Biophysical controls of marsh soil shear strength along an estuarine salinity gradient

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Abstract. Sea-level rise, saltwater intrusion, and wave erosion threaten coastal marshes, but the influence of salinity on marsh
10 erodibility remains poorly understood. We measured the shear strength of marsh soils along a salinity and biodiversity gradient
in the York River estuary in Virginia to assess the direct and indirect impacts of salinity on marsh erodibility. We found that
soil shear strength was higher in monospecific salt marshes (5 - 36 kPa) than biodiverse freshwater marshes (4 - 8 kPa), driven
by differences in belowground biomass and rooting structure. However, we also found that shear strength at the marsh edge
was controlled by sediment characteristics, rather than vegetation or salinity, suggesting that inherent relationships may be
15 obscured in more dynamic environments. Our results indicate that freshwater marsh soils are weaker than salt marsh soils, and
suggest that salinization of freshwater marshes may lead to simultaneous losses in biodiversity and erodibility.

1 Introduction

Tidal marshes are rapidly evolving ecosystems that sit at the boundary between land and sea, and are influenced by a tight
coupling between biological and geomorphic processes (Redfield, 1972). Marshes provide a wide variety of ecosystem
20 services, such as improving water quality, sequestering carbon, and reducing the impacts of storm surge and coastal erosion
(Barbier et al., 2011). However, tidal marshes are vulnerable to climate change and its effects—such as sea-level rise, increased
storm frequency, and saltwater intrusion (Craft et al., 2009; FitzGerald et al., 2008; Kirwan and Megonigal, 2013).

Erosion of salt marsh edges is a primary cause of marsh loss (Fagherazzi et al., 2013; Ganju et al., 2017). Relative sea-level
25 rise potentially increases wave height, wave power, and edge erosion rates (Marani et al., 2011; Mariotti and Fagherazzi, 2010;
McLoughlin et al., 2015), but also leads to non-linear changes in vegetation that could alter the strength of eroding soils (Feagin
et al., 2009; Kirwan and Guntenspergen, 2012; Stagg et al., 2017; Wilson et al., 2012). Sea-level rise tends to increase lateral
erosion rates depending on wind direction and duration (Valentine and Mariotti, 2019). Numerical models of marshes have
shown that erosion rates and shoreline morphology depend on interactions between shear stress from waves and the shear

30   strength of marsh soils (Bernik et al., 2018; Leonardi and Fagherazzi, 2014; Marani et al., 2011; Mariotti and Fagherazzi, 2010).

While many studies have analyzed how sea-level rise and storms influence wave erosion (Howes et al., 2010; Leonardi et al., 2016), less is known about the processes driving the strength of marsh soils and their impact on erosion rates (Jafari et al.,
35   2019). In general, vegetation increases the shear strength and decreases the erodibility of marshes (Ameen et al., 2017; Sasser et al., 2018; Wilson et al., 2012). Nevertheless, it is difficult to attribute large-scale controls on shear strength in marshes due to the heterogeneous distribution of roots, stems, soil types, and shells which all yield variable influences (Jafari et al., 2019). Previous work has examined shear strength in marsh soils in the context of vegetation, geomorphic setting, and methodology (Ameen et al., 2017; Jafari et al., 2019; Lin et al., 2016; Sasser et al., 2018; Watts et al., 2003; Wilson et al., 2012). However,
40   additional research is required to fully understand the biophysical drivers of marsh soil shear strength.

Predicting how erosion rates will change in tidal marshes with increased salinization from sea-level rise requires a more mechanistic understanding of the drivers of shear strength. Salinity likely influences shear strength through ecological factors, such as dominant vegetation communities or distribution of belowground biomass (Ameen et al., 2017; Sasser et al., 2018).
45   An increase in salinity may increase marsh soil shear strength assuming high salinity marshes favor species with deeper roots (Howes et al., 2010). Alternatively, shear strength may decrease with increasing salinity due to the loss of vegetation biodiversity (Ford et al., 2016). Here, we measure soil shear strength and biophysical parameters along an estuarine salinity gradient and use them to determine how salinity influences marsh soil shear strength.

