Received: 10 January 2023 | Revised: 2 October 2023 | Accepted: 5 November 2023
DOI: 10.1002/esp.5747

RESEARCH ARTICLE

ESPL WILEY

Geographic variability in headward erosion of marsh tidal creeks: Ecological and physical causes

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Funding information
National Science Foundation, Grant/Award Numbers: EAR-1131393, EAR-1800810, EAR-2022934; U.S. Department of the Interior, Grant/Award Number: 32324-F²; U.S. Fish and Wildlife Service, Grant/Award Number: F5AP00821

Abstract

Expansion of drainage networks through the headward erosion of tidal creeks is an eco-geomorphologic response of salt marshes to accelerated sea-level rise (SLR). This response can counter the negative impacts of an elevation deficit by increasing drainage and encouraging plant health, thereby reducing potential for submergence and marsh platform loss. In the wetlands of Cape Romain, SC, intense bioturbation near creek heads by the common marsh crab *Sesarma reticulatum* has been found to facilitate sediment erosion and rapid creek growth. This keystone grazer has been recently observed to have increasing influence on landscape evolution throughout the southeast US coast. Here, we compare measurements taken at Sapelo Island, GA, with those previously collected at Cape Romain, to confirm that eco-geomorphic feedbacks facilitating creek growth at each location are similar, and to compare these processes under differing background conditions. We use sediment cores, precise elevation measurements and historical imagery to compare substrate properties, elevation within the tidal frame, creek growth rates and drainage morphology at both sites. Our results show identical processes; however, the higher elevation of the marsh at Sapelo Island leads to shallower and shorter periods of tidal inundation, explaining the greater soil strength and lower belowground biomass compared with the marsh at Cape Romain. The smaller tidal range at the site in Cape Romain compared with Sapelo Island translates to a proportionally shallower depth of tidal creeks, which therefore requires less erosion to produce headward creek extension. These effects are likely to have contributed to slower growth rates of tidal creeks at Sapelo Island during the past several decades of SLR. Our findings highlight the similarities in process but differences in rates in how marshes are responding to climate-related stress.

KEYWORDS
ecogeomorphology, ecological engineering, marsh geomorphology, marsh geotechnical properties, salt marsh, sea-level rise, *Sesarma reticulatum*, tidal creek extension

1 | INTRODUCTION

Salt marshes are economically and ecologically valuable systems, but their existence is currently threatened by sea-level rise (SLR; Crosby et al., 2016). It is widely accepted that SLR causes marsh loss through morphological responses to submergence (Reed, 2002), salinity-driven dieback (Mendelssohn & McKee, 1988) or coastal squeeze (Torio & Chmura, 2013). As SLR accelerates, the marsh platform adapts in a variety of ways including pond expansion (Mariotti, 2016; Wilson et al., 2012), edge erosion (Bendoni et al., 2016; Mel et al., 2022), landward migration onto uplands (Fagherazzi et al., 2019) and by increasing drainage density (Chirol et al., 2018; D'Alpaos et al., 2010; French & Stoddart, 1992; Mariotti, 2018). This paper focuses on the response of drainage density increase and the attendant process of headward creek extension, specifically on marshes behind Sapelo Island, GA, and in Cape Romain, SC.

Previous studies have investigated various aspects of headward eroding creeks. It is well accepted that drainage density and creek morphology vary to reflect the tidal prism flowing through the channels (e.g., D'Alpaos et al., 2010). SLR causes greater inundation (depth and frequency) of the marsh, which increases tidal prism and hydroperiod. This has been demonstrated empirically (e.g., French & Stoddart, 1992; Stefanon et al., 2012), numerically (e.g., D'Alpaos et al., 2005, 2006) and analytically (e.g., D'Alpaos et al., 2010). A channel cannot be maintained unless there is sufficient flow velocity to prevent infilling, and the channel length or cross-section can only expand when the velocity increases enough to cause erosion. Such an increase in velocity in a tidal environment is often related to an increase in the volume of water transported during the constant period of a tidal cycle (i.e., an increase in tidal prism). When the same expansion in tidal prism, and consequent response in drainage density, is seen over a large geographic extent, SLR seems a likely driver. It has been suggested that this is the process driving tidal creek formation and extension along the southern Atlantic Bight (Crotty et al., 2020; Hughes et al., 2009; Wilson et al., 2022). A similar response to SLR and increased tidal prism has been observed in other regions, globally, including the Dyfi estuary, UK (Shi et al., 1995), northern Australia (Knighton et al., 1991) and the Bahamas (Rankey & Morgan, 2002).

Tidal creek extension through headward erosion occurs because of a positive feedback mechanism whereby ebbing flow is concentrated in topographically low areas, increasing bed shear stress and erosion, causing a deepening of the topographic low and the eventual lengthening of the channel (Coco et al., 2013; Symonds & Collins, 2007; Whitehouse et al., 2000). Creek initiation has also been observed where topographic gradients focus tidal flow in both natural environments (Chapman, 1960; Pethick, 1969) and numerical models (D'Alpaos et al., 2005; Fagherazzi et al., 2012; Rinaldo et al., 1999). Expansion of tidal creek drainage density is linked to an increase in tidal prism, which, physically, means longer periods of flooding and deeper inundation over the tidal cycle (Novakowski et al., 2004). As sea level rises, a larger, more efficient Hortonian drainage density may also facilitate temporary marsh survival by allowing increased sediment deposition that occurs with greater inundation depth (Kirwan & Temmerman, 2009; Morris et al., 2002) while preventing waterlogging and hypoxia caused by longer flooding periods (Reed, 2002).

The impact of bioturbation has been found to influence changes in creek geomorphology. Bioturbation by the herbivorous crab *Sesarma reticulatum* has been connected to vegetation die-off along marsh edges in salt marshes in New England (Coverdale et al., 2012; Holdredge et al., 2009). This region is dominated by highly organic, high marsh platforms, with comparatively strong soil strengths (e.g., Houttuijn Bloemendaal et al., 2021). This species has also been found in high populations at creek heads in South Carolina (Hughes et al., 2009), Georgia (Wilson et al., 2012) and elsewhere (Crotty et al., 2020). Zones of vegetation die-off at creek heads coincide with dense *S. reticulatum* burrows (e.g., >800/m^2; Hughes et al., 2009). This extensive bioturbation has been shown to cause a combination of biochemical and physical alterations to the substrate. Aeration due to the presence of burrows facilitates greater decomposition of organic matter (Wilson et al., 2012), and, in addition to herbivory, burrow excavation causes physical destruction of *Spartina alterniflora* roots (Vu et al., 2017). The reduction in sediment strength caused by removal of vegetation and excavation (Wilson et al., 2012) of formerly compacted sediment, in turn, reduces the critical erosion threshold (Blanchard et al., 1997; Farron et al., 2020; Le Hir et al., 2007). This ecological engineering by crabs has been linked to rapid expansion of tidal creeks in Cape Romain. The speed of the process was also linked to low sinuosity channels and a unique creek head morphology exhibiting bare, easily erodible semi-circles at their heads (Hughes et al., 2009; Wilson et al., 2012).

Impacts of ecological engineers, such as *S. reticulatum*, on creek growth and morphology are not limited to Cape Romain. *S. reticulatum* inhabit marshes all along the East Coast of the United States, from Cape Cod, MA, to the Gulf of Mexico (Abele, 1992). Feedbacks among bioturbation, vegetation, flow dynamics and salt marsh topography have been found to facilitate creek initiation and extension in marshes in Argentina, and along the southeast US Atlantic coast (Crotty et al., 2020; Escapa et al., 2007, 2015; Minkoff et al., 2006; Perillo et al., 2005; Perillo & Iribarne, 2003; Vu et al., 2017; Wilson et al., 2012).

Studies of creek formation in South America found that crab burrowing changed the physical properties of the sediment and created dead vegetation patches (Escapa et al., 2007). Low rates of sedimentation in the absence of vegetation, combined with erosion and collapse of the burrowed marsh, eventually formed topographically low areas on the marsh surface. These then developed into either salt pans (Escapa et al., 2015) or tidal creeks (Perillo et al., 2005; Perillo & Iribarne, 2003).

Vu et al. (2017) demonstrate that the manual removal of vegetation (as opposed to herbivory) also leads to accelerated creek extension (in the presence of the same high densities of *S. reticulatum* as the control creeks). There are several studies that have examined the physical properties of marshes and their bearing on platform stability. For example, a recent investigation by Brooks et al. (2021) provides a detailed account of marsh properties and how substrate resistance to hydrodynamic forcings can affect erosional processes. This work also explores how grazing can impact vegetative cover and the ensuing susceptibility to erosion. A detailed investigation by Chirol et al. (2021) showed a close correlation between the structure of pores and root systems and peat shear strength. Gillen et al. (2021) demonstrated that shear strength was related to water and organic content which depend on drainage efficiency and vegetation productivity, respectively.

