Author's accepted copy of:

Blum, L. K., R. R. Christian, D. R. Cahoon, and P. L. Wiberg 2020. Processes influencing marsh elevation change in low- and high-elevation zones of a temperate salt marsh. *Estuaries and Coasts*. doi 10.1007/s12237-020-00796-z

Processes influencing marsh elevation change in low- and high-elevation zones of a temperate salt marsh

Linda K. Blum[1*], Robert R. Christian[2], Donald R. Cahoon[3], and Patricia L. Wiberg[1]

[1] Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904-4123

[2] Department of Biology, East Carolina University, Greenville, NC 27858

[3] US Geological Survey, Patuxent Wildlife Research Center, Laurel, MD 20708

Acknowledgements

This paper could not have been written without contributions of Mark M. Brinson to the experimental design, data collection, and early drafts of the manuscript before his death. We dedicate this paper to Mark's memory. We gratefully acknowledge the assistance of numerous students and volunteers for help with field measurements, especially Patricia Willis and Arthur Schwarzschild. James Lynch and Aaron Mills assisted with the installation of SET and RSET stations. The Virginia Coast Reserve of the Nature Conservancy provided access to study site. We wish to thank James Lynch, Aaron Mills, and two anonymous individuals for their review comments. This material is based in part upon work supported by the National Science Foundation under Grants No. BSR-8702333-06, DEB-9211772, DEB-9411974, DEB-0080381, DEB-0621014, DEB-1237733 and DEB-1832221 to the Virginia Coast Reserve Long Term Ecological Research Program. Use of trade, product, or firm names does not imply endorsement by the U.S. Government.

*Corresponding author; Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22904-4123; tele: 434-924-0560; fax: 434-982-2137; email: lkb2e@virginia.edu

Key words: marsh elevation, biogenic, minerogenic, sea-level, tidal inundation, precipitation

Abstract

The movement of salt marshes into uplands and marsh submergence as sea level rises is well documented; however, predicting how coastal marshes will respond to rising sea levels is constrained by a lack of process-based understanding of how various marsh zones adjust to changes in sea level. To assess the way in which salt-marsh zones differ in their elevation response to sea-level change, and to evaluate how potential hydrologic drivers influence the response, surface elevation tables, marker horizons, and shallow rod surface elevation tables were installed in a Virginia salt marsh in three zones that differed in elevation and vegetation type. Decadal rates of elevation change, surface accretion, and shallow subsidence or expansion were examined in the context of hydrologic drivers that included local sea-level rise, flooding frequency, hurricane storm-surge, and precipitation. Surface elevation increases were fastest in the low-elevation zone, intermediate in the middle-elevation zone, and slowest in the high-elevation zone. These rates are similar to (low- and middle-marsh) or less than (high-marsh) local rates of sea-level rise. Root-zone expansion, presumably due to root growth and organic matter accumulation, varied among the three salt marsh zones and accounted for 37%, but probably more, of the increase in marsh surface elevation. We infer that, during marsh transgression, soil-forming processes shift from biogenic (high marsh) to minerogenic (low marsh) in response, either directly or indirectly, to changing hydrologic drivers.

Introduction

Acceleration in the rate of sea-level rise beginning ca. 1980 (Rahmstorf 2007) and evidence of ice sheet collapse (Rott et al. 2014; Schmidtko et al. 2014) leads to an overriding concern about the ability of salt marshes to maintain elevation relative to current and projected sea levels. For salt marshes to persist as they exist currently, they must increase elevation at rates at least equal to those at which sea level is rising. This adjustment to sea-level rise occurs through vertical elevation change, lateral transgression into uplands to offset losses from erosion of the seaward edge, or both (Brinson et al. 1995; Redfield 1972). Salt marshes have the capacity to adapt vertically to a wide range of relative sea-level rise rates resulting from feedbacks between tidal flooding, plant growth, and sediment deposition (Anisfeld et al. 1999; Morris et al. 2002; Nolte et al. 2013), and laterally when transgression is not limited by topography or human-built structures (Kastler and Wiberg 1996; Kirwan et al. 2016b; Smith 2009; Smith 2015). Understanding how processes generating vertical change might also generate horizontal migration will allow for better prediction of salt marsh responses to accelerating relative sea-level rise (Cahoon et al. 2009).

Based on observations at Upper Phillips Creek marsh (37 27'N 75 50'W, 75° 50’ 05” W), Virginia, Brinson et al. (1995) provided a framework of ecosystem state change within salt marshes that are migrating landward (Electronic Supplementary Material, ESM 1). The framework identifies mechanisms underlying change from upland to high marsh, high marsh to low marsh, and low marsh to subtidal mudflats within the mainland landscape along the mid-Atlantic region of the United States. Germane to the study reported here, they postulated that high marsh conversion to low marsh is fostered when biogenic processes in high marshes fail to maintain elevation relative to sea level. This results in deterioration of peaty high-marsh soils, development of hummock-and-hollow topography and ponding. Disturbance by storm deposition of wrack and herbivory may foster this development. Replacement by low marsh is fostered by headward erosion of creeks and filling in of hollows with *Spartina alterniflora* Loisel. (reclassified as *Sporobolus alterniflorus* (Peterson et al. 2014)). However, the internal salt-marsh processes that lead to replacement of high-marsh plants by low-marsh plants are still poorly understood (Kirwan et al. 2016a; Wiberg et al. 2020).

Two primary sources of material contribute to elevation increases through accretion: deposition of mineral sediments on the marsh surface (surface accretion) and accumulation of organic matter in the root zone from *in situ* plant growth (Reed 2002). Accretion in salt marshes can be dominated by either process (minerogenic or biogenic, respectively). For mineral soil formation to dominate, two conditions are necessary; adequate sediment supply (Brinson et al. 1995; Meade 1982; Morris et al. 2002) and a low elevation that allows frequent tidal inundation of the salt-marsh surface for sediments to be deposited (Day et al. 2007; Morris et al. 2002). The extensive salt marshes of the Gulf coast and southeast USA meet both of these conditions. As sea level rises, the ability of sediment-dominated marshes to "keep-up" will be determined by sediment load, hydroperiod (frequency, depth, and duration of flooding), and positive feedbacks between vegetation and sediment deposition (Morris et al. 2002). In contrast, salt marshes dominated by biogenic processes either lack adequate sediment supply or are infrequently flooded by tides. The capacity of marshes with organic-rich soils to accrete biogenically and increase in elevation is limited by the capacity of plants to produce belowground biomass and the rate at which the material is removed by microbial decay (Anisfeld et al. 1999; Blum 1993; Blum and Christian 2004; Bricker-Urso et al. 1989; Callaway et al. 1997; Chmura and Hung 2004; Hatton et al. 1983; McCaffrey and Thomson 1980; Mudd et al. 2009; Turner et al. 2000). Many

New England marshes are noted for their high organic matter content (biogenic soils) as a consequence of the low sediment supply (Meade 1982), the infrequent tidal flooding (Bricker-Urso et al. 1989), and the colder conditions found in higher latitudes. Salt marshes in the mid-Atlantic region, exhibit both types of accretionary processes, i.e., biogenic and minerogenic (Cahoon et al. 2009; Ganju et al. 2015; Kirwan et al. 2016a). While there are clear regional differences in the relative proportion of the processes that contribute to salt-marsh accretion and elevation change, minerogenic and biogenic processes also can vary within individual salt marshes (Nyman et al. 2006).

Many studies of elevation change in salt marshes have been conducted in zones where *S. alterniflora* dominates (e.g., Chmura et al. 2001; Delaune et al. 1978; Donnelly and Bertness 2001; Kim et al. 1997; Kraft et al. 1992; Orson et al. 1998; Turner et al. 2006). Until relatively recently, fewer data were available for irregularly flooded, high marsh where meadows of *Spartina patens* (Aiton) Muhl. (reclassified as *Sporobolus pumilus* (Peterson et al. 2014)) and *Distichlis spicata* and stands of *Juncus roemerianus* or *Juncus gerardii* often dominate (but see, Raposa et al. 2016). In high marshes, Cs^{137}- and Pb^{210}-dating confirms the capacity of these zones in some salt marshes to respond to rising sea level in spite of the weaker connection to a tidal regime than low marsh zones (Kaye and Barghoorn 1964; Kelley et al. 1995). Predicting how coastal marshes will respond to rising sea levels is constrained by lack of understanding of how processes allow various zones to adjust to changes in sea level. These processes include regional environmental drivers, such as precipitation and sea-level dynamics, acting in concert with local processes, such as primary production and soil properties (Cahoon and Guntenspergen 2010; Morris et al. 2002).