2 Methods

50   ### 2.1 Study area and approach

We measured the erodibility of marshes along a salinity gradient in the York River Estuary, a tributary of the Chesapeake Bay (Virginia, USA). The York River is a microtidal, partially-mixed estuary with a mean tidal range of 0.7 meters at the mouth of the river and 1 meter near the freshwater river sources (Fig. 1a) (Friedrichs, 2009). The York River salinity gradient is created by saltwater from the Atlantic Ocean, and freshwater from the Mattaponi and the Pamunkey rivers (Reay, 2009). Sea-
55   level rise rates are 3-4 times faster than the eustatic levels in this region, which could facilitate faster rates of salinization (Ezer and Corlett, 2012). Various wetland types exist along the York River within different salinity regimes: polyhaline salt marshes that have monocultures of *Spartina alterniflora* (saltmarsh cordgrass), mesohaline brackish marshes with an extensive array of halophytic grasses, and oligohaline freshwater marshes with dominant plant species *Peltandra virginica* (arrow arum) and *Zizania aquatica* (wild rice) (Perry and Atkinson, 2009). Saltwater intrusion is driving an increase in salt-tolerant species at
60   the freshwater marsh sites (Perry and Atkinson, 2009).

We chose five marshes along the York River salinity gradient for this study (Fig. 1a). Salinity decreases upriver from 18 ppt at the Goodwin Islands to 0 ppt at the Pamunkey Indian Reservation (Reay, 2009). Within these overall sites, we chose sampling locations along tidal creeks 5-10 m wide, with marsh widths beyond 20 meters and consistent elevations across all study sites (Fig. 1b). We collected samples from both the tidal channel marsh edge and from the marsh interior. Edge sites were located between the tidal channel and any levee (1 m from edge), while interior sites were located at a measured distance of 10-12 m away from the edge site (Fig. 1b). All field work was done in July-August 2018, except for the collection of cores for belowground biomass at the Sweet Hall Marsh and Pamunkey Indian Reservation marsh edge sites (September 2018) and elevation profiles of the Pamunkey Indian Reservation (March 2020).

2.2 Measurements of shear strength, vegetation, and soil properties

We measured shear strength and a variety of biophysical characteristics at each location in this study. We used a Humboldt Shear Vane to determine the shear strength of marsh soils. Although the effectiveness of the shear vane in wetland soils is undetermined (Jafari et al., 2019), it remains the most widely used method to quantify wetland soil shear strength in coastal science (Ameen et al., 2017; Howes et al., 2010; Valentine and Mariotti, 2019). We used a 1 m long shear vane, with a 10 cm-long head for relatively weak marsh soils, and a 5 cm-long head to measure relatively strong marsh soils. The shear vane was turned until the marsh soil was broken, and unitless values on the shear vane were converted to kPa using the manufacturer's conversion formulas (10 cm head: kPa=shear vane value*10*0.0625; 5 cm head: kPa=shear vane value*10*0.5). Each shear strength profile was one meter long with measurements taken at 10 cm intervals. Ten replicate profiles were taken per marsh location at each study site for a total of 100 total soil shear strength profiles along the York River.

We measured elevation profiles for all five sites using real-time kinematic (RTK) GPS across a transect from the marsh edge to the interior (Fig. 1b). For each site, five ground control points were taken on the marsh edge, 1 meter in from the edge, and in the marsh interior to obtain more accurate elevations at our specific sampling locations. All sites were located at similar elevations except for the Pamunkey Indian Reservation, which was lower in elevation than the other sites. This discrepancy is likely due to the other elevation profiles being measured during the growing season while the Pamunkey Indian Reservation profile was measured in early Spring. There is no vegetation cover in freshwater marshes along the York River during colder months (Perry and Atkinson, 2009), and the marsh platform may lose elevation due to seasonal erosion or subsidence.

Aboveground and belowground biomass were measured destructively. We collected standing vegetation from three replicate above-ground stem clip plots (25 cm x 25 cm) per marsh location at each study site. Samples were counted for the total number of stems, dried to a constant weight, and separated by species to calculate species richness. Three replicate belowground biomass soil cores (15 cm diameter, 50-70 cm depth) were collected at each location within sites (except for the edge site at the Pamunkey Indian Reservation where only 2 cores were taken), and used to measure belowground root and rhizome biomass. We sectioned cores into 10 cm increments and washed over a 1 mm screen sieve. Live belowground biomass was

95   separated based on color, turgidity, and buoyancy in water. Live belowground biomass was dried to a constant weight, and
used to generate belowground biomass profiles for each study site.