Vu & Pennings (2021) conclude that the *S. reticulatum* 'front' at the edge of a creek head *follows* rather than leads the creek head; crabs move into areas with favourable conditions that are created by increased flooding and flushing as the creek extends. Mesocosm and flume experiments confirm that it is the high *S. reticulatum* population that leads to the high rate of burrowing near creek heads and that their activity increases percolation, decomposition and deflation of the platform surface. It should be noted that these creeks could not maintain their length or cross section if the volume of water transported (and therefore the flow velocity) was insufficient. In fact, further data by Vu (pers. comms) demonstrate that 2 years of removal of *S. reticulatum* from creek heads on Sapelo Island led to a slowing of creek incision, not a stop. Despite crab removal, the creeks continued to extend—indicating that other drivers are leading to creek extension in the absence of the crabs.

It is clear, therefore, that creeks on Sapelo Island and in Cape Romain are both eroding headward in response to SLR, both facilitated by *S. reticulatum*. Given these observations, findings and relationships, this study seeks to explore geotechnical and physical factors to confirm that the processes occurring at the creek head are the same in both locations. We look to explain why tidal creeks in Cape Romain, SC, consistently exhibit greater extension rates over a period of 35 years than those in Sapelo Island, GA, despite having similar headward eroding creek morphology (Figures 1b,c and S3). The same species of ecological engineer (*S. reticulatum*; Vu et al., 2017) are present at both sites, and both are experiencing similar rates of SLR (3–3.5 mm/year; NOAA, 2023b; Figure S4). However, the background conditions in terms of elevation and tidal range do differ between the sites. We hypothesize that the geographic setting may differentially affect sediment stability and creek evolution. To explore this hypothesis, this study has been designed to (1) quantify rates of morphological changes of the tidal creeks behind Sapelo Island, (2) document the geotechnical properties of the marsh and the eroding tidal creeks in GA and (3) compare the marsh conditions and geomorphic evolution of tidal creeks at Sapelo Island with those of Cape Romain (as measured by Wilson et al., 2012). GIS analyses of historical aerial photos were used to assess the morphological development of tidal creeks, in terms of channel sinuosity (to confirm similarity in morphology) and growth rates over time. Geotechnical analysis of sediment cores and precise elevation measurements from each location were used to evaluate the influence of site-specific conditions on creek growth and morphology. The results improve our understanding of the role of both biological and physical factors impacting sediment erosion and creek extension in response to SLR.

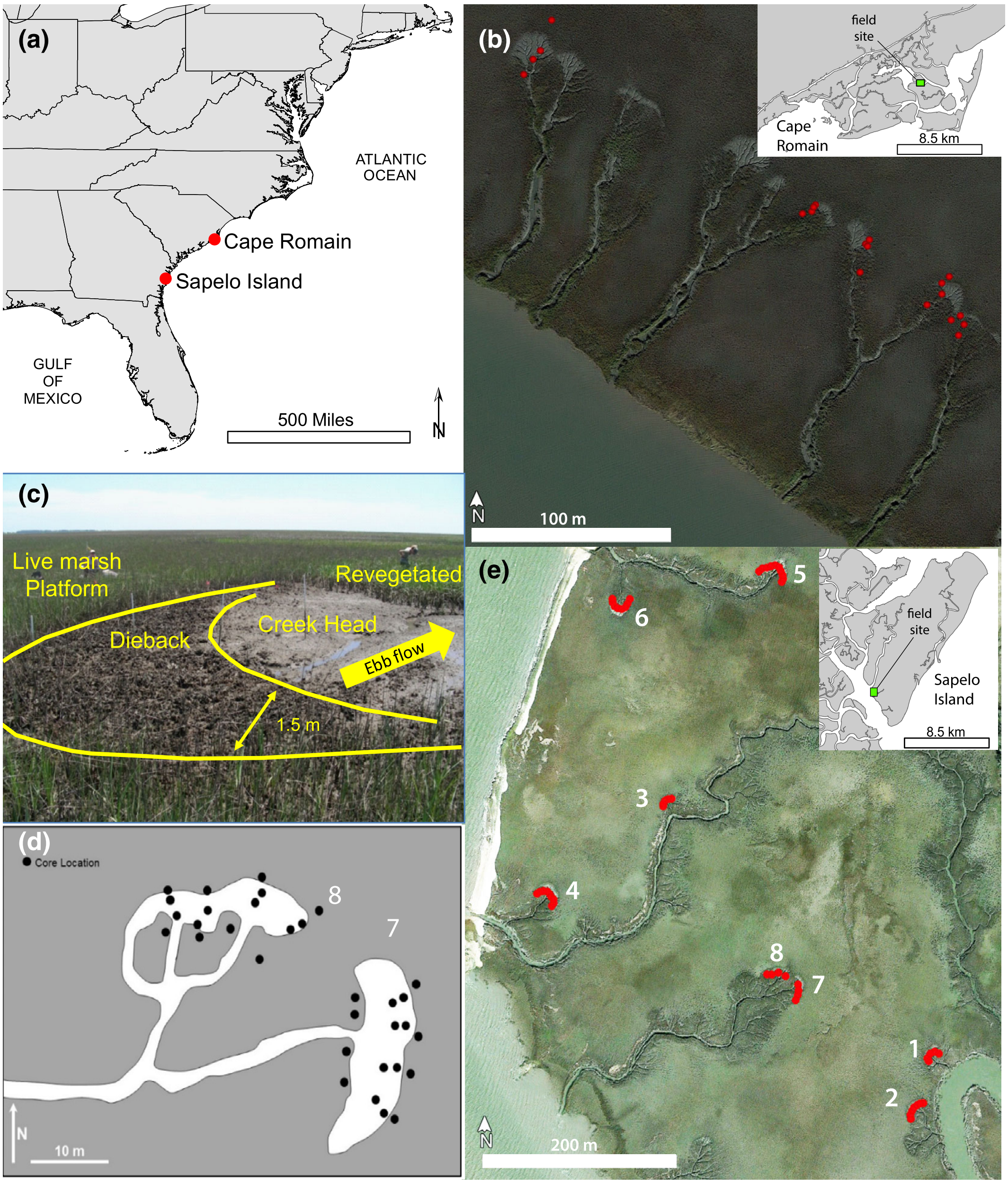

FIGURE 1 (a) Study site locations; (b) location of creek head elevation and core measurements at Cape Romain, SC (over 2013 image and adapted from Wilson et al. (2012); (c) photograph of creek head in Cape Romain, SC, with zones illustrated and labelled; (d) zoom of sediment core locations on creeks 7 and 8, Sapelo Island, GA for May 2013. Additional sediment cores collected in GA during July 2012 and October 2013 are not shown but were distributed similarly; and (e) location of creek head elevation measurements at Sapelo Island, GA.

2 | PHYSICAL SETTING

Cape Romain in central SC and Sapelo Island in central GA are located along the wide, flat South Atlantic coastal plain approximately 250 km apart (Figure 1a). The study area in South Carolina is fronted by a set of thin transgressive barriers (<0.1 km wide) defining the cuspate foreland known as Cape Romain, whereas the marsh in GA is positioned behind a Pleistocene and Holocene-age regressive barrier system (3–5 km wide; Hayes, 1994). The spring tidal range in Cape Romain is 1.5 m increasing to 2.4 m in Sapelo Island (NOAA, 2023a). Both study areas are dominated by *S. alterniflora*-dominated, platform marshes incised by a network of tidal creeks. Fine-grained sediment is fed to the marsh system at Cape Romain via the Intracoastal Waterway and coastal ocean from the Santee River and several rivers discharging into Winyah Bay to the north of the system. The marsh behind Sapelo Island receives suspended sediment from the Altamaha River, located to the south, through a complex system of tidal channels. Sediment at both marshes is dominated by silts, with a mean grain size of 58 and 55 mm at Sapelo Island and Cape Romain, respectively, and D_{50} of 27 and 24 mm, respectively. Using a *t*-test, we determined that there was statistically no difference in grain size between the sites (details of the grain size analyses can be found in the Supporting Information). Both areas are also experiencing similar SLR conditions (see Supporting Information and Figure S4). In Cape Romain, tidal flows in the shallow creek heads and on the marsh platform tend to be low (<10 cm/s in Cape Romain) increasing further along the creek (up to 0.8 m/s) with a clear ebb dominance (figure 4 in Hughes et al., 2009). Similar observations in Sapelo Island just seaward of the creek head show maximum flows of 0.2–0.3 m/s and, again, strong ebb dominance (Figure S5). Ebb dominance in salt marsh tidal channels is a response to the platform geomorphology (Fagherazzi et al., 2008) and implies a potential for net export of sediment. Farron et al. (2020) used passive tracers to measure shallow flows in the creek heads on Sapelo Island during the end of the ebb tide when the water was lower than 10 cm in depth and found that velocity ranged between 8 and 39 cm/s.

Marsh accretion rates vary across the marsh platform; however, in Cape Romain, rates at the platform edge (~10 m into the marsh) averaged 5.37 mm/year, compared with 7.94 mm/year for similar locations around Sapelo Island, based on ^{210}Pb measurements (Hein et al., 2023). However, Sediment Elevation Table measurements available in the literature indicate that the marsh elevation change is negative in Cape Romain (−3.97 mm/year) and averages only 0.3 mm/year around Sapelo Island (Crotty et al., 2020). This suggests that despite some areas receiving a reasonable amount of sediment, the marshes of the South Atlantic Bight are not keeping pace with local sea level.