Here we present the results of a multi-decadal study designed to assess the way in which saltmarsh zones differ in their response to sea-level change, and to identify which processes and environmental drivers have the greatest potential to influence those responses. We focused on hydrologic drivers because of the role tidal flooding and precipitation play in sediment delivery and deposition on the marsh surface, marsh plant productivity, and peat formation (Morris et al. 2002). Twenty years of measurements of vertical marsh-surface dynamics were partitioned into surface elevation change, surface accretion (as defined above), and shallow subsidence or expansion (as defined below). The contribution of root-zone processes to elevation change were quantified for thirteen years. We determined whether rates of elevation change, surface accretion, and shallow subsidence or expansion in salt-marsh zones with different plant communities and hydroperiods were equivalent to each other and to concurrent rates of local rising sea level. The influence of hydrologic drivers on rates of biogenic and minerogenic processes were examined to help understand how processes in the high-marsh zones might change during the transition to low-marsh zones. Our findings were placed into the context of the Brinson et al. (1995) ecosystem state change framework (ESM 1).

Materials and Methods

Study Site

Upper Phillips Creek marsh (UPC) (37 27'N 75 50'W, 75° 50’ 05” W) is a focal-study area of the Virginia Coast Reserve (VCR) Long Term Ecological Research (LTER) program (Fig. 1). This salt marsh developed along the edges of the Phillips Creek stream channel that drains the upland. Salt marshes like UPC are common along Virginia’s Atlantic Ocean coastline. Approximately 67% of the creeks that drain the uplands in this region are surrounded by extensive salt marshes

(Ricker 1999), and of the 5,607 ha of marshes that directly adjoin the mainland, 3,757 ha (67%) are similar to UPC (Flester and Blum, in review). The UPC marsh has two important, hydrogeomorphic characteristics: it has low relief, and sits high in the tidal frame (Kirwan et al. 2012). The mean tide range in Phillips Creek is typically between 1.5 - 2 m (Christiansen et al. 2000), and the 20-year average mean high-water level in meters relative to mean sea level (hereafter, msl) was 0.551 ± 0.064 (SE) between 1997 and 2017. When compared with the elevation of the marsh platform (1.000 to 1.119 m above msl, Table 1), these tide data support visual observations that tidal flooding of the marsh platform occurs only on the very highest of tides and during storms. The extensive, topographically flat marsh-platform is irregularly flooded by tides with salinities that are typically 27 ± 5 ppt, total suspended solids of 100 ± 198 mg L^{-1}, and total dissolved inorganic nitrogen ranges from 1 to 8 μM (McGlathery and Christian 2020). Anthropogenic nutrients are low in this system relative to other similar shallow coastal systems (McGlathery et al. 2007). Soils across all elevations of the salt-marsh platform have pore-water salinities that range between 25 to 34 ppt (Blum and Christian 2004). The importance of tidal flooding decreases from the low to high zones of the platform. In the high zone, precipitation is the predominant source of water, accounting for 81% of the total water inputs in this portion of the marsh (Stasavich 1999). Although areas of the interior high marsh are flooded only by storm tides, in most years the soil is continuously covered by brackish water from late fall through spring. During warmer months, when evapotranspiration exceeds precipitation, the water table is generally at or near the soil surface (Christian et al. 2000).

Study sites were established in three distinct areas of the UPC marsh platform: a site dominated by short-form *Spartina alterniflora* nearest to Phillips Creek, one at the boundary between intact turf of mono-specific stands of *Juncus roemerianus* and mixed *Spartina patens* and *Distichlis* *spicata* communities, and another site within a *D. spicata/S. patens* dominated community near an area with developing hummock-and-hollow microtopography (Table 1). Based on differences in elevation (Table 1) and tidal flooding frequency, the short-form *S. alterniflora*-dominated area is referred to hereafter as the low zone, the intact turf area as the middle zone, and the hummock and hollow area as the high zone (Fig. 1).

Surface Elevation Table (SET), Shallow Rod SET (sRSET), and Marker Horizon (MH) Installation and Measurement

Marsh elevation responses were evaluated by the surface-elevation-table marker-horizon approach that simultaneously quantifies surface accretion and surface elevation change with a level of accuracy (~ 1-2 mm) and precision sufficient to distinguish between the influence of surface and subsurface processes on marsh elevation (Cahoon et al. 2002a; Cahoon et al. 1995; Lynch et al. 2015). Surface accretion was determined from repeated cryogenic coring of feldspar marker horizon (MH) plots established on the marsh surface (Cahoon and Turner 1989; Lynch et al. 2015). The depth of the marker horizons below the marsh surface is generally considered an estimate of largely minerogenic processes in the short-term (Fig. 2). Marsh surface elevation change was repeatedly measured relative to a subsurface datum using version 4 of the surface elevation table (SET) (Cahoon et al. 2002a). The calculated difference between the simultaneous measures of surface accretion (MH) and surface elevation (SET) gives an estimate of the effect of processes occurring below the marker horizon and above the base of the SET bench mark on marsh surface elevation change (Cahoon 2015) (Fig. 2).

To examine the contribution of root-zone processes to surface elevation change, shallow-rod surface-elevation tables (sRSET) were used to measure repeatedly the marsh surface relative to the base of the sRSET (i.e., the depth of the root zone) in a manner similar to that used for the SET. When an sRSET is installed to the bottom of the root zone it provides an estimate of root-zone elevation, which comprises surface accretion, subsidence or expansion within the root zone, and biogenic processes both on the soil surface and in the root zone (Fig. 2) (Cahoon et al. 2002b; Lynch et al. 2015). The difference between measures from the sRSET and MH yields information about root zone processes occurring below the marker horizon and above the base of the sRSET, *i.e.*, the bottom of the root zone. However, like the SETs, sRSETs measure surface accretion (deposition), which is determined by marker horizons (Fig 2).

Three SETs were established in each marsh zone on the UPC marsh platform in July 1997 for a total of nine SETs (Fig. 1). Small wooden sampling platforms were constructed to allow access to the soil surface while minimizing disturbance. Each SET benchmark pipe was driven into the substrate until it no longer moved (Table 1) and the pipe cut so that approximately 50 cm extended above the marsh surface. In July 1997, a month preceding the first marsh surface elevation reading, feldspar was spread (1-2 cm deep) within six 0.25 m^2-plots at each SET station for a total of 54 marker horizon plots. In July 2003, a sRSET was installed adjacent to each SET. Each sRSET was pushed into the soil to a depth of 20 cm; a depth that encompassed the entire root zone at the time of installation. In December 1998, the elevation of the marsh surface at each of the SET benchmarks was determined by laser-level relative to permanent VCR benchmarks established by the VCR LTER in 1992 using GPS survey. The elevation of the marsh surface around the sRSET benchmarks was determined in September 2003. At four places equidistance around the SET pipe and approximately 0.5 m from SET pipe, the elevation of the soil surface was determined. Thus, the elevation of each SET is the mean of the four measurements (Table 1). The VCR permanent benchmark used for leveling was BROWNSVILLE (+37° 27' 38.4985028, -75° 50' 4.961264). All VCR permanent benchmarks are referenced to VCR1 (+37° 17' 42.156630", -75° 55' 59.492560", elevation = 8.7000 m), which is a benchmark that is part of the High Accuracy and Resolution Network (HARN). Subsequent to installation of VCR1, the GEOID93 model and a correction for the GEOID12A model were applied to the original data (Thomas and Carlson 1999). Elevations in Table 1 are based on this single point (VCR1) which is referenced to NAVD88 and where a value of zero corresponds to msl. All elevations reported herein are based on the VCR1 datum.