Water content, bulk density, and organic matter content were determined from two Russian peat cores (2 cm diameter, 1 m
depth) collected at each sampling location per study site. Cores were sectioned into 1 cm segments for the top 50 cm, every 3
100 cm for the bottom 50 cm. Samples were dried to a constant weight, homogenized, and combusted for 6 h at 550°C to burn off
organic material.

3 Results

3.1 Shear strength

Shear strength measurements generally ranged from 0-36 kPa, but differed between locations within a site, and across sites.
105 There was an observable trend of shear strength increasing with depth at freshwater marsh sites for the upper 30 cm of the soil
profile (Fig. 2). For brackish and salt marsh sites, patterns of shear strength with depth were inconsistent. There was a large
increase in shear strength below 30 cm at the Goodwin Islands edge location (Fig. 2a), which we attribute to measurements
that were within the antecedent lithology (i.e. non-marsh soils). In analyses related to the effect of salinity on soil shear strength
(discussed below), we used depth-averaged shear strength values from the upper 30 cm of the soil profile. We selected the
110 upper 30 cm as our window of averaging, because shear strength varied little with depth beyond 30 cm at most sites, it excludes
any influence of antecedent parent material, and corresponds to typical vegetation rooting depths. This approach allows for
comparisons between sites that are based on the same depth interval at each site.

Depth-averaged shear strength increased significantly with salinity across study sites for interior locations only ($R^2 = 0.81$;
115 $p = 0.038$) (Fig. 3b). There was no significant relationship between shear strength and salinity for edge locations across all
sites ($R^2 = 0.04$; $p = 0.74$) (Fig. 3a). At the high salinity sites (Goodwin Islands and Catlett Islands), shear strength values
range from 5.3-36.0 kPa for the upper 30 cm of the marsh interior, with an overall interior average of 18.5 kPa. Shear strength
values at the low salinity sites (Sweet Hall Marsh and the Pamunkey Indian Reservation), ranged from 3.6-8.0 kPa for the
upper 30 cm of the marsh interior, with an overall average of 5.4 kPa. Interior sites yielded higher values of shear strength than
120 edge sites in the brackish and the salt marshes (Fig. 4). Shear strength values were nearly equal between the edge and interior
sites for freshwater marshes (Fig. 4). The most substantial difference between edge and interior shear strength values occurred
at the salt marsh sites, with an increase from 5.1 kPa at the edge to 18.5 kPa in the interior.

3.1 Biophysical drivers

In the marsh interior, vegetation properties largely explained variability in soil shear strength. Belowground biomass had the
125 most significant influence on shear strength in the marsh interior ($p = 1.086e-5$) (Fig. 5). Aboveground biomass was also

correlated with shear strength in the marsh interior but was marginally significant ($R^2 = 0.64; p = 0.105$). At the marsh edge, soil properties explained most of the variability in shear strength on edge sites. Organic content was correlated with edge shear strength values but was marginally significant ($R^2 = 0.72; p = 0.059$). However, other properties that co-varied with organic content (i.e. water content, bulk density) were also important, including the relationship between bulk density and shear

130   strength in salt marshes (Fig. 6).

4 Discussion

The results from this study are consistent with previous work that identifies vegetation and soil properties as important drivers of marsh soil shear strength. For example, soil shear strength is well known to vary with dominant plant species (Howes et al., 2010; Sasser et al., 2018). Our work extends this concept and finds that soil shear strength is positively correlated with

135   belowground biomass in the marsh interior (Fig. 5). This finding aligns with natural and manipulative experiments that show shear strength increases with belowground biomass (Wilson et al., 2012), and that the mortality of belowground roots and rhizomes is related to enhanced erosion (Coleman and Kirwan, 2019; Lin et al., 2016; Silliman et al., 2019; Wilson et al., 2012). Like previous work (Ameen et al., 2017; Wilson et al., 2012), our results demonstrate that soil properties such as bulk density are also important drivers of marsh erodibility (Fig. 6). However, we uniquely show that the relative importance of

140   vegetation and soil properties depends on the location within a marsh (edge vs. interior).