3 | MATERIALS AND METHODS

3.1 | Creek growth tracking

Historical aerial photographs of Sapelo Island including 1945, 1976, 1984, 1992, 2003 and 2010 were evaluated to track the development of tidal creeks over time. Imagery for the study site was obtained from the Sapelo Island LTER and the Georgia GIS Clearinghouse and orthorectified to facilitate tracking of each creek from year to year. Imagery was orthorectified and creek channels were digitized using ArcGIS software; subsequent analysis of channel form was performed using MATLAB. Fifty creeks were digitized and tracked over the study period to determine the rate of channel incision. Digitizing was carried out by a single individual and the spacing/scale of the digitization was kept consistent. The number of creeks visible in the available in each image varied with a minimum of 41 being visible in all images. Changes in shoreline position due to erosion or differences in tide level were corrected for by beginning each channel from a common position near the channel mouth, so that changes in length over time were only a result of headward growth. One standard deviation in length change across the data set was used to represent the error for each image (incorporating rectification and measurement error). A subset of these creeks ($N = 25$) was further analysed to determine creek sinuosity, measured as the ratio of the channel length over the straight-line distance from mouth to head. Sinuosity was considered as it is known to increase with creek maturity (Pethick, 1969) and may provide an indication of how recently and rapidly formed these creeks are. These measurements were then compared with those documented for creek development at Cape Romain based on imagery from years: 1968, 1974, 1982, 1987, 1990, 1992, 1999, 2003 and 2006 (Wilson et al., 2012). One hundred creeks were measured at Cape Romain, although not all creeks were visible in every image, and thus, the measured number varied for each year ($N = 25$–100). Differences in creek growth rate and sinuosity between the two study sites (Sapelo Island and Cape Romain) were assessed using a two-sample *t*-test to determine whether the means differed significantly at the 5% significance level.

3.2 | Soil properties

A total of 88 sediment cores were collected along eight transects at the Sapelo Island study site. These were analysed to determine whether sediment properties in areas adjacent to tidal creeks differed substantially from those of the marsh platform and to determine if this varied seasonally. The cores were also used to compare with conditions previously measured at Cape Romain (Figure 1c); a full description of the Cape Romain cores and their analysis can be found in Wilson et al. (2012). At Sapelo Island, 32 cores were collected in late April–early May 2013 (Figure 1d), during the same month as those obtained at Cape Romain in 2010 to avoid potential seasonal variations when comparing differences in biomass productivity. These cores were taken at the very beginning of the growing season and are considered to represent Spring conditions. Additional cores collected in mid-June 2012 ($N = 32$; summer/mid-growing season) and late October 2013 ($N = 24$, fall/late growing season) provided a means to assess seasonal variations at the Sapelo Island site, and whether conditions changed over a short timescale.

Half-cylinder gouge auger cores (8-cm diameter, 60-cm depth) were collected along transects through the creek heads (eight transects each in June 2012 and May 2013 and six transects in October 2013). Each transect included one core from each of four identified zones (sensu Hughes et al., 2009): (1) marsh platform near the tidal creek vegetated by healthy *S. alterniflora* (hereafter referred to as the ‘live’ zone); (2) the region of dead vegetation adjacent to the creek head (the ‘dieback’ zone); (3) the collapsed mudflat, devoid of vegetation, at the creek head (the 'creek' zone); and (4) the zone directly down current from the creek head that has been recolonized by tall-form *S. alterniflora* (the 'revegetated' zone). The upper 50 cm of each core was subdivided into 10-cm increments, except for the upper 10 cm, which was divided into two 5-cm increments.

After collection, cores were refrigerated continuously to minimize biomass degradation. To determine bulk density, each sub-sample was dried at 60°C to a constant weight and divided by the original volume of the 5- or 10-cm segment within the 8-cm diameter core tube. To obtain belowground biomass content (consisting of *S. alterniflora* roots and rhizomes), samples were washed through a 500-μm sieve to remove mud and other inorganic particles. Any large shells or other non-vegetative material was removed by hand, and the remaining organic material trapped in the sieve was then collected, dried and weighed. Bulk organic content of the sediment was determined by homogenizing the sample and performing standard loss on ignition (550°C for 14 h; Heiri et al., 2001).

Shear strength measurements were taken using a handheld Seiken shear vane at each core location using a torsional spring with a maximum reading of 50 cN m. *In situ* measurements were collected at 10-cm depth intervals directly adjacent to each core location using a 3-cm vane head inserted vertically into the marsh substrate, providing shear strength readings (range 0 to 40 kPa) for the horizontal x–y axis of the soil with a precision of ±0.8 kPa. Shear strength measurements have been found to positively correlate with sediment erosion thresholds in soils with a dominant clay-water matrix (Chen et al., 2012; Jacobs et al., 2011). Measurements in Cape Romain were taken with the same instrument and exhibited a similar standard deviation (±3% average). Here, however, the final shear measurements presented by Wilson et al. (2012) were an average of in-ground (*in situ*) and in-core measurements. These two methods of data collection tested different planes of the soil. The two measurements were mostly found to agree (within the bounds of error), with the in-core measurements providing slightly higher strengths in the upper 20 cm of the core and slightly lower strength down core (Wilson et al., 2012). As the combined-plane method for determining strength was not found to differ significantly from the *in situ* method, they were considered suitable for comparison to the *in situ*-only measurements from GA.

3.3 | Marsh surface elevation

A total of 84 elevation measurements were collected at eight creek heads, including observations along the coring transects in creeks 7 and 8 (Figure 1b), and onto the marsh platform well beyond the live–dead vegetation interface. These were surveyed using a Real Time Kinematic (RTK) GPS receiver (TopCon hiper II) with vertical accuracy of ±2 cm. The measurements were collected to determine: marsh platform elevation relative to mean sea level (MSL) at each geographic location; the extent of elevation loss in the heavily burrowed creek head areas; and whether surface elevations recovered in the revegetated zone once tidal creeks extended farther into the marsh interior. Elevation data collected with the RTK were corrected to MSL at each location using data from nearby NOAA tide stations: 8677344 (St Simons Island, GA) and 8663618 (McClellanville, SC). Elevations within the Sapelo Island site were compared by ANOVA for similarity and a post hoc Tukey–Kramer test was used to assess which, if any, creeks or cross-transect position exhibited a significant difference.

4 | RESULTS

4.1 | Creek growth and morphology

Analysis of historical changes in channel length shows that growth rates of tidal creeks at Sapelo Island have varied somewhat over time, ranging from 0.7 to 1.6 m/year (Figure 2). The overall average growth rate for the 1945–2010 period was 1.2 ± 0.5 m/year ($N = 41$ creeks). This average growth rate was significantly slower [$t(128) = -4.19$, $p = 0.00005$] than that of tidal creeks in Cape Romain, which grew at an average rate of 1.9 ± 1.0 m/year ($N = 61$ creeks) between 1968 and 2006, varying from 1.5 to 3.2 m/year. Despite the high degree of variability in growth at both sites, average rates differ significantly. Creek sinuosity has remained largely unchanged over the same period. Tidal creeks at Sapelo Island exhibit an average sinuosity of 1.13 ± 0.07 ($n = 41$ creeks), slightly lower but not significantly different [$t(125) = -1.86$, $p = 0.07$] than that of creeks at Cape Romain, which have an average sinuosity of 1.20 ± 0.19 ($n = 97$ creeks). These values are lower than the averages reported for tidal channels in salt marsh environments (1.95, Garofalo, 1980; 1.4–1.8, Zeff, 1999), although not unexpected for first order (i.e., Strahler number of 1), dead-end tidal channels such as these, which tend to range in sinuosity from 1 to 1.2 (Chirol et al., 2018; Steel, 1996). That said, both Pethick (1969) and Fagherazzi et al. (2004) note that rapidly growing marsh creeks may be straight, developing meanders as they mature; thus, the lower sinuosity observed in this study may be a function of the recent creek expansion in both areas.

4.2 | Soil properties

Although sediment cores were collected and analysed to 50-cm depth (Figure 3), comparisons among the zones, locations and seasons will focus on the surface soil (upper 0–10 cm), where the most variability among zones was observed (Figure 3; following, Wilson et al., 2012). Average values for each zone and at each location are presented in Figure 4 and Table 1. Here and elsewhere, error is reported as ± one standard deviation, unless otherwise noted.