To measure changes in marsh elevation, the portable SET or sRSET device was attached to the pipe or shallow rod benchmark, respectively, and leveled in all dimensions such that the table or arm reoccupied the same reference plane in space for each reading, and each pin fell on the exact same location on the marsh surface at each reading. Each of nine pins was lowered individually until it touched, but did not penetrate, the soil surface. This procedure was repeated at four different directions around each SET and each sREST (high and low zones), and six different directions around each SET (middle zone). The two extra arm positions that were measured for middle zone SET were placed so that half the arm positions were in a mono-specific *J. roemerianus* community and the other three positions were in the neighboring *S. patens-D. spicata* community. Within four years, the *S. patens-D. spicata* community was replaced by *J. roemerianus,* but we continued to measure the same six arm positions for the duration of the experiment. For the middle-zone sRSET, a total of eight arm positions were measured. Change in elevation (in millimeters) was determined by comparing pin measurements from sequential samplings. Simultaneously with SET measurement, a minimum of one core was collected by cryogenic coring from at least two of the six marker horizon plots per SET-sRSET benchmark pair (Cahoon et al. 1996) (i.e., $\geq$6 cores per zone). The depth from the surface to the marker layer was measured to the nearest millimeter with a ruler at up to four positions on each core. The surface elevation and surface accretion measurements were made semi-annually beginning in August 1997, while the semi-annual root-zone elevation measurements did not begin until September 2003. Beginning in April 2010, both types of elevation and surface accretion measurements were made annually.

Statistical Approach: Comparison of Elevation, Root-Zone Elevation, and Surface Accretion Rates among Marsh Zones

The 20-year cumulative trends in marsh surface elevation were regressed against time for each SET pin resulting in 36 estimates of the linear trends (or 54 for middle zone SETs) for each SET benchmark. Next the mean of the nine linear trend rates for each arm position was determined and then these rates were averaged to give a rate of elevation change for each SET benchmark (Lynch et al. 2015). This approach was used for each of the three benchmarks in each of the three marsh zones to give three independent estimates of elevation change within a marsh zone. An approach similar to that used for the SETs was used to calculate elevation changes for the sRSET in each of the three marsh zones. For surface accretion, up to eight measured estimates of marker depth were averaged to yield one measure per SET-sRSET pair yielding three independent measurements of surface accretion per marsh zone. The rates of surface and root-zone elevation change, and surface accretion were determined by regression against time. Statistical significance of differences in these three rates among marsh zones was determined by one-way ANOVA using SPSS (SPSS Statics, ver. 17, 2008) with an α-level of 0.05 and N=3 for each of the three marsh zones. Tukey's HSD post-hoc test determined significance of individual pairs of means.

Rates of subsidence within the root zone, and rates of shallow subsidence below the root zone were calculated as the simple differences between the appropriate variables; i.e., shallow subsidence rate by difference between surface accretion rate and elevation change rate (Fig. 2, III), subsidence within the root zone by difference between surface accretion and shallow elevation change (Fig. 2, V), and subsidence below the root zone by difference between root-zone elevation change and elevation change (Fig. 2, VI). Note that negative values of subsidence indicate expansion, while positive values indicate subsidence. Statistical significance of differences in subsidence rates among marsh zones was determined by one-way ANOVA using SPSS (SPSS Statics, ver. 17, 2008) with an α-level of 0.05 and N=3 for each of the three marsh zones. Tukey's HSD post-hoc test determined significance of individual pairs of means.

Calculation of Local Sea Level, Relative Sea-Level Rise Rates, and Tidal Inundation Index of Marsh Zones

Previous studies (Christiansen et al. 2000; Kastler and Wiberg 1996; Turaski 2002) have found a strong correlation between tides at Phillips Creek and the National Oceanographic and Atmospheric Administration (NOAA) Wachapreague Channel tide station (station ID 8631044; 37° 36.5' N, 75 41.1' W; https://tidesandcurrents.noaa.gov), even though tidal range is smaller at Wachapreague and the timing of high tide is approximately one hour later at Phillips Creek than at Wachapreague. The relationship between measured tide levels at Wachapreague and Phillips Creek is determined by the following equation (Christiansen 1998; Turaski 2002):

$$Tide,_{\ Phillips\ Creek}\ (cm) = [Tide,_{\ Wachapreague}\ (m) + 1.85m]*1.08(cm\ m^{-1}) - 1.89 \quad \text{(eq.1)},$$

where *Tide* is water level relative to mean sea level.

Gaps in verified water levels exist at the Wachapreague station during portions of the period between 2000 and 2008, so it was necessary to use another tide station to determine local, Phillips Creek tide levels. We examined the relationships between the measured water levels for NOAA Wachapreague, Kiptopeke (station ID = 8632200;), Sandy Hook (station ID = 8531680), and Atlantic City (station ID = 8534720) tide station (https://tidesandcurrents.noaa.gov) between 1979 and 1999 using a MATLAB correlation routine. The most closely correlated data were between Wachapreague and Kiptopeke ($r = 0.99$) with the following relationships:

$$Tide,_{\ Wachapreague}\ (m, MSL) = 1.0574*Tide,_{\ Kiptopeke}\ (m) - 0.0027\ m \quad \text{(eq. 2), and}$$

$$Tide,_{\ Wachapreague}\ (m, MHHW) = 0.9622*Tide,_{\ Kiptopeke}\ (m) + 0.1994\ m \quad \text{(eq. 3)}$$

We used Equations 2 and 3 to estimate Wachapreague tide elevations from measured water levels from the Kiptopeke station data, and then used Equation 1 to predict the tide elevations in Phillips Creek. The mean water-level values obtained were used to determine the local rate of relative sea-level rise at UPC by regressing msl for the time period 1997 and 2017.

The local, 20-year rate of sea-level rise in Phillips Creek was determined by linear regression in SPSS ver. 25. The 95% confidence limits of the sea-level rise trend line and the standard error of the sea-level rise rate estimate were determined by linear regression analysis. To determine if the rates of sea-level rise differed from the rates of marsh surface elevation increase, an ANCOVA analysis (SPSS ver. 25) was done with an α-level of 0.05.

An index of tidal flooding potential (hereafter, the tidal flooding index) was calculated between 1997 and 2017 to provide an estimate of the relative differences in tidal flooding among the SET replicates. The tidal flooding index was established by counting the number of times the high tide elevation in Phillips Creek was equal to, or greater than, the elevation of the marsh surface. The elevation of the marsh surface was recalculated each time a SET measurement was made. Then the number of potential high tides flooding a zone for each month during the interval between elevation measurements was used to calculate the mean number of potential high tides flooding each SET replicate per month for the interval between SET measurements to give the tidal flooding index. Note that this approach overestimates the frequency of actual flooding at a location because the effect of plants on the tides was not considered (Leonard and Reed 2002). Nor does the index provide an estimate of the duration of flooding, although the duration of flooding may have varied by as much as 15 to 20 minutes for each 4-cm of difference in elevation (Scholten and Rozema 1990).

Precipitation

Daily measurements of precipitation were obtained from the NOAA Climate Data Center (*http://cdo.ncdc.noaa.gov/ulcd/ULCD)* for the Accomack County Airport (MFV) at Melfa, Virginia (latitude 37º38'57.48" N, longitude 75º44'28.74" W). The NOAA MFV station is located approximately 22 km north of UPC and average monthly rainfall at MFV provides estimates of precipitation very highly correlated ($r > 0.98$) with historical records between 1988 and 1999 from the UPC met station.

Between 1997 and 2010, we examined the correlation of precipitation with incremental surface elevation and surface accretion change, and with incremental root-zone elevation change between 2004 and 2010 for the growing season. The growing season was considered to be April through August, and coincides with when semi-annual measurements were done. We also examined the correlation between annual precipitation (April through March) and annual incremental change of surface elevation, surface accretion for the entire record from 1997 to 2017, and root-zone elevation between 2004 and 2017. Daily precipitation measurements were summed to obtain the total amount of rainfall during the intervals between measurements (either April through August for the growing season or April through March for annual increments). SPSS (SPSS Statistics, ver. 17, 2008) was used to carry out the correlation analysis.

Soil Organic Matter Content

During the summer of 2000 and 2001, soil cores, (8.89 cm diameter by at least 30 cm long), were collected near, but not within 5 m of, the SET benchmark pipes and at marsh elevations similar to that of the soil surface at the base of the SET pipes. Five cores were collected in the low and middle zones, while only three cores were collected in the high zone. Compaction from core collection was determined by measuring from the top of the core tubing to the soil surface on the inside and outside of the core tubing. Only cores with less than 0.5 cm difference between the two measurements were used for soil organic matter analysis. The cores were capped and stored in a cold room at 3° C in the aluminum core tubes. Each soil core was extruded from the aluminum pipe, and then cut into 2-cm segments over the top 6 cm and 5-cm segments over the remaining length of the core. Soil organic matter was determined by loss-on-ignition at 450 °C to a constant mass. Data are expressed as percentage of dry mass. SPSS (SPSS Statistics, ver. 17, 2008) was used to carry out a one-way ANOVA analysis of depth-averaged organic matter content. Tukey's HSD post-hoc test determined significance of individual pairs of means.