Our work indicates that the marsh interior has a higher soil strength than the marsh edge at our salt and brackish marsh sites (Fig. 4). We ascribe this variability in saline marshes to biological drivers influencing marsh interior soils (Fig. 5), and soil properties determining soil shear strength at the seaward marsh boundary (Fig. 6). The differing influences are due primarily

145   to various processes occurring at different places in the marsh. Sedimentation is low in the marsh interior leading to more compacted stronger soils, and biomass tends to be concentrated closer together with higher stem densities. The tightly packed belowground root network adds cohesion to marsh soils without the active edge processes frequently reworking sediment (Silliman et al., 2019). In contrast, the marsh edge is typically more dynamic, where increased inorganic sediment deposition and resuspension leads to more unconsolidated, mineral-rich soils that can impact soil cohesion and shear strength (Ameen et

150   al., 2017). Enhanced nutrient loading, particularly in wetlands undergoing eutrophication, at the marsh edge weakens soils and may also influence shear strength variability at the seaward boundary (Turner et al., 2020). It is unclear why similar spatial patterns were not observed in the freshwater marsh locations. Perhaps the overall lower belowground biomass and shear strength of the freshwater marshes precludes our ability to detect patterns across the marsh. Nevertheless, our findings indicate that belowground biomass drives soil shear strength variability in the marsh interior (Fig. 5), and soil properties influence

155   marsh edge shear strength (Fig. 6) for brackish and salt marshes.

Salinity potentially plays an important role in determining the erodibility of marsh soils, through its combined influence on vegetation type and belowground biomass. Prior work examining the relationship between salinity and marsh soil strength concludes that salt marshes are more resistant to lateral edge erosion than freshwater marshes, ascribing variation in rooting depth to differences in soil shear strength (Howes et al., 2010). While our study also finds that salt marshes are stronger than freshwater marshes in the marsh interior (Fig. 3), we find that salt marshes are generally stronger than freshwater marshes regardless of the depth within the soil and rooting profile (Fig. 2b). We therefore attribute stronger salt marsh soils in our study area simply to the greater belowground biomass of *Spartina alterniflora* relative to freshwater species such as *Peltandra virginica*. Interestingly, we found no relationship between salinity and soil shear strength at the marsh edge, where erosion would actually occur (Fig. 3a). Although this finding warrants more attention, we suggest that processes associated with a more dynamic marsh edge (e.g. sediment deposition, erosion, and resuspension) obscure patterns that would otherwise be evident.

Root structure and geometry may also have considerable influence over marsh soil shear strength (Ameen et al., 2017; Howes et al., 2010). In the salt marsh, *Spartina*-dominated systems, the belowground root network consists of fibrous, tightly interlocking strands that may hold soil more effectively (Fig. 7a). *Peltandra virginica* is the most abundant plant species in the freshwater sites examined in this study, whose belowground biomass consists of large tubers with aerenchyma tissue and easily broken roots spaced out throughout the marsh (Fig. 7b). This laterally heterogeneous distribution of roots across the surface of the freshwater marsh may lead to overall decreased soil shear strength.

Previous work in U.K. marshes finds that freshwater marshes with a more diverse array of vegetation species have stronger marsh soils due to greater belowground biomass (Ford et al., 2016). However, our study finds that marsh soil shear strength increases with a decrease in plant biodiversity. Like other estuaries (Brock et al., 2005; Engels and Jensen, 2010; Grenier La Peyre et al., 2001; Odum, 1998), biodiversity decreases from freshwater sites to salt marsh sites in our study area (species richness = 6 for Pamunkey Indian Reservation, species richness = 1 at Goodwin Islands and Catlett Islands). Salt marshes in the York River are dominated by *S. alterniflora* and *S. patens*, which are highly productive species that create a dense network of belowground biomass (Perry and Atkinson, 2009; Silliman et al., 2019). We suggest that the overwhelming influence of these highly productive salt marsh species explains the high shear strength of less biodiverse marshes, as these species are absent in our freshwater York River estuary sites along the York River and those studied in the U.K (dominant species: *Puccinellia maritima* and *Juncus gerardii/maritimus*). While there was a positive correlation between shear strength and belowground biomass in both the York River and U.K. marshes, the relationship between biodiversity and belowground biomass differs. We find that a decrease in biodiversity leads to an increase in belowground biomass, while the U.K. work determines the opposite trend (Ford et al., 2016). While biodiversity may not be driving soil shear strength variability in this study, it may be a more critical factor in the typically low productivity, high salt marsh platforms present across the U.K. (Ford et al., 2016).