At Sapelo Island, bulk density increased down core in all zones except the dieback region and, below 10 cm of depth, all zones exhibited similar values (Figure 3). Average bulk densities ranged from a low of 0.11 ± 0.03 g/cm^3 in the dieback region to between 0.15 ± 0.03 and 0.16 ± 0.05 g/cm^3 in all other zones. The loss of surface bulk density in the dieback region is attributed to the void space created by extensive burrowing and was also observed by Wilson et al. (2012). Closer to the creek head, the substrate becomes consolidated because of the removal of vegetation and burrow collapse, and thus, bulk densities increase, eventually returning to background levels in the revegetated zone. Inorganic content values for the dieback, bare creek head and revegetated zones (77.8 ± 4.0, 80.5 ± 3.5, 79.7 ± 2.8%, respectively) are approximately 13% higher than for the live marsh platform (70.7 ± 3.9%). A higher proportion of inorganic sediment within these zones reflects the loss of biomass as well as

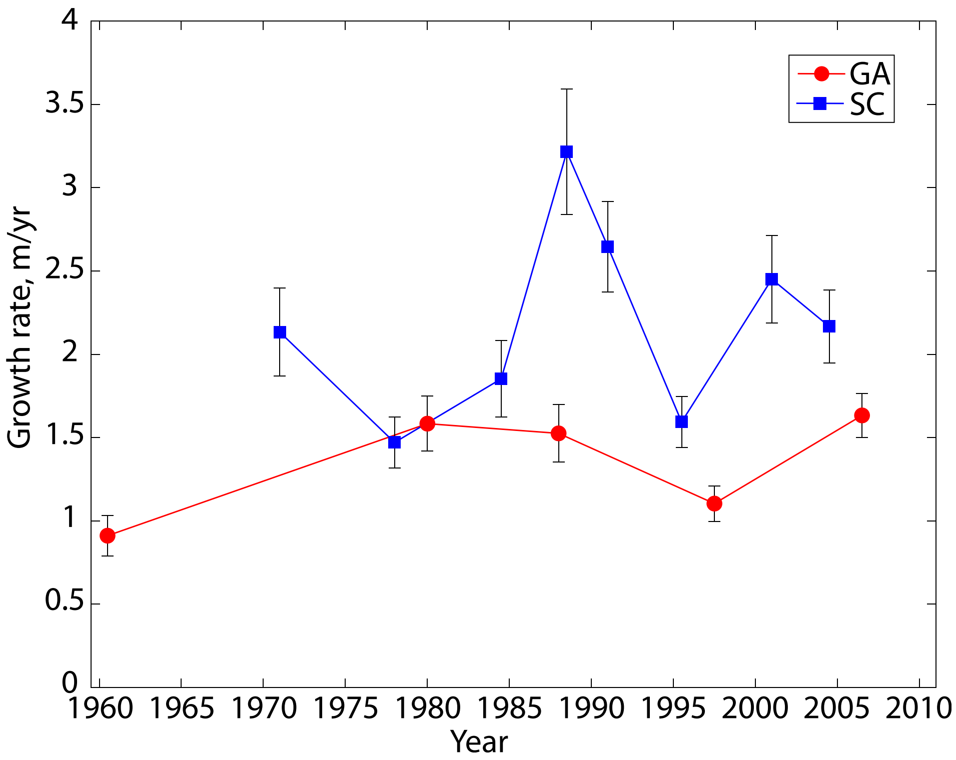

FIGURE 2 Historical rates of creek growth for Cape Romain, SC, and Sapelo Island, GA based on analyses of aerial photographs. *N* for each point varies depending on the presence of a creek in a given year, $N = 25$–100 (average 61) in Cape Romain and $N = 41$ in Sapelo Island. Error bars represent one standard error.

additional inorganic sediment deposited near creek heads. Biomass is predictably highest on the live marsh platform (6.92 ± 2.10 g) because of the presence of healthy *S. alterniflora*.

A 69% loss in biomass occurs in the heavily burrowed dieback zone (2.14 ± 1.38 g) compared with the marsh platform because of destruction of the root system and vegetation die-off, with an almost complete loss (95%) of biomass in the mudflat at the creek head (0.32 ± 0.22 g). Even in the revegetated zone (0.86 ± 1.02 g), belowground biomass remains minimal (88% less than the marsh platform). This indicates that, despite some recovery of the root system as vegetation returns, there is a significant loss of the preserved roots and rhizomes developed over the long term over previous growing seasons.

As with biomass, there is a significant reduction in shear strength transitioning from the live marsh platform (31.02 ± 3.97 kPa) into the dieback (13.64 ± 4.46 kPa; 56% lower), creek head (7.88 ± 2.67 kPa; 75% lower) and revegetated zones (11.52 ± 3.52 kPa; 63% lower). The lowest shear strengths occur on the mudflats of the creek head zone, where the incipient channel extension is developing and growing. Shear strength does not fully recover to the same level as the marsh platform after the creek head advances and the formerly bare area becomes revegetated. This is potentially due to the loss of intense rooting shown in the biomass data. It should be noted that the large size of *S. alterniflora* rhizomes can create heterogeneity on similar scales to the size of the shear vane (~1–3 cm); thus, many measurements should be taken in order to provide an average that reduces this noise. Shear vane measurements, therefore, represent an integral of the roots and soil matrix, and the average includes values where measurements of roots increase the shear strength. Occasionally, there were measurements in the live region that incorporated thick roots producing a shear strength above the measuring capacity of the instrument. Consequently, the average shear strength of the soil is likely slightly greater than the values shown in Table 1 for this zone.

A Welch's ANOVA was used to test the null hypothesis of no difference between populations followed by a post hoc Games–Howell test to determine which populations differed significantly. Analyses of these relationships are reported in detail in Tables S1 and S2 and primarily demonstrate that the geotechnical properties are significantly different between the live platform and the other 'modified' zones. In comparing the Sapelo Island marsh geotechnical data with that of Cape Romain (Wilson et al., 2012), bulk density and inorganic content were similar in most of the zones, with no significant differences between the sites or among the different zones (Tables 1, S1 and S2). Belowground biomass on the marsh platform in Sapelo Island was slightly lower than Cape Romain, but not significantly different. However, the Sapelo Island site experiences a much greater loss in biomass in the dieback and creek head zones, with little recovery in the revegetated zone despite the presence of tall form *S. alterniflora*. Despite this, shear strengths were significantly higher in all zones at the Sapelo Island locations compared with their counterparts in Cape Romain (which varied from only 7% to 31% of the Sapelo Island strengths).

Seasonal variability at the Sapelo Island location is illustrated in Figure 5. Statistical analyses (Welch's ANOVA followed by a Games–Howell test) demonstrate no significant difference between seasons for each zone (to $p < 0.05$), except for belowground biomass, which was seen to increase significantly ($p = 0.04$) between Spring (pre-growing season) and Summer (growing season). However, seasonal changes did have some impact on the significance of differences *between* zones. For example, higher bulk densities in the dieback zone observed in summer remain significantly different from the live zone in the summer, but if compared with the live zone data for other times of the year, the difference is not significant. Likewise, differences between soil shear strength in live and dieback zones do not always show significance across seasons, with soil shear strength in the dieback zone measured in Fall showing no significant difference