Results

Marsh-surface elevation increased in all three marsh zones during the 20-year study period. Only in the case of the high marsh is there the potential for elevation increase to be unable to maintain pace with estimated local sea-level rise rate of 4.1 ± 0.2 mm yr^{-1} during the 20-year period. The elevation of the low-, middle-, and high-marsh zones (calculated from rates in Table 2) changed between 1997 and 2017 by 98.4 ± 0.1, 86.0 ± 0.2, and 65.8 ± 0.1 mm (± standard error of the estimated rate), respectively. Based on the local rate of sea-level rise in Phillips Creek (see Fig. 3), sea level rose by 82 ± 0.2 (mm ± standard error of the estimated rate) during this same period of time. The rate of marsh surface increase in the high zone was less than the rate of sea-level rise, and significantly different from the sea-level rise rate (ANCOVA, $F = 5.118$, $p = 0.027$). Neither of the rates of marsh surface increase in the low- or middle-marsh zones were significantly different from the Phillips Creek sea-level-rise rate. There was considerable variation in belowground dynamics as indicated by the temporal changes in the rates of surface accretion, surface elevation change, and root-zone elevation change (Tables 2 and 3), but the root-zone elevation change always exceeded both elevation change and surface accretion, highlighting the importance of root and rhizome dynamics to elevation change on the marsh platform (Fig. 4, Table 3). Below, we first present the multi-year trends in elevation, surface accretion, root-zone elevation change, and shallow subsidence. Then we examine the potential drivers affecting the dynamics of elevation change including the tidal flooding index (a relative measure of the frequency of tidal flooding), variation in precipitation, an extended drought, and two hurricanes.

Elevation, Surface Accretion, and Shallow Subsidence Rates

Over the full 20-year period of measurements, surface elevation (SET) increases were significantly different among the three marsh zones ($F = 69.29$, $p < 0.001$) (Table 2). Variation in rates of surface accretion over the original marker horizons limited the ability to detect differences in the mean rate of surface accretion among marsh zones, even though surface accretion patterns were similar to those for elevation change (Fig. 4, Table 2). The rate of surface elevation increase was greatest in the low zone (4.9 mm yr^{-1}), intermediate in the middle zone (4.2 mm yr^{-1}), and smallest in the high zone (3.3 mm yr^{-1}). Similarity in the 20-year rates of surface accretion among these three regions is likely due to the high variance associated with differences in the accretionary processes among the three individual replicate sites in the high marsh. Those rates were 2.9 mm yr^{-1} (site 4A), 3.8 mm yr^{-1} (site 4B), and 4.1 mm yr^{-1} (site 4C) and likely reflect the developing hummock-and-hollow topography in the high marsh (Fig. 1). Subsurface change (expansion or shallow subsidence) was small and of the same magnitude as the standard errors associated with rates of surface accretion (Table 2).

Root-Zone Contributions to Elevation Change between 2004 and 2017

The surface elevation change (measured by SET) was significantly different from the elevation change within the root zone (measured by sRSET) (t = -2.363, p = 0.046). That overall difference was due to the greater change in the root zone relative to the observed change in surface elevation for the low and middle zones. In the high-marsh zone, the surface elevation and root-zone elevation measurements were not different. Because the surface elevation change is the sum of processes occurring in the root zone and those occurring below the root zone (e.g., shallow subsidence), the imbalance in elevation change (in the positive vertical dimension) must be due to higher rates of processes in the root zone. While Table 3 indicates that shallow subsidence below the root zone occurred in the low and middle zone, the greater change in the root-zone elevation (thickness of the root zone) in these zones was enough to overcome the subsidence and add to the change in surface elevation.

Surface accretion rates were always less than root-zone elevation change rates. In other words, in all marsh zones, root-zone expansion of the soil profile occurred to a greater amount than could be accounted for by surface accretion alone (Table 3, column V). This result indicates that processes occurring below the marker horizon, but within the root-zone, contribute to elevation increases in all marsh zones between 2004 and 2017.

Rates of subsidence below the root-zone (difference between elevation change in the root- zone and surface elevation) were not significantly different among the three marsh-platform zones (Table 3, column VI). The fact that surface elevation changes were less than root-zone elevation changes in the low and middle marsh zones indicates that between 0.7 and 0.8 mm yr^{-1} of shallow subsidence occurred below the root zone. In the high-marsh zone, root-zone elevation change and elevation change rates were similar (Table 3, columns II and IV), indicating little contribution of subsidence below the root zone to elevation dynamics.

Flooding Frequency and Precipitation Influences on Surface Elevation, Root-Zone Elevation, and Shallow Subsidence

We examined the potential for selected hydrologic drivers related to soil saturation to influence marsh elevation and surface accretion dynamics within each of the marsh zones in two ways – incremental changes between measurements and the long-term rates. Drivers included frequency of tidal flooding, which was based on a tidal flooding index, and precipitation. Incremental changes (difference from one measurement to the next) in surface elevation, root-zone elevation, and surface accretion were not correlated with either of these drivers indicating that they had little effect on elevation or surface accretion change in the short-term.

Although the elevation of the low, middle, and high zones differed by less than 10 cm (Table 1), during the twenty years of tidal data examined, the tidal flooding index for the low zone was always significantly different from, and greater than, the other two zones (ANOVA, $F = 46.488$; $p = 0.001$). Over the entire study, the number of times the tidal flooding index exceeded the elevation of the marsh surface at the sample sites was generally small and highly variable (the tidal flooding index range was 1 to 12 tides per month) (Fig. 5). All sites are located at elevations on the marsh platform well above the mean highest high tides (Table 1). During the study period, the estimated mean highest high tides in Phillips Creek, the source of tidal water in the UPC marsh, was 0.71 ± 0.02 m (± one standard error) above mean sea level while the lowest elevation SET and sRSET benchmark pipes were located at or above 1.000 m (Table 1). Variation of the tidal flooding index among years was large. For example, in 2001 and 2002 (study years 4 and 5; Fig. 5) the low-zone tidal flooding index suggests that the low zone was flooded less frequently than the high zone in 1998, 1999, and 2003 (study-years 1, 3, and 6; Fig. 5). The middle and higher zones could have flooded only on the very highest of spring high tides for 2001 and 2002 (study-years 4 and 5; Fig. 5). Flooding frequency likely was much higher in all zones between October 2009 and March 2010 (study year 12) when the tidal flooding index in the low zone was 12 events per month, and in the middle and high zones when the index was eight events per month. That the tidal flooding index was higher during this time, reflects the higher than normal tides reported in 2009 and 2010 along the entire USA east coast (e.g., National Oceanographic and Atmospheric Administration 2009). These unusually high tides likely resulted from persistent strong northeast winds coupled with a weak Florida Current that was coincident with perigean-spring tides (Sweet et al. 2017).

During this study, two hurricanes affected the study site, Hurricane Isabel in September 2003, and Hurricane Sandy in October 2012 (Allen and Oertel 2005; Cahoon et al. 2019). There was no evidence of elevation or surface accretion increases associated with either hurricane that persisted for more than six months.

Precipitation during the study was highly variable (Fig. 6), but tended to be higher in July and August than in other months (Fig. 6A). During the latter half of the study, annual precipitation was consistently lower than the 30-year annual average (1961-1990; Fig. 6B). Growing season rainfall (April through August) was notably lower for a five-year period between 2007 and 2011. Nevertheless, the total amount of precipitation that occurred in the interval (either semi-annually between 1997- 2011 or annually between 2011-2017) between measurements was not significantly correlated with incremental changes in surface elevation, root-zone elevation, or surface accretion during the study period.

Soil Organic Matter Content (SOM) of Marsh Zones

Soil organic matter content with 2 cm of the surface to 10 cm below the surface at all zones was greater than 40% of the soil dry mass (Fig. 7). Near surface soils at middle and high zones had substantially more soil organic matter than at the low zone. The depth-averaged organic matter content was greatest in the high and middle zone, and significantly less in the low zone (ANOVA, $F = 5.817$, $p = 0.021$). In all marsh zones, the soil organic matter content decreased with depth to less than 10% at depths greater than 20-cm below the marsh surface.

