties or wind waves, edge erosion may occur as part of an edge's evolution from a newly formed, laterally accreting edge to a vertical scarp that surpasses a certain elevation or thickness threshold and then erodes or fails because of factors such as tidal level or wave energy (FitzGerald and Hughes, 2019). Although many studies have found relationships between edge morphology, wave exposure and/or geotechnical properties, and explained the presence and spatial distribution of edge erosion through those relationships (Bale et al., 2007), we found that in the Great Marsh these characteristics do not correlate strongly with the presence and distribution of eroding morphologies and cannot solely explain edge erosion. This study is unique in its wide range and high number of measurements, compared to these previous studies that had a narrower focus and investigated single study sites or parameters. Marshes are highly complex and a product of many different drivers, which explains the lack of correlation with any measured parameter and edge erosion type. Thus, other parameters and interactions must be contributing to the variability in edge morphologies and erosion, and established relationships between geotechnical properties, wind waves, and edge erodibility do not always hold.

5. Conclusion

Because of heterogeneities in marsh edges, we found no relationship among geotechnical properties at a marsh edge, fetch, and the presence of edge erosion. Edges that experience fetch or sheltered areas alike can erode, and the geotechnical properties at an edge are no indicator of edge erosion. Here, we provide a range of values for geotechnical properties at marsh edges that can be used for modeling studies; this study shows that assigning a single or handful of values to marsh edge properties does not accurately encompass the significant heterogeneity found within a marsh, and may skew the modeling results. Parameters or interactions beyond the ones typically measured, such as in this study, may also be responsible for edge erosion and these relationships are not captured by current field and modeling studies.

Declaration of competing interest

The authors declare no competing financial interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2021.107745.

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