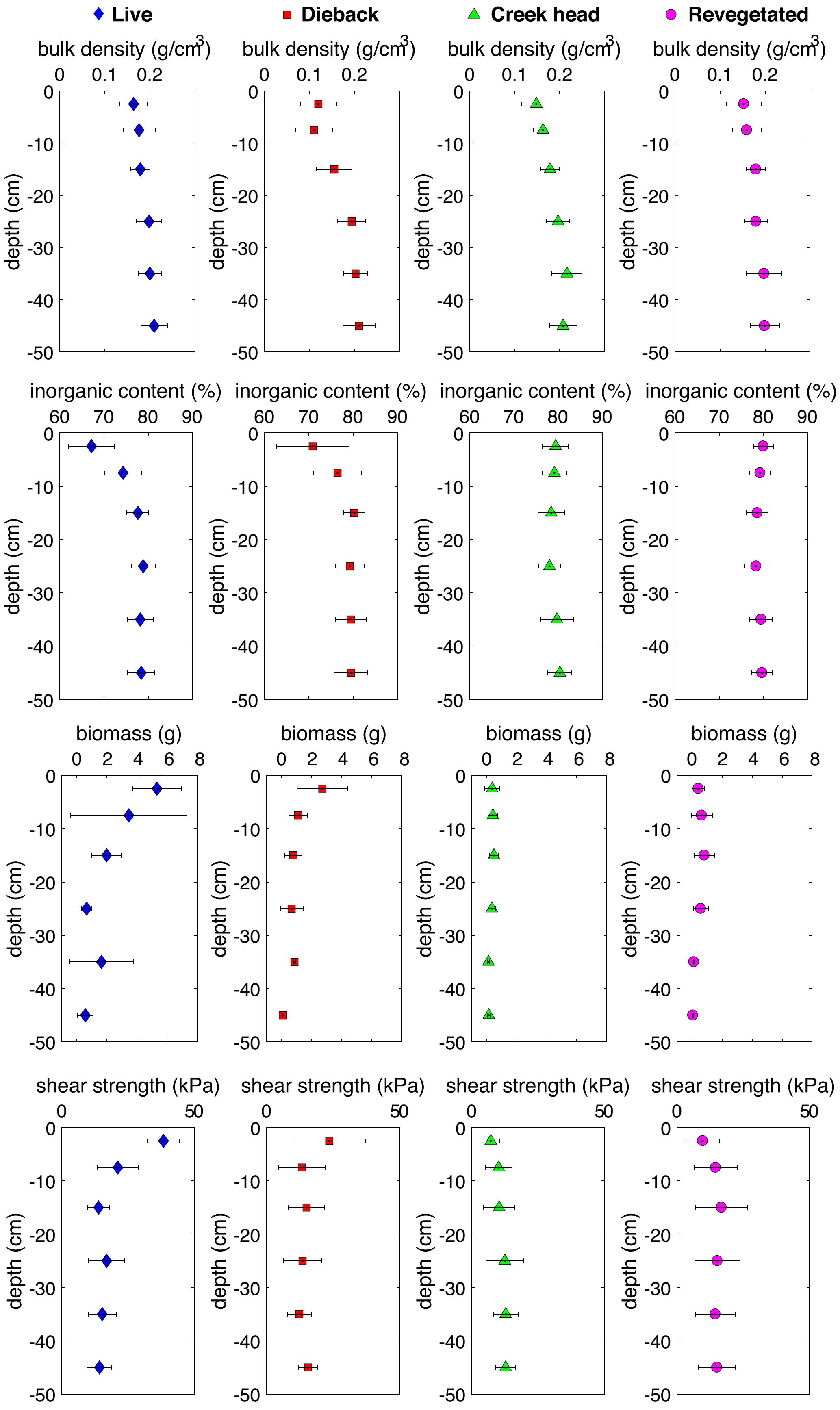

FIGURE 3 Down-core measurements of geotechnical properties from cores collected in early May 2013 for the four sub-environments at Sapelo Island, GA.

from strength in the live zones measured during Spring or Summer. This emphasizes the need for care with the timing of data collection due to increases in rooting over the growing season.

Linear regression was applied to determine the relationship between shear strength (as a proxy for erodibility) and other soil properties at each location (again following Wilson et al., 2012). These

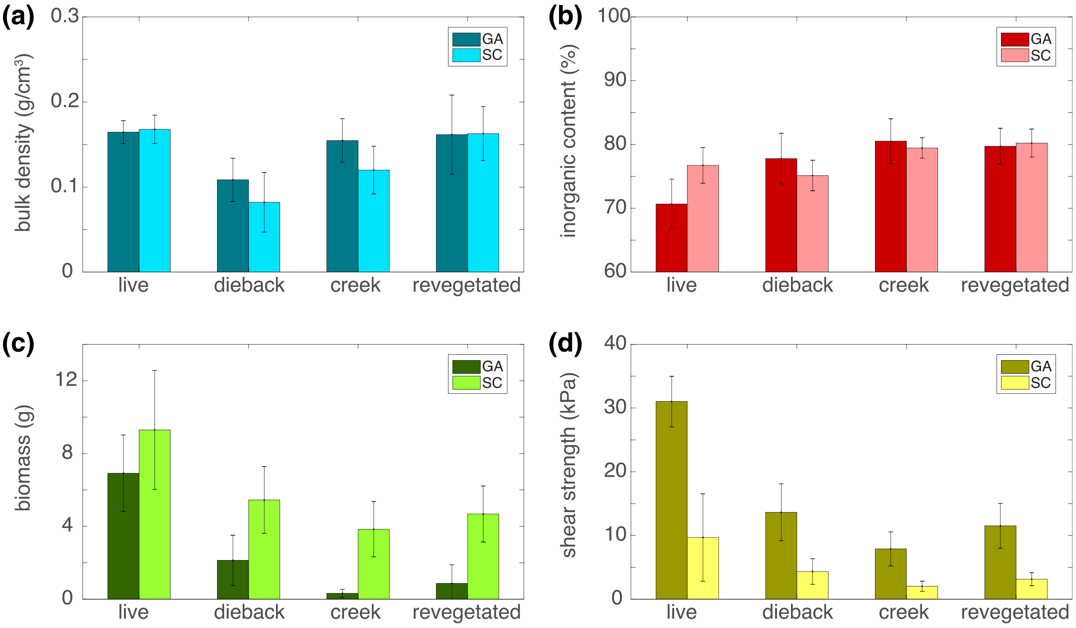

FIGURE 4 Comparison of surficial sediment (0–10 cm depth) geotechnical properties between Sapelo Island, GA, and Cape Romain, SC, for each of the sub-environments. Error bars represent one standard deviation. Note that shear strength measurements in SC were collected both *in situ* and within sediment cores; only *in situ* measurements were used for this analysis. Note the sharp differences in biomass and shear strength for GA versus SC.

TABLE 1 Average sediment core geotechnical properties for both study sites, including plus or minus one standard deviation.

	Zone	Bulk density (g/cm^3)	Inorganic content (%)	Biomass (g)	Shear strength (kPa)
GA	Live	0.16 ± 0.01	70.7 ± 3.9	6.92 ± 2.10	31.02 ± 3.97
	Dieback	0.11 ± 0.03	77.8 ± 4.0	2.14 ± 1.38	13.64 ± 4.46
	Creek Head	0.15 ± 0.03	80.5 ± 3.5	0.32 ± 0.22	7.88 ± 2.67
	Revegetated	0.16 ± 0.05	79.7 ± 2.8	0.86 ± 1.02	11.52 ± 3.52
SC	Live	0.17 ± 0.02	76.7 ± 2.8	9.30 ± 3.27	9.68 ± 6.87
	Dieback	0.08 ± 0.04	75.1 ± 2.4	5.45 ± 1.84	4.36 ± 2.01
	Creek Head	0.12 ± 0.03	79.5 ± 1.6	3.84 ± 1.52	2.03 ± 0.80
	Revegetated	0.16 ± 0.03	80.2 ± 2.2	4.68 ± 1.54	1.03 ± 1.01

Note: Values for Cape Romain, SC, previously reported (Wilson et al., 2012). Note that although shear strength measurements in Cape Romain were collected both *in situ* and within sediment cores, only *in situ* measurements were used for this analysis and comparison with Sapelo Island, GA.

relationships were assessed for the surface (1–10 cm) of each core (Figure 6a) as well as an average for the surface sediment for each zone (Figure 6b). No correspondence was observed between bulk density and shear strength at either site. A correlation of $r^2 = 0.48$ was found between inorganic content and shear strength for all the surface samples regardless of zone at Sapelo Island, and a correlation of $r^2 = 0.99$ was determined using the averages of the zones.

These relationships were not replicated at Cape Romain ($r^2 = 0.15$, $p = 0.15$ using values for all the cores, and $r^2 = 0.25$, $p = 0.48$ using averages of each zone), which may be partly a result of fewer data points. Overall, the strongest relationship occurred between shear strength and belowground biomass, with the highest correlations found at Sapelo Island compared with Cape Romain for both the core surface data ($r^2 = 0.71$ vs $r^2 = 0.65$, respectively) and the averages for each zone (both $r^2 = 0.99$).

The greater soil strength of belowground biomass at Sapelo Island versus Cape Romain suggests that this attribute may be the chief soil factor controlling differences in sediment stability and eventual erosion seen at creek heads at both locations, which is predictably faster in Cape Romain. However, despite overall strength being significantly greater in Sapelo Island for a certain biomass, relative to Cape Romain, the same along transect trends of erosion and elevation loss along transect are observed. This suggests the same geomorphic processes are occurring at both sites, but the rates are controlled by local variables.

4.3 | Marsh surface elevation

Both the Sapelo Island and Cape Romain sites exhibit a loss in elevation between the live marsh platform and the dieback region (Figure 7). This trend is followed by a further decent into the creek head mudflat and then a slight recovery in elevation within the revegetated zone. Also noted was a greater loss in elevation observed

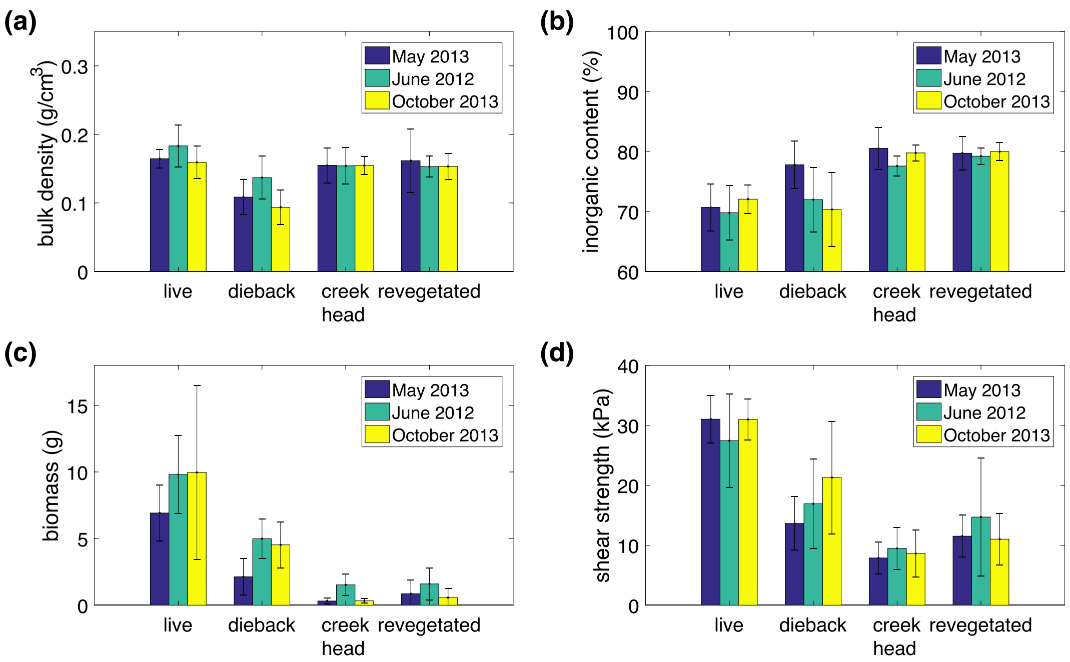

FIGURE 5 Seasonal comparison of geotechnical properties (1–10 cm) for each of the sub-environments at Sapelo Island, GA. Error bars represent one standard deviation.