Discussion

Insight into the processes directly or indirectly controlling horizontal migration of salt marshes in response to sea-level rise can come from examination of vertical processes of elevation change, surface accretion, and shallow subsidence (Cahoon et al. 2009). Others have examined the processes controlling transition of marsh to subtidal (Hackney and Cleary 1987; Marani et al. 2011; McLoughlin et al. 2015; Reed and Cahoon 1992; Stevenson et al. 1985) and upland to high marsh (Anisfeld et al. 2017; Fagherazzi et al. 2019; Gardener et al. 1992; Kearney et al. 2019). Although others have documented the transition from high to low marsh (Kastler and Wiberg 1996; Smith 2009; Smith 2015), we are not aware of papers focused on the internal dynamics that could lead to conversion from high to low zones within a marsh.

Brinson et al. (1995) provide a framework (ESM 1) for examining the mechanisms underlying marsh transitions and hypothesized a switch from biogenic processes at higher elevations to minerogenic processes at lower elevations within broad marsh platforms. In fact, our high zone sites were in the process of forming the hollow-and-hummock topography at the beginning of our study and were near the "subsiding high marsh" condition described in Brinson and Christian (1999). Our measurements (Tables 2 and 3; Fig 4) document a difference between the high-elevation and low-elevation zones in the relative importance of biogenic accumulation within the root zoned compared to surface, minerogenic processes. Both surface accretion and root-zone elevation processes were greater and soil organic matter content was less at lower elevations than higher on the marsh platform (Table 3, Figure 7B). We infer that the transition from high-marsh to low-marsh is accompanied by changes in soil characteristics – i.e., peaty, high-marsh soils transition to mineral, low-marsh soils – and that the respective soils reflect process or process rate changes facilitating the transition. Sedimentation combined with similar rates of biogenic accretion within the soil, results in greater rates of vertical change than in the high marsh where vertical change is dominated by biogenic processes. Further, we hypothesize below that hydrologic drivers, particularly infrequent tidal inundation in the high marsh zone, controls the rate of biogenic processes, as well as minerogenic processes.

Surface Elevation Change as an Indicator of High to Low Zone Transition

The marsh surface elevation of all zones on the Upper Phillips Creek marsh platform increased during the 20 years of this study, and the rates of increase differed among the lower-, middle-, and higher-elevation zones. Both measures of elevation increase (surface and root-zone) were greatest in the low zone nearest the source of tidal flooding than in the less frequently flooded, high zone (Table 2, Fig. 3). Rate changes in the middle zone were intermediate or equal to those in the low zone. The rates of change for the low and middle zones were not significantly different from the rate of sea-level rise in Phillips Creek. In contrast, the rate of high-zone elevation change was significantly less than sea-level rise in Phillips Creek. Given these local, relative sea-level-rise rates, the low and middle zones of the UPC marsh platform appear to be in equilibrium with the decadal local relative sea-level rise, while the irregularly and infrequently flooded high zone is decreasing relative to sea level at about 0.5 mm yr^{-1} and is not in equilibrium with sea-level rise in Phillips Creek.

Disequilibrium between rates of soil surface elevation and relative sea-level change may cause transition from high- to low-marsh to occur nonlinearly. If the current long-term trajectories of sea level and soil surface elevation change persist at UPC, tidal flooding should become more frequent in the high zone and may increase the rate of formation of marsh ponds and the extent of hummock-and-hollow topography. Brinson et al. (1995) indicate that ponding of water and hummock-and-hollow topography signal intermediate stages in the conversion of high- to low-marsh during marsh transgression. Since 1995, microtopography of the UPC high marsh has continued to increase. Brinson and Christian (1999) reported that the high marsh zone exhibited greater microtopography than either the low or middle zones, and Blum and Christian (personal observations 2000 – 2017) note that microtopographic relief continues to develop both vertically and horizontally. Given the rates of marsh surface elevation change that are less than rates of sea-level rise, we expect more extensive ponds or greater hummock-and-hollow formation to continue into the future. Concurrent with increasing ponding and hummock-and-hollow formation in the high zone, the ratio of unvegetated to vegetated area should increase, indicating increasing marsh vulnerability to sea-level rise (Ganju et al. 2015). An implication of these observations, given current precipitation patterns, is that there may in fact be thresholds of tidal flooding that result in rapid transitions from high to low zones with concomitant changes in the soil forming processes at a fixed point.

Processes Contributing to Surface Elevation Change

Both deposition of materials on the soil surface (surface accretion) and processes below the surface (root-zone elevation) made important contributions to the elevation increases and soil composition in all three marsh zones, but at different rates. Differences in elevation change among the zones must result from expansion of the soil between the bottom of the active rooting zone and the bottom of the marker horizon (Table 3, column V). For example, the proportion of the elevation increase directly attributable to root-zone processes vs surface accretion were 0.11, 0.37, and 0.11 in the low, middle, and high zones respectively (Table 3, column V divided by column II). These estimates of root zone contributions to soil surface elevation increases are conservative because they do not include roots that have grown above the marker horizons (i.e., underestimates of biogenic processes and overestimates of minerogenic processes) (Fig. 2). Roots of *S. patens* are known to grow on the soil surface when soils are flooded and to contribute to surface accretion and elevation increases (Nyman et al. 2006), and we observed abundant roots above the marker horizons during coring in all marsh zones (Fig 7a). Further, soil organic matter within 2 cm of the surface at all zones was similar down to a depth of 10 cm (Fig. 7). Even after 20 years, the original marker horizons were still being recovered during cryogenic coring and the depth to the marker layers was $>$ 4 cm; thus, providing ample space for roots and rhizomes to grow, contribute to surface accretion rates, and inflate estimates of mineral deposition on the marsh surface.

These findings highlight differences in processes in the root zone, including near the surface, that contribute to soil elevation change at UPC marsh and, potentially, in other, nearly flat, salt marshes that sit high in the tidal frame. These contributions likely derive from organic matter accumulation of roots for several reasons: previous measures of organic matter decay rates were similar and root production rates were different between high and low zones (Blum and Christian 2004), and organic matter content of the three zones is different (Fig 7b, and Blum and Christian 2004). Both plant communities and the tidal flooding index differed among the three salt marsh zones so it is not clear which of these factors, individually or in combination, account for the slower elevation change in the high zone compared to the low and middle zones. What is clear is that soil expansion occurring in the root zone below the marker horizon is similar in the high and low zone (Table 3, column V) while the organic content of the near-surface high zone is significantly greater than in the low zone (Fig. 7b). These observations suggest that mineral sediment deposition in the low zone “dilutes” organic matter and, when combined with similar rates of biogenic accretion within the soil, results in greater rates of elevation change than in the high zone where elevation change is dominated by biogenic processes.

Rates of Marsh Elevation Change, Water Budgets, and High to Low Zone Transition

Marsh elevation can be responsive to precipitation volume and frequency (Cahoon and Lynch 1997), tidal flooding (Bradley and Morris 1990; Nuttle et al. 1990), groundwater elevation (Smith and Cahoon 2003; Whelan et al. 2005), and evapotranspiration (Paquette et al. 2004) on hourly to monthly time scales. None of the environmental drivers examined, including tides, were linearly correlated with vertical elevation changes of the marsh surface in UPC marsh at time scales appropriate to capture these dynamics (hourly over tidal cycles and monthly over 15 months) (Willis 2009). However, at longer temporal scales, the difference in the rates of elevation increase in the three zones corresponded to the tidal flooding index reported here, and to the relative abundance and production of live plant roots in these same marsh zones reported by Blum and Christian (2004). Areas most frequently receiving tidal water had lower rates of root production and were associated with the highest rates of elevation increase (e.g., low zone); those least frequently flooded by tides with greater root production (e.g., high zone, Blum and Christian 2004) had the slowest rates of elevation change (Table 2).

In addition to tidal delivery of sediments, we suggest that tides affect the water budget of the soils on the marsh platform and its elevation by controlling accumulation of belowground biomass and organic matter preservation. Although high marsh plants produce a thick thatch on the soil surface in the high zone (personal observations), the presence of thatch was not reflected in differences in surface accretion among the zones (Table 2). This is most likely due to rapid decomposition of these materials during the warm summer months when the ground water levels are below the surface litter layer, particularly in the middle and high zones (Kirwan and Blum 2011). As organic materials produced belowground accumulate in the high zone, water storage capacity should increase, creating a robust feedback that promotes the saturated conditions necessary for organic matter preservation, and hence, biogenic accretion within the soil and soil surface elevation increases.