Sea-level rise and saltwater intrusion are impacting wetlands in the York River estuary (Perry and Atkinson, 2009), and globally (Herbert et al., 2015; Neubauer, 2013; Noe and Zedler, 2000). While accelerated rates of sea-level rise could enhance wave erosion (Mariotti and Fagherazzi, 2010), and threaten the survival of marshes (Kirwan and Megonigal, 2013), sea-level

195 rise also leads to changes in vegetation type and productivity (Donnelly and Bertness, 2001; Kirwan et al., 2009; Morris et al., 2002). Although these changes will have a variety of ecological and geomorphic consequences, our work suggests that saltwater intrusion may be accompanied by stronger salt marsh soils that are less easily eroded.

Data Availability

200 Data has been archived to the Long Term Ecological Research repository, and can be found at doi:10.6073/pasta/26c848ab288cc14a2edb106f5800cfc8.

Author Contributions

All authors contributed to the organization of the study. MNG and TCM conducted field surveys and sample processing in the

205 lab. MNG performed data analysis. MNG composed the manuscript with significant contributions from MLK. All authors edited the paper.

Competing Interests

The authors declare they have no conflict of interest.

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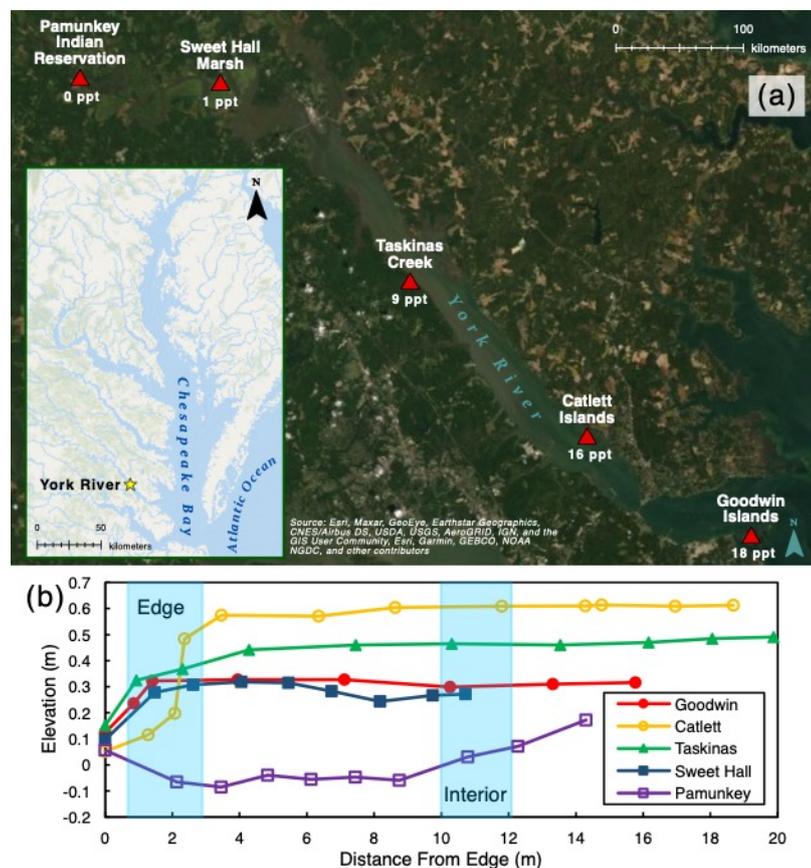
Figures

Figure 1: (a) Map of the York River Estuary study area, highlighting specific study site locations and their salinities. Average channel salinities are from Reay, 2009. (b) Elevation profile for each study site where elevation is relative to NAVD. Blue
325   shading indicates the location of marsh edge and interior sampling locations.