between the live and creek head zones in Sapelo (0.26 m) compared with Cape Romain (0.12 m). Average elevations for each zone at the two study areas were compared within each site via Welch's ANOVA to test the null hypothesis of no difference among the populations, followed by a post hoc Games–Howell test to determine which populations differed significantly (Tables S1 and S2). The results of these statistical analyses highlight the steeper elevation drop into the Sapelo Island creek heads compared with those in Cape Romain and are discussed in the Supporting Information. The two sites show a significant difference in relative elevation.

A similar analysis was used to compare the elevations of different creek heads in GA. The majority (6) of the creeks surveyed ($N = 8$) displayed similar elevations at the live–dead boundary (average of 0.795 m above MSL). Only one creek exhibits a significant difference to the others (creeks 5; Figure S1). No pattern was observed between length, size or stream number of creek and significant difference in elevation. This boundary represents the herbivory front of *S. reticulatum*, and the observed similarity in elevation suggests a water level control on the crabs' activities and thus a likely tie to SLR. The dieback, creek head, and revegetated zones are consistently significantly different (lower) in elevation than any live marsh area, whether close to a creek head or mid-marsh (Figure S2).

The data in Figure 7 also reveal that the marsh platform surface (live marsh) at Sapelo Island (based on eight creek head transects) is 0.62 m higher than the marsh at Cape Romain in relation to MSL, with the dieback, creek head and revegetated regions ~0.5 m higher than their SC equivalent. The high marsh elevation in Sapelo Island is 0.80 m above MSL compared with 0.18 m at Cape Romain. The base of the creeks along the fully developed portion of the channels close to the creek head have elevations of 0.3 and −0.18 m (to MSL) in the Sapelo Island and Cape Romain study areas, respectively. Close to the creek mouth, these values are −0.5 and −0.6 m. Given these elevation differences, it can be estimated that, as the creeks headward erode through the marsh, the Sapelo creeks must remove a column of sediment between 0.49 and 1.3 m high compared with between 0.36 and 0.76 m in Cape Romain.

5 | DISCUSSION

5.1 | Soil properties

A thorough discussion and interpretation of the physical and chemical properties of the marsh substrate adjacent to creek heads in Cape Romain and their implications for the effects of *S. reticulatum* burrowing can be found in Wilson et al. (2012). However, to gain a better understanding of ecogeomorphic factors affecting creek extension and to confirm that the two sites are undergoing the same process of crab-facilitated extension, this analysis focuses on the differences and patterns in soil properties among zones at Sapelo Island, GA, and between the study geographically distant sites in GA and Cape Romain, SC. Belowground biomass and shear strength show the most notable differences between these sites (Figure 4). Although belowground biomass levels are similar on the marsh platform for both sites, there is a greater loss of biomass at Sapelo in areas adjacent to tidal creeks. There are several potential explanations for these differences. One possibility could be that *S. reticulatum* population densities are higher at the Sapelo Island site. Mesocosm studies found that excavation rates increase, and belowground biomass decreases, with increasing *S. reticulatum* population density (Vu et al., 2017). More densely populated creek heads could lead to greater vegetation and soil removal and, thus, faster creek incision. However, reported populations are very similar: ~30 crabs/m^2 at Sapelo Island (observed by Crotty et al., 2020), compared with 35 crabs/m^2 in Cape Romain (Vu et al., 2017).

Alternative explanations for the differences in the change in belowground biomass between the two locations include a potentially greater resilience of the *S. alterniflora* marsh grass at the Cape Romain

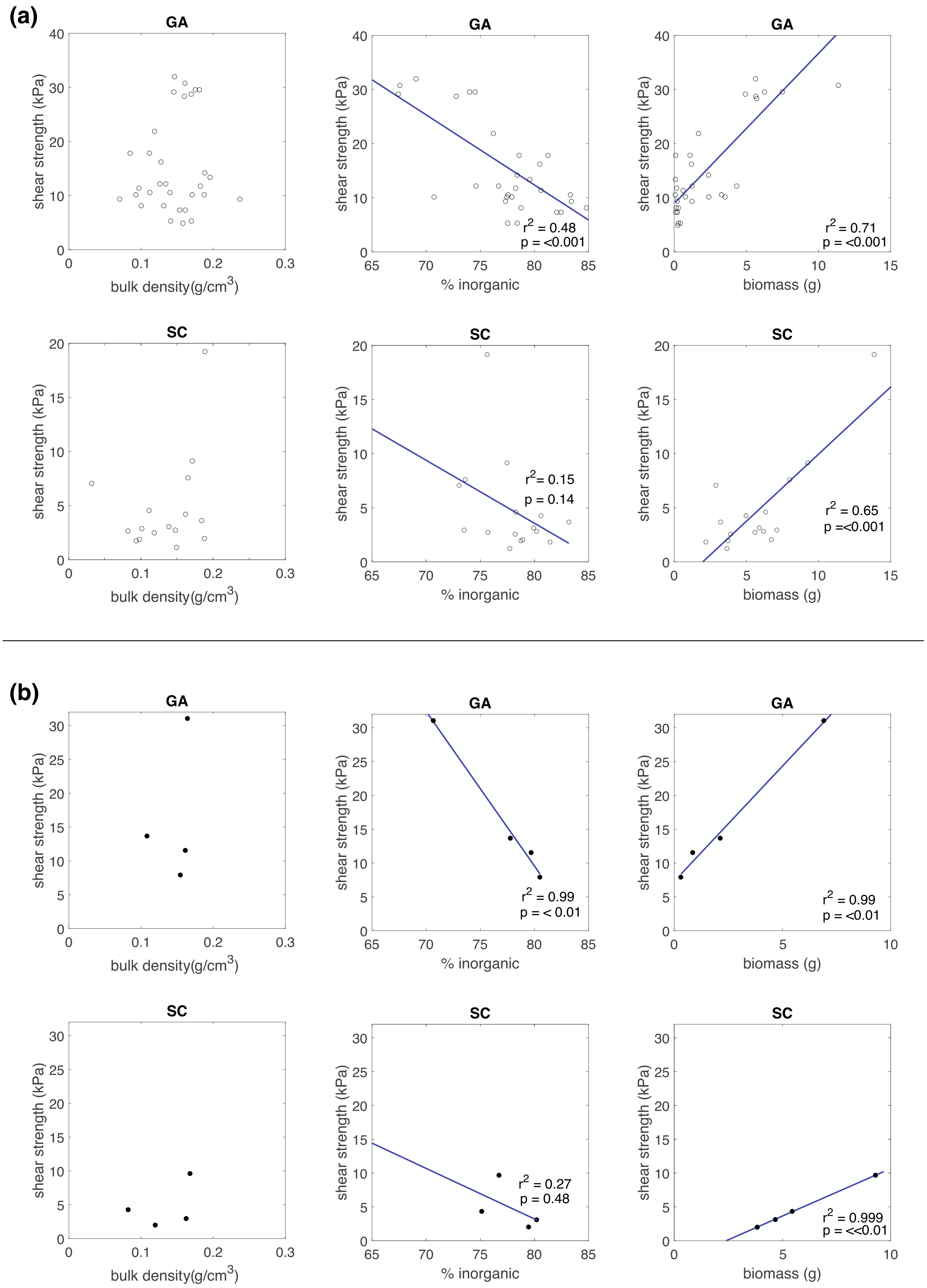

FIGURE 6 Correlation between shear strength and geotechnical properties for (a) surficial sediment (1–10 cm) for each core and (b) averages for surficial sediment within each zone.

site. Below a certain threshold, where inundation becomes detrimental, increasing tidal inundation leads to increased primary productivity (Morris et al. 2002) and, thus, greater above and below ground biomass. A comparatively higher productivity rate, due to the lower elevation of the marsh compared with MSL, could explain the higher levels of belowground biomass at the lower elevation site, despite crab-grazing. A more robust root system may also allow for greater *S. alterniflora* survival in creek head areas, as this species spreads via the lateral outgrowth of rhizomes (Redfield, 1972). Healthier plants nearby would aid in the maintenance of vegetation in creek heads. This may also explain the significantly greater recovery of belowground biomass levels in the revegetated zone in Cape Romain compared with Sapelo Island (Figure 4 and Tables S1 and S2). However, the lower biomass at Sapelo Island could also be a function of the rate of decomposition in burrowed areas (Wilson et al., 2012). A larger tide range and higher position in the tidal range suggest that creeks on Sapelo Island remain high and dry for longer during the tidal cycle than those at Cape Romain. During this time, the intense burrowing at the edge of the creek head allows oxygen to reach the normally anoxic marsh soils for longer, increasing decomposition.