Such a feedback is analogous to the way that organic matter accumulation rates in raised bogs are driven by changes in soil saturation related to the water balance (Belyea and Baird 2006). Similar to bogs, the development of extensive areas of high salt marsh may be dependent on a water balance that maintains fully or nearly fully saturated soils (Christian et al. 2000). In the humid climate of the USA mid-Atlantic, the UPC high marsh water balance is dominated by precipitation (Hmieleski 1994; Stasavich 1999). In the six years immediately preceding the beginning of the SET record, the water budget in a nearby area of the UPC high zone was dominated by precipitation (67%) inputs, while tides accounted for the remaining 33% of the budget even though mean tidal inundation was less than three times per year (Christian et al. 2000; Stasavich 1999). Thus, even when tidal inundation frequency is low, tides may contribute a significant portion of the water required to preserve organic matter, form organic soils, limit plant community composition to salt-tolerant high-marsh species, and influence the rate of plant production of organic matter. If tides represent an infrequent, but essential contribution to the water budget of the marsh platform, then it is reasonable to hypothesize that sea level is a critical component of the water budget affecting elevation increase even though the elevated position of the three marsh zones (Table 1) suggests a lack of functional, direct connection to estuarine dynamics.

Other evidence for the critical contribution of tides to the UPC-marsh water budget comes from observations of elevation response to the tidal flooding index (Fig. 5) and precipitation patterns (Fig. 6) in the three SET zones between the years 2000-2003 and 2007-2009 (Fig. 4, study years 3-6 and 10-12, respectively). Assuming that the tidal flooding index is an accurate predictor of the relative frequency of tidal flooding, the less frequent tidal flooding in the high and middle marsh between 2000 and 2003 (Fig. 5) coincided with a period of no elevation change (Fig. 4).

Lower than typical rainfall in the latter half of 2007 through 2009 (Fig. 6), however, had no apparent effect on elevation change (Fig. 4). The difference between the years 2007-2009 and 2000-2003 is that the tidal flooding index of the high zone is nearly twice as great during 2008-2009, when the elevation continued to increase, than observed for the period 2000-2002, when soil elevation did not increase. In the low zone, the tidal flooding index also decreased (Fig. 5), but no relationship with soil elevation change was apparent (Fig. 4). Our interpretation of these observations is that there is a lower threshold of flooding (about 1-2 times each month) below which elevation does not increase because precipitation alone cannot maintain sufficiently saturated soils to promote organic matter accumulation in the mid and high zones. Even when precipitation was much below average, as occurred in 2007-2009 (Fig. 6B), if the tidal flooding index exceeded 2 per month (Fig. 5), the actual tidal flooding was apparently adequate to maintain soil saturation conditions sufficient to favor biogenic accretion rates high enough to increase surface elevation. However, the rates of biogenic increase in soil elevation were insufficient to maintain the relative difference between the high marsh elevation and local sea level. This result suggests that the current combination of high marsh flooding frequency, and precipitation amounts and distributions, have initiated the transition to low marsh as the relative difference in elevation between local sea level and the high marsh becomes smaller.

In summary, through the use of a combination of surface elevation tables installed to different depths in the soil, and marker horizons, we show that within a salt-marsh, the vertical rates of surface change differ among lower-, middle-, and higher-elevation zones on the marsh platform due to differences in accretion within the root zone. In the lower and middle zones, the rates of elevation increase were equal to the short-term, local rate of sea-level rise, while those of the high zone were positive, but less than the short-term, local rate of sea-level rise. Relative to sea-level, the elevation of the high marsh is decreasing, providing support for the prospect that the current high marsh is transitioning to low marsh, as predicted by the conceptual model of Brinson, et al. (1995). To understand and predict how sea-level rise will impact the extent and functioning of salt marshes depends on such high-resolution determination, such as presented in this report, of the processes that lead to marsh surface elevation change within a marsh. The challenge is identifying at what rates and what combinations of flooding frequency, precipitation amounts and distributions, and elevations maintain a marsh plant community or initiate change to a different coastal habitat.

Literature Cited

Allen, T.R., and G.F. Oertel. 2005. Landscape modifications by Hurricane Isabel, Fisherman Island, Virginia. In *Hurricane Isabel in Perspective*, ed. K.G. Sellner, 73-79. Edgewater, MD: CRC Publication 05-160. Chesapeake Research Consortium.

Anisfeld, S.C., K.R. Cooper, and A.C. Kemp. 2017. Upslope development of a tidal marsh as a function of upland land use. *Global Change Biology* 23: 755-766. doi: 10.1111/gcb.13398.

Anisfeld, S.C., M.J. Tobin, and G. Benoit. 1999. Sedimentation rates in flow-restricted and restored salt marshes in Long Island Sound. *Estuaries* 22: 231-244.

Belyea, L.R., and A.J. Baird. 2006. Beyond "The limits to peat bog growth": Cross-scale feedback in peatland development. *Ecological Monographs* 76: 299-322.

Blum, L.K. 1993. *Spartina alterniflora* root dynamics in a Virginia marsh. *Marine Ecology Progress Series* 102: 169-178.

Blum, L.K., and R.R. Christian. 2004. Belowground production and decomposition along a tidal gradient in a Virginia salt marsh. In *Ecogeomorphology of Tidal Marshes*, ed. S. Fagherazzi, M. Marani and L.K. Blum, 47-75. Washington, D.C.: American Geophysical Union.

Bradley, P.M., and J.M. Morris. 1990. Physical characteristics of salt marsh sediments: ecological implications. *Marine Ecology Progress Series* 61: 245-252.

Bricker-Urso, S., S.W. Nixon, J.K. Cochran, D.J. Hirschberg, and C. Hunt. 1989. Accretion rates and sediment accumulation in Rhode-Island salt marshes. *Estuaries* 12: 300-317.

Brinson, M.M., and R.R. Christian. 1999. Stability of *Juncus roemerianus* patches in a salt marsh. *Wetlands* 19: 65-70.

Brinson, M.M., R.R. Christian, and L.K. Blum. 1995. Multiple stages in the sea-level induced transition from terrestrial forest to estuary. *Estuaries* 18: 648-659.

Cahoon, D.R. 2015. Estimating relative sea-level rise and submergence potential at a coastal wetland. *Estuaries and Coasts* 38: 1077-1084.

Cahoon, D.R., and G.R. Guntenspergen. 2010. Climate change, sea-level rise, and coastal wetlands. *National Wetlands Newsletter* 32: 8-12.

Cahoon, D.R., J.A. Lynch, P. Hensel, R. Boumans, P.T. Pereira, B. Segura, and J.W. Day Jr. 2002a. High-precision measurements of wetland sediment elevation: I. Recent imporvements to the sedimentation-erosion table. *Journal of Sedimentary Research* 72: 730-733.

Cahoon, D.R., and J.C. Lynch. 1997. Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, USA. *Mangroves and Salt Marshes* 1: 173-186.

Cahoon, D.R., J.C. Lynch, B.C. Perez, B. Segura, R.D. Holland, C. Stelly, G. Stephenson, and P. Hensel. 2002b. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. *Journal of Sedimentary Research* 72: 734-739.

Cahoon, D.R., J.C. Lynch, and A.N. Powell. 1996. Marsh vertical accretion in a southern California estuary, USA. *Estuarine Coastal and Shelf Science* 43: 19-32.

Cahoon, D.R., J.H. Olker, A.G. Yeates, G.R. Guntenspergen, J.B. Grace, Adamowicz, S. C., S. Anisfeld, A.H. Baldwin, N. Barrett, L. Beckett, A. Benzecry, L.K. Blum, D.M. Burdick, W. Crouch, M.C. Ekberg, S. Fernald, K.W. Grimes, J. Grzyb, E.K. Hartig, D.A. Kreeger, M. Larson, S. Lerberg, J.C. Lynch, N. Maher, M. Maxwell-Doyle, L.R. Mitchell, J. Mora, V. O’Neill, A. Padeletti, D. Prosser, T. Quirk, K.B. Raposa, W.G. Reay, D. Siok, C. Snow, A. Starke, L. Staver, J.C. Stevenson, and V. Turner. 2019. Hurricane Sandy impacts on coastal wetland resilience. *U.S. Geological Survey Open-File Report 2018-1142.* doi: 10.3133/ofr20181142.