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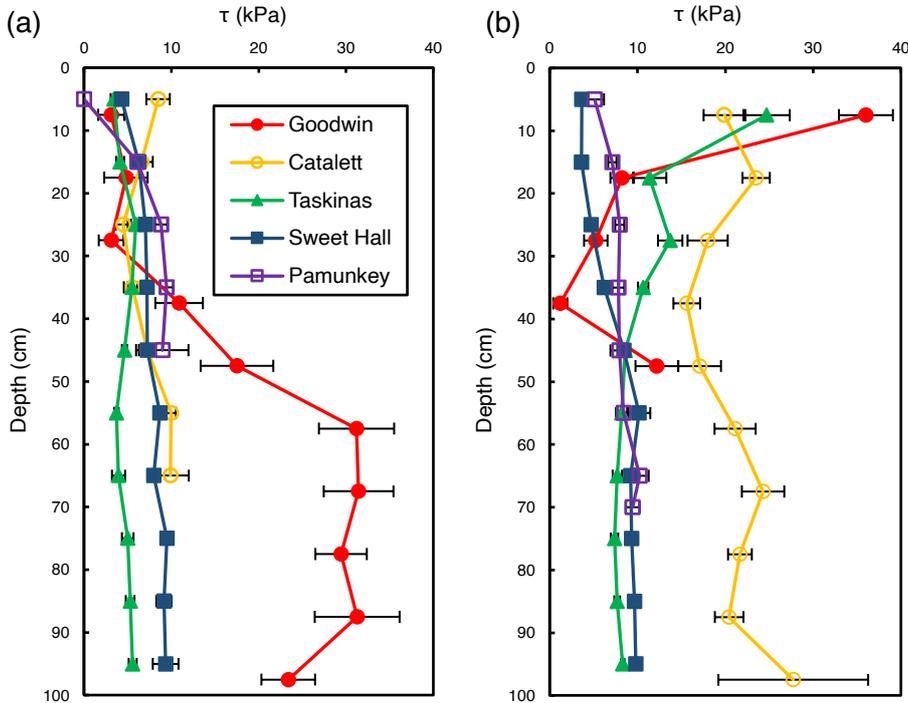
Figure 2: Average shear strength (τ) profiles for marsh edge (a) and marsh interior (b) locations at each study site. Each profile represents the average of 10 replicate profiles, where error bars represent standard error.

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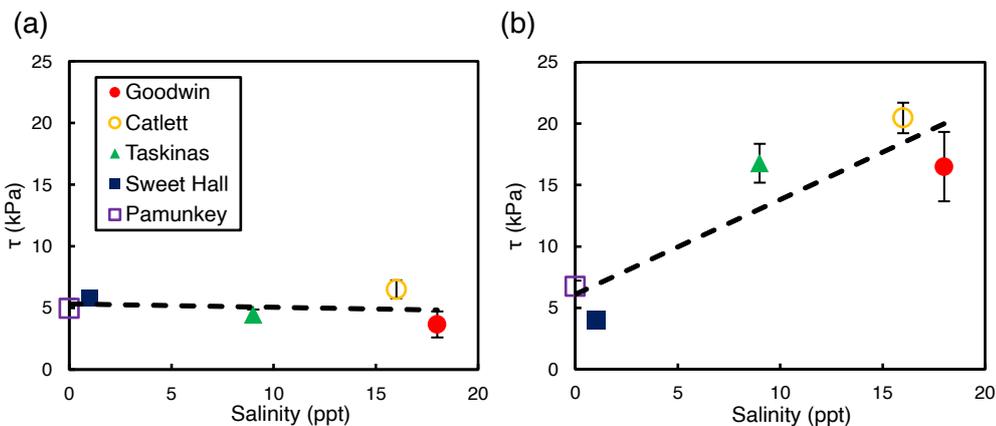
Figure 3: Relationship between salinity and shear strength (τ) for edge sites (a) and interior sites (b). Each point represents the depth-averaged shear strength value for the upper 30 cm of the soil profile, where error bars represent the standard error

335 associated with 10 replicate profiles for each site and location. Only the interior sites yielded a significant relationship between shear strength and salinity ($R^2 = 0.81$; $p = 0.038$).