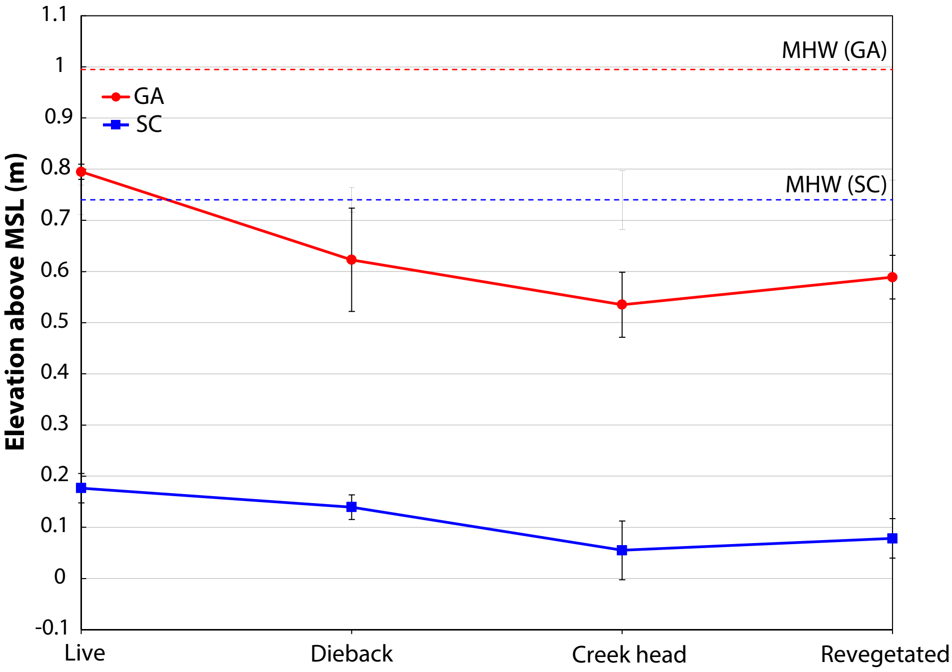

FIGURE 7 Average elevation within each zone at Sapelo Island, GA (red circles, N varies by zone = 8 to 84) and Cape Romain, SC (blue squares, *N* = 5). Error bars represent one standard deviation. Water level data for GA and SC obtained from NOAA Tide Stations 8677406 (Brunswick, GA) and 8662245 (Oyster Landing, SC).

Shear strength of the marsh platform is considerably greater at Sapelo Island than at Cape Romain, and despite the generally lower levels and greater loss of biomass in the dieback and creek heads in Sapelo, shear strengths there remain significantly higher compared with those in Cape Romain (Figure 4). The higher background stability of the substrate may, again, be related to the marsh's elevation relative to MSL and position within the tidal frame, with soils that are inundated for longer tending to be weaker (Watts et al., 2003). This is supported by the statistical analyses in the Supporting Information, which indicate that the two locations are similar in bulk density, inorganic content and, for the most part, biomass but show significant differences in both soil strength and elevation. The more resistant substrate in Sapelo Island relative to Cape Romain will contribute to the lower rates of erosion and slower headward retreat of the tidal creeks (Figure 2).

5.2 | Effects of sea level and marsh elevation on creek development

Wilson et al. (2012) concluded that site-specific factors, such as tidal range, relative SLR and vegetation, control hydrodynamic forcing and rates of creek extension at a particular location, which appears to be consistent with our findings. SLR is similar at both sites, it is possible that it is slightly lower at Sapelo Island (Figure S4 and discussion), which may contribute to the overall slower creek incision at that site. There is also some indication that variability of creek incision over time reflects shorter-term variability in sea level variation. The decrease in rates of creek growth at both locations from the late 1980s–early 1990s to early 2000s (Figure 2) may be related to a slowdown in the rate of SLR or decadal variations in local sea level related (Figure S4). Likewise, the relative influence of SLR is also higher in Cape Romain compared with Sapelo Island, as relative SLR is proportionally larger compared with the smaller tidal range in Cape Romain and the deficit between accretion rates and SLR and net change in elevation from SET is also greater at Cape Romain.

The marsh at Sapelo Island is higher in elevation with respect to MSL, has a larger tidal range and is positioned higher in the tidal frame than the marsh at Cape Romain. As a result, over the course of an average tidal cycle, the marsh in Sapelo is flooded for a shorter period with a shallower depth of water than in Cape Romain. These hydrodynamic differences likely influence vegetation growth (related to hydro-period) and sedimentation at these two sites (Morris et al., 2002). When the marsh surface is exposed to air for longer periods of time, it undergoes greater drying and consolidation. Conversely, marsh sediment that is inundated more frequently has a higher water content and, as a result, a lower shear strength (Watts et al., 2003). A comparison with the Great Marsh in Massachusetts further illustrates this point; here, the tidal range is 2.8 m, and the marsh platform there is predominantly a high marsh positioned at 1–1.5 m above MSL, approximately the same elevation as MHW. This marsh has an average shear strength of ∼25 kPa (Houttuijn Bloemendaal et al., 2021), greater than most measurements taken as part of this study, excluding the marsh platform in Sapelo Island.

In addition to greater shear strength, the larger tidal range and higher marsh platform in Sapelo will impact erosion rates in several ways. As the marshes in Sapelo Island sit higher in the tidal frame, the volume of the tidal waters (tidal prism), which covers them (and drains through them), is smaller than that in Cape Romain (Figure 7). Tidal prism is known to drive expansion of marsh drainage (D'Alpaos et al., 2005; Fagherazzi et al., 2012), helping to explain more rapid creek incision observed in Cape Romain.

The greater difference in elevation between platform and creek in Sapelo Island versus Cape Romain means that a larger volume of sediment must be removed to produce a comparable rate of creek incision in Cape Romain. Moreover, the steeper gradient at Sapelo may lead to greater acceleration in flow velocities as water is funnelled into tidal creeks during the ebb cycle. Greater flow velocities may partially compensate for the more resistant substrate and the larger volume of sediment to erode in Sapelo, making creek erosion rates more comparable with those in Cape Romain. There is some evidence for faster flow velocities on Sapelo island compared with Cape Romain

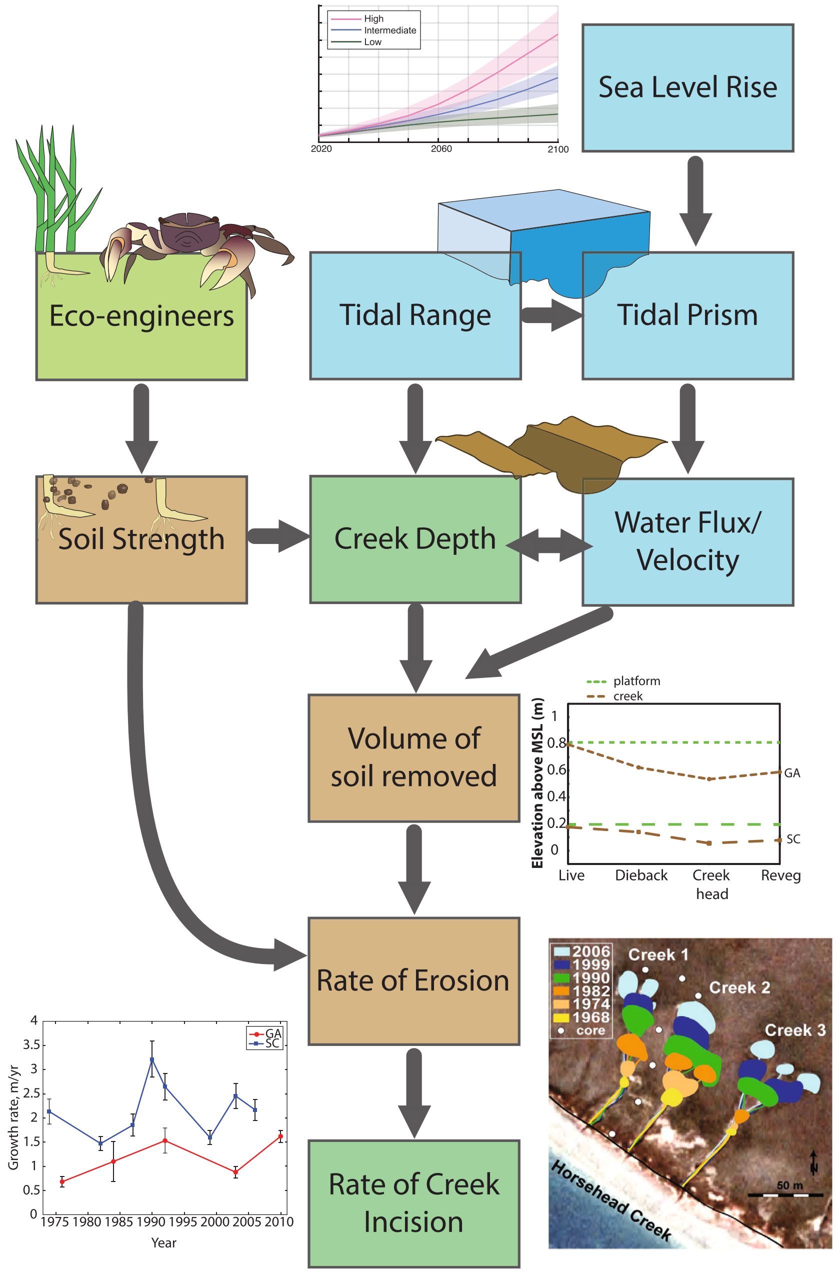

FIGURE 8 Conceptual diagram illustrating the factors influencing the rate of creek incision in a marsh responding to sea level rise.