Cahoon, D.R., D.J. Reed, and J.W.J. Day. 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology* 128: 1-9.

Cahoon, D.R., D.J. Reed, A.S. Kolker, M.M. Brinson, J.C. Stevenson, S. Riggs, R.R. Christian, E. Reyes, C. Voss, and D. Kunz. 2009. Chapter 4: Coastal wetland sustainability. In *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*, ed. J.G. Titus, 57-72. Washington, D.C.: U.S. Climate Change Science Program.

Cahoon, D.R., and R.E. Turner. 1989. Accretion and canal impacts in a rapidly subsiding wetland. II. Feldspar marker horizon techniques. *Estuaries* 12: 260-268.

Callaway, J.C., R.D. DeLaune, and W.H. Patrick. 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. *Journal of Coastal Research* 13: 181-191.

Chmura, G.L., A. Coffey, and R. Crago. 2001. Variation in surface sediment deposition on salt marshes in the Bay of Fundy. *Journal of Coastal Research* 17: 221-227.

Chmura, G.L., and G.A. Hung. 2004. Controls on salt marsh accretion: A test in salt marshes of Eastern Canada. *Estuaries* 27: 70-81.

Christian, R.R., L.E. Stasavich, C.R. Thomas, and M.M. Brinson. 2000. Reference is a moving target in sea-level controlled wetlands. In *Concepts and Controversies in Tidal Marsh Ecology*, ed. M.P. Weinstein and D.A. Kreeger, 805-925. Dordrecht, Netherlands: Kluwer Academic Publishers.

Christiansen, T. 1998. *Sediment deposition on a tidal salt marsh*. Ph.D. Dissertation, University of Virginia Charlottesville, VA.

Christiansen, T., P.L. Wiberg, and T.G. Milligan. 2000. Flow and sediment transport on a tidal salt marsh surface. *Estuarine Coastal and Shelf Science* 50: 315-331.

Day, J.W., D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, K. Orth, H. Mashriqui, D.J. Reed, L. Shabman, C.A. Simenstad, B.J. Streever, R.R. Twilley, C.C. Watson, J.T. Wells, and D.F. Whigham. 2007. Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science* 315: 1679-1684. doi: 10.1126/science.1137030.

Delaune, R.D., W.H. Patrick, and R.J. Buresh. 1978. Sedimentation-rates determined by Cs-137 dating in a rapidly accreting salt-marsh. *Nature* 275: 532-533.

Donnelly, J.P., and M.D. Bertness. 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America* 98: 14218-14223.

Fagherazzi, S., S.C. Anisfeld, L.K. Blum, E.V. Long, R.A. Feagin, A. Fernandes, W.S. Kearney, and K. Williams. 2019. Sea level rise and the dynamics of the marsh-upland boundary. *Frontiers in Environmental Sciences* 7: 25. doi: 10.3389/fenvs.2019.00025.

Ganju, N.K., M.L.Kirwan, P.J. Dickhudt, G.R. Guntenspergen, D.R. Cahoon, and K.D. Kroeger. 2015. Sediment transport-based metrics of wetland stability. *Geophysical Research Letters* 42: 7992-8000.

Gardener, L.R., B.R. Smith, and W.K. Michener. 1992. Soil evolution along a forest-salt marsh transect under a regime of slowly rising sea level, southeastern United States. *Geoderma* 55: 141-157.

Hackney, C.T., and W.J. Cleary. 1987. Saltmarsh loss in southeastern North Carolina lagoons: importance of sea level rise and inlet dredging. *Journal of Coastal Research* 3: 93-98.

Hatton, R.S., R.D. Delaune, and W.H. Patrick, Jr. 1983. Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. *Limnology and Oceanography* 28: 494-502.

Hmieleski, J.I. 1994. *High marsh-forest transitions in a brackish marsh: the effects of slope*. MS Thesis, East Carolina University Greenville, NC.

Kastler, J.A., and P.L. Wiberg. 1996. Sedimentation and boundary change in Virginia salt marshes. *Estuarine Coastal and Shelf Science* 42: 683-700.

Kaye, C.A., and E.S. Barghoorn. 1964. Late Quaternary sea-level change and crustal rise at Boston, MA, with notes on autocompaction of peat. *Geological Society of America Bulletin* 75: 63-80.

Kearney, W.S., A. Fernandes, and S. Fagherazzi. 2019. Sea-level rise and storm surges structure coastal forests into persistence and regeneration niches. *PLos ONE* 14: e0215977.

Kelley, J.T., W.R. Gehrels, and D.F. Belknap. 1995. Late Holocene relative sea-level rise and the geological development of tidal marshes at Wells, Maine, USA. *Journal of Coastal Research* 11: 136-153.

Kim, G., N. Hussain, T.M. Church, and W.L. Carey. 1997. The fallout isotope Bi-207 in a Delaware salt marsh: A comparison with Pb-210 and Cs-137 as a geochronological tool. *Science of the Total Environment* 196: 31-41.

Kirwan, M.L., and L.K. Blum. 2011. Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. *Biogeosciences* 8: 987-993. doi: 10.5194/bg-8-1-2011.

Kirwan, M.L., R.R. Christian, L.K. Blum, and M.M. Brinson. 2012. On the relationship between sea level and *Spartina alterniflora* production. *Ecosystems* 15: 140-147. doi: 10.1007/s10021-011-9498-7.

Kirwan, M.L., S. Temmerman, E.E. Skeehan, G.R. Guntenspergen, and S. Fagherazzi. 2016a. Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change* 6: 253-260.

Kirwan, M.L., D.D. Walters, W.G. Reay, and J.A. Carr. 2016b. Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophysical Research Letters* 43: 4366-4373. doi: 10.1002/2016GL068507.

Kraft, J.C., H.I. Yi, and M. Khalequzzaman. 1992. Geologic and human-factors in the decline of the tidal salt-marsh lithosome - the Delaware estuary and Atlantic coastal zone. *Sedimentary Geology* 80: 233-246.

Leonard, L.A., and D.J. Reed. 2002. Hydrodynamics and sediment transport through tidal marsh canopies. *Journal of Coastal Research* 36: 459-469.

Lynch, J.C., P. Hensel, and D. Cahoon. 2015. The surface elevation table and marker horizon technique: A protocol for monitoring wetland elevation dynamics. *National Park Service Natural Resource Report NPS/NCBN/NRR-2015/1078.*

Marani, M., A. D'Alpaos, S. Lanzoni, and M. Santalucia. 2011. Understanding and predicting wave erosion of marsh edges. *Geophysical Research Letters* 38. doi: 10.1029/2011GLO48995.

McCaffrey, R.J., and J. Thomson. 1980. A record of the accumulation of sediment and trace metals in a Connecticut salt marsh. *Advances in Geophysics* 22: 165-236.

McGlathery, K., and R.R. Christian. 2020. Water Quality Sampling - integrated measurements for the Virginia Coast, 1992-2019. *Virginia Coast Reserve Long-Term Ecological Research Project Data Publication knb-lter-vcr.247.14.* doi: 10.6073/pasta/db7f8fe720ddfcdfab1352adc9c22702.

McGlathery, K., K. Sundbäck, and I.C. Anderson. 2007. Eutrophication in shallow coastal bays and lagoons: the role of plants in the coastal filter. *Marine Ecology Progress Series* 348: 1-18. doi: 10.3354/meps07132.

McLoughlin, S.M., P.L. Wiberg, I. Safak, and K.J. McGlathery. 2015. Rates and forcing of marsh edge erosion in a shallow coastal bay. *Estuaries and Coasts* 38: 629-638. doi: 10.1007/s12237-014-9841-2.

Meade, R.H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *Journal of Geology* 90: 235-252.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83: 2869-2877.

Mudd, S.M., S.M. Howell, and J.T. Morris. 2009. Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. *Estuarine Coastal and Shelf Science* 82: 377-389. doi: 10.1016/j.ecss.2009.01.028.

National Oceanic and Atmospheric Administration. 2009. High sea level along U.S. Atlantic Coast due to ocean current and wind changes. ScienceDaily. August 31, 2009. www.sciencedaily.com/releases/2009/08/090831132943.htm.