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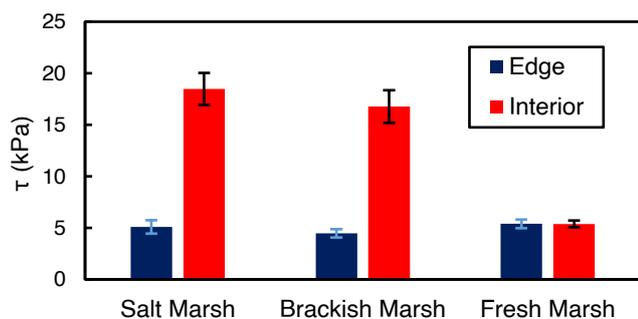


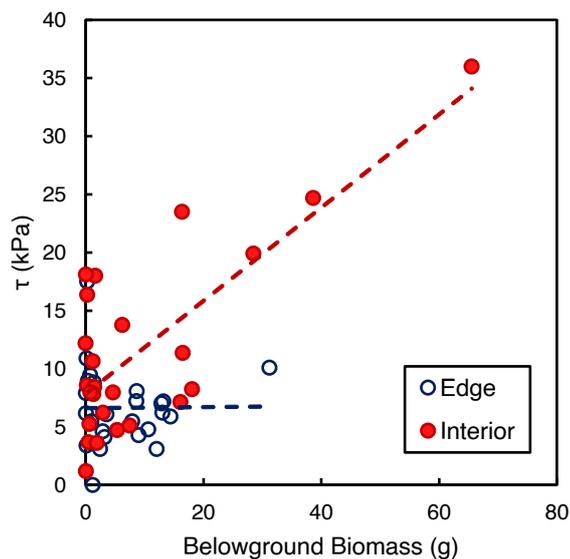
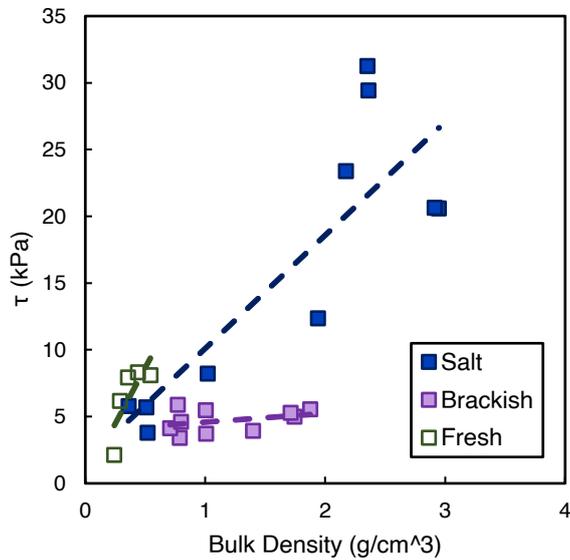
Figure 4: Average shear strength (τ) values for marsh edge and interior locations. Salt marsh locations are Goodwin Islands
340   and Catlett Islands, brackish marsh location is Taskinas Creek, and freshwater marsh locations are Sweet Hall Marsh and the
Pamunkey Indian Reservation. Each column represents the depth-averaged shear strength for the upper 30 cm of soil of each
marsh type. Error bars represent the standard error of 10 replicate shear strength profiles for each marsh type.

345   **Figure 5:** Shear strength (τ) compared to live belowground biomass for edge and interior locations. Each point represents a
biomass measurement with its associated shear strength value at concurrent depths in the soil profile. Only the relationship
between belowground biomass and shear strength in the interior was significant ($R^2 = 0.58; p = 1.09e\text{-}5$).

350 **Figure 6:** Shear strength (τ) compared to bulk density at concurrent depths in the soil profile. Relationships between shear strength and bulk density are as follows: salt marshes (Goodwin Islands and Catlett Islands) ($R^2 = 0.71; p = 0.002$), brackish marsh (Taskinas Creek) ($R^2 = 0.12; p = 0.318$), and freshwater marsh (Sweet Hall Marsh and the Pamunkey Indian Reservation) ($R^2 = 0.60; p = 0.126$).

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Figure 7: Photographs of belowground biomass root networks at concurrent depths for freshwater species *Peltandra virginica* (a) and salt marsh species *Spartina alterniflora* (b).