(see Section 2 and Figure S5); however, the flows were not recorded at exactly the same positions along-creek or stage of the tide.

Creeks at both sites had similar low sinuosity, which is typically a sign of immaturity (Allen, 2000; Pethick, 1969) and low stream order (Steel, 1996). The rapid extension of the tidal creeks at these sites explains this low sinuosity, since creeks tend to be straight during periods of rapid headward growth, becoming more sinuous as they age (Fagherazzi et al., 2004; Pethick, 1969). This is somewhat contrary to the results of a stochastic model of drainage network formation, in which faster rates of incision lead to more branching, irregular creeks, whereas slower incision leads to fewer, straighter creeks (Fagherazzi & Sun, 2004). However, the authors attributed creek incision to slumping caused by substrate heterogeneities, where more heterogeneity produces faster incision via larger slumping, causing more irregular channel patterns. In the case of ecosystem engineers facilitating creek extension at our study sites, sediment erosion and creek incision are likely being facilitated not by large-scale slumping, but by a reduction in sediment shear strength and frequent removal of smaller amounts of burrowed sediment near the incipient channel (Farron et al., 2020).

Although storms may create high creek velocities or wave energy over a very short timescale, a comparison of the influence of storm impacts is beyond the scope of this paper. Georgia and South Carolina have experienced a similar number of landfalls by major hurricanes (category 3–5): 3 and 6, respectively, over the period of record (0.03 and 0.032 per mile when normalized by coastline length; see Table S3). This can be compared with, for example, 35 (0.026/mile) in Florida, 12 (0.04/mile) in North Carolina and 19 (0.052/mile) in Texas, and normalized by coastline length (1851–2022; NOAA, 2023c). Both are regularly impacted by storms, and so the differences in creek incision rates are unlikely to be related to differences in storm frequency and intensity. In addition, hurricanes are more often associated with sediment deposition on marshes, as opposed to large scouring events (e.g., Tweel & Turner, 2012), and recent studies suggest little sediment removal across the marsh platform due to storm waves (Spencer et al., 2015). However, although any large precipitation event or storm-related surge may increase the volume of flow in the creeks and thus impact creek incision, it is also important to note that any response to storm surge would be modulated based on each site's soil properties and elevation (and what that means in terms of erodibility and tidal prism, as discussed above).

6 | SUMMARY AND CONCLUSIONS

These findings demonstrate similar patterns of geotechnical changes that occur within *S. reticulatum* grazed creek heads in both South Carolina and Georgia, confirming the same ecogeomorphologic processes are at work at both sites. It also provides a greater understanding of factors controlling the rates of creek extension, summarized in Figure 8, and highlights how marshes in two geographic areas with differing physical settings maybe responding to SLR at different rates.

Morphological data indicate that the same pattern of degradation (related to the same infauna species) facilitates headward creek erosion at Sapelo Island (GA) as in Cape Romain (SC) marshes (Wilson et al., 2012) and elsewhere (Crotty et al., 2021). Similarities in the geomorphology among sites include channel morphologies with low sinuosity, low-order creeks and a semi-circular region denuded of vegetation at the creek heads.

Down-core measurements of geotechnical properties within the zones of the headward eroding creeks at Sapelo Island show that most of the variability in bulk density, inorganic content, belowground biomass and shear strength occurs in the top 10 cm (Figure 3). This pattern was also observed in creek heads at Cape Romain by Wilson et al. (2012). From this, we conclude that the process of biological facilitation in each place is the same.

A comparison of the geotechnical properties of the creek head zones demonstrates that bulk density and inorganic content show the least degree of change from the live marsh towards the creek head, as well as between the Sapelo Island and Cape Romain sites (Figure 4). At Sapelo Island, both biomass and shear strength decreased sharply from the live zone to the creek head, whereas these parameters exhibit much less change at the Cape Romain sites. Despite the marsh at Cape Romain containing greater belowground biomass at all zones, the Sapelo Island marsh shows considerably higher shear strengths (Figure 4 and Tables S1 and S2). However, a strong correlation between shear strength and belowground biomass exists within each site (Figure 5).

Steeper and deeper tidal creek heads are observed in Sapelo Island, GA (mean of 1.7 m), compared with those in Cape Romain, SC (mean of 0.7 m). This is most likely the result of a greater tidal range in GA versus central SC. In addition, the marsh platform in SC sits 0.25 m lower in the tidal frame (with respect to MHW) (Figure 7). This results in deeper flooding and a shorter period for drainage in SC, likely leading to a higher soil water content and, therefore, weaker soil, despite higher biomass. This is a significant finding as it implies a reduction in marsh resilience as SLR accelerates and marshes become less able to keep pace leading to increasing tidal prism. Although deeper flooding can increase productivity in marsh vegetation, thus producing greater belowground biomass (Morris et al., 2002), soils may not, in fact, be strengthened because a longer flooding period, as observed here, leads to a weaker mud matrix surrounding the rooting (Figure 8).

The Sapelo Island creeks are headward eroding at an average rate of 1.2 ± 0.5 m/year compared with the Cape Romain creeks' rate of 1.9 ± 1.0 m/year. In addition to the larger tidal prism in Cape Romain, flooding and draining the marsh platform driving faster drainage expansion, the slower rate of creek incision in Sapelo (Figure 2) is also explained by the greater shear strength of the marsh there, suggesting that marsh in Cape Romain is more easily eroded. Additionally, the deeper eroding creeks in Sapelo require a greater column of sediment to be eroded (0.62 m) to achieve the same distance of retreat compared with the Cape Romain creeks (Figure 8).

Similarities in the elevation (to MSL) of the *S. reticulatum* herbivory front in creeks throughout the Sapelo Island site indicate that this front is driven by an inundation period, as suggested by Crotty et al., 2020 and confirmed by Vu et al. (2021). Our data, therefore support the observation that the front is driven forward onto the marsh by rising sea level.

This study demonstrates that the rate at which the marsh is responding to SLR and the consequent increase in flooding and draining is strongly influenced by the geographic setting. Despite the same bio-engineering and physical processes operating in Cape Romain, SC, and Sapelo Island, GA, the Cape Romain system appears to be responding more rapidly to the SLR, whereas the greater freeboard of the Sapelo Island marsh implies a greater resilience.

AUTHOR CONTRIBUTIONS

Zoe J. Hughes: conceptualization, funding acquisition, methodology, investigation, supervision, writing—initial draft and writing—reviewing and editing. **Sarah J. Farron:** methodology, investigation and writing—initial draft. **Duncan M. FitzGerald:** conceptualization, funding acquisition, methodology, supervision and writing—reviewing and editing.

ACKNOWLEDGEMENTS

The authors would like to thank the GCE-LTER for their help and assistance, as well as those at UGAMI (this paper is contribution 1091). We also acknowledge the valuable input from Huy Vu, Steve Pennings, the University of Houston summer interns 2012–2013 and Boston University undergraduate research assistants: Brittany Schwartz, Ana Fioretti, Danielle Trahon and Sarah Black. Grain size measurements were undertaken by Alice Staro at the Hein Lab, Virginia Institute of Marine Science, gratefully received, and then analyzed for this paper. Funding for this research was provided by the following grant awards: NSF EAR-1131393; DOI/FWS F5AP00821; DOI/NWF 32324-F^2; NSF EAR-1800810, NSF EAR-2022934.

DATA AVAILABILITY STATEMENT

Data for this paper (core data, RTK data, vector GIS data of creeks and creek length data) are being submitted to the National Centers for Environmental Information before publication. This process is in progress.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Hughes, Z.J., Farron, S.J. & FitzGerald, D.M. (2023) Geographic variability in headward erosion of marsh tidal creeks: Ecological and physical causes. *Earth Surface Processes and Landforms*, 1–15. Available from: https://doi.org/10.1002/esp.5747