Nolte, S., E.C. Koppenaal, P. Esselink, K.S. Dijkema, M. Schuerch, A.V. DeGroot, J.P. Bakker, and S. Temmerman. 2013 Measuring sedimentation in tidal marshes: A review on methods and their applicability in biogeomorphological studies. *Journal of Coastal Conservation* 17: 301–325 doi: 10.1007/s11852-013-0238-3.

Nuttle, W.K., H.F. Hemond, and K.D. Stolzenbach. 1990. Mechanisms of water storage in salt marsh sediments - the importance of dilation. *Hydrological Processes* 4: 1-13.

Nyman, J.A., R.J. Walters, R.D. Delaune, and W.H. Patrick, Jr. . 2006. Marsh vertical accretion via vegetative growth. *Estuarine Coastal and Shelf Science* 69: 370-380. doi: 10.1016/j.ecss.2006.05.041.

Orson, R.A., R.S. Warren, and W.A. Niering. 1998. Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. *Estuarine Coastal and Shelf Science* 47: 419-429.

Paquette, C.H., K.L. Sundberg, R.M.J. Boumans, and G.L. Chmura. 2004. Changes in salt marsh surface elevation due to variability in evapotranspiration and tidal flooding. *Estuaries* 27: 82-89.

Peterson, P.M., K. Romaschenko, Y.H. Arrieta, and J.M. Saarela. 2014. A molecular phylogeny and new subgeneric classification of *Sporobolus* (Poaceae: Chloridoideae: Sporobolinae). *Taxon* 63: 1212-1243.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise *Science* 315: 368-370. doi: 10.1126/science.1135456.

Raposa, K.B., M.L. Cole Ekberg, D.M. Burdick, N.T. Ernst, and S.C. Adamowicz. 2016. Elevation change and the vulnerability of Rhode Island (USA) salt marshes to sea-level rise. *Regional Environmental Change* 17: 389-397. doi: 10.1007/s10113-016-1020-5.

Redfield, A.C. 1972. Development of a New England salt marsh. *Ecological Monographs* 42: 201-237.

Reed, D.J. 2002. Sea-level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi delta plain. *Geomorphology* 48: 233-243.

Reed, D.J., and D.R. Cahoon. 1992. The relationship between marsh surface topography, hydroperiod, and growth of *Spartina alterniflora* in a deteriorating Louisiana salt-marsh. *Journal of Coastal Research* 8: 77-87.

Ricker, L.D. 1999. *Resistance to state change by coastal ecosystems under conditions of rising sea level*. MS Thesis, East Carolina University Greenville, NC.

Rott, J., D. Floricioiu, J. Wuite, S. Scheiblauer, T. Nagler, and M. Kern. 2014. Mass changes of outlet glaciers along the Nordensjköld Coast, northern Nataractic Peninsula, based on TanDEM-X satellite measurements. *Geophysical Research Letters* 41: 8123-8129. doi: 10.1002/2014GL061613.

Schmidtko, S., K.J. Heywood, A.F. Thompson, and S. Aoki. 2014. Multidecadal warming of Antarctic waters. *Science* 346: 1227-1231. doi: 10.1126/science.1256117.

Scholten, M., and J. Rozema. 1990. The competitive ability of Spartina angilica on Dutch saltmarshes. In *Spartina angilica: A Research Review, 2.*, ed. A.J. Gray and P.E.M. Benham, 39–47. London UK: Institute of Terrestrial Ecology Research Publication. Natural Environment Research Council and HMSO

Smith, S.M. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: photographic analyses of vegetation loss, species shifts, and geomorphic change. *Northeastern Naturalist* 16: 183-208.

Smith, S.M. 2015. Vegetation change in salt marshes of Cape Cod National Seashore (Massachusetts, USA) between 1984 and 2013. *Wetlands* 35: 127-136. doi: 10.1007/s13157-014-0601-7.

Smith, T.J.I., and D.R. Cahoon. 2003. Wetland sediment elevation in the Florida Everglades: response to surface water stage variation. In Proceedings of the International Conference on Coastal Sediments 2003. Clearwater Beach, FL: World Scientific Publishing and East Meets West Productions.

Stasavich, L.E. 1999. *Hydrodynamics of a coastal wetland ecosystem*. MS Thesis, East Carolina University Greenville, NC.

Stevenson, J.C., M. Kearney, and E. Pendleton. 1985. Sedimentation and erosion in a Chesapeake Bay brackish marsh system. *Marine Geology* 67: 213-235.

Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas. 2017. Global and regional sea level rise scenarios for the United States. *National Oceanic and Atmospheric Administration NOS CO-OPS 083*.

Thomas, C., and C.R. Carlson. 1999. GPS Elevations of VCR/LTER Marshes. *Virginia Coast Reserve Long-Term Ecological Research Project Data Publication* http://www.vcrlter.virginia.edu/knb/metacat/knb-lter-vcr.66.17/lter.

Turaski, S.J. 2002.. MS Thesis, University of Virginia Charlottesville, VA.

Turner, E.R., C.S. Milan, and E.M. Swenson. 2006. Recent volumetric changes in salt marsh soils. *Estuarine, Coastal and Shelf Science* 69: 352-359.

Turner, E. R., E.M. Swenson, and C.S. Milan. 2000. Organic and inorganic contributions to vertical accretion in salt marsh sediments. In *Concepts and controversies in tidal marsh ecology*, ed. M.P. Weinstein and D.A. Kreeger, 583-595. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Whelan, K.R.T., T.J. Smith, D.R. Cahoon, J.C. Lynch, and G.H. Anderson. 2005. Groundwater control of mangrove surface elevation: Shrink and swell varies with soil depth. *Estuaries and Coasts* 28: 833-843.

Wiberg, P., S. Fagherazzi, and M.L. Kirwan. 2020. Improving predictions of salt marsh evolution through better integration of data and models. *Annual Review of Marine Science* 12: 6.1-6.25.

Willis, P. 2009. *Hydrologic controls on marsh surface elevation and accretion*. MA Thesis, University of Virginia Charlottesville, VA.

Table 1. Elevation of the marsh surface around the SET and sRSET benchmarks. MHHW for Phillips Creek was 0.71 (m, NAVD88). Station locations are shown in Figure 1. Elevations are based on this single point (VCR1) which is referenced to NAVD88 and where a value of zero corresponds to msl.

Zone (replicate)	SET		sRSET		Dominant Vegetation of Zone
	Installation Depth (m)	Marsh Elevation 1997 (m, NAVD88)[a]	Installation Depth (m)	Marsh Elevation 2003 (m, NAVD88)[a]	
Low (A)	2.30	1.000 ± 0.000[b]	0.20	1.018	
Low (B)	1.45	1.014 ± 0.003	0.20	1.019	
Low (C)	1.36	1.002 ± 0.002	0.20	1.013	
Low Zone		**1.005 ± 0.002**[c]		**1.017 ± 0.003**	short-form *S. alterniflora*
Middle (A)	1.30	1.061 ± 0.010	0.20	1.068 ± 0.003	
Middle (B)	1.30	1.076 ± 0.005	0.20	1.071 ± 0.015	
Middle (C)	1.09	1.086 ± 0.009	0.20	1.061 ± 0.005	
Middle Zone		**1.074 ± 0.005**		**1.067 ± 0.002**	*J. roemerianus/ D. spicata/ S. patens*
High (A)	1.24	1.119 ± 0.003	0.20	1.089	
High (B)	1.18	1.098 ± 0.008	0.20	1.113	
High (C)	1.24	1.095 ± 0.013	0.20	1.075	
High Zone		**1.104 ± 0.006**		**1.092 ± 0.012**	*D. spicata /S. patens*

[a] referenced to VCR1, a High Accuracy and Resolution Network (HARN) benchmark. See text for details.
[b] mean of four replicate measurements of marsh surface elevation ± one standard error
[c] average of zone replicates ± one standard error

Table 2. Differences among marsh zones of rates of accretion (I), elevation (II), and shallow subsidence (III) on the marsh platform (1997-2017). Superscripts indicate statistical differences within the column (among marsh zones) for each variable; differences are based on one-way ANOVA of n = 3 independent rates at $\alpha = 0.05$. Tukey's HSD post-hoc test determined significance of individual pairs of means. Units of measurement for all variables = mm yr^{-1}. Values are means with one standard error of the mean shown in parentheses.

Marsh Platform Zone	(I) Surface accretion	(II) Elevation change	(III) Shallow subsidence or expansion[1] (I-II)
Low	4.8 (0.2)^{a}	4.9 (0.1)^{a}	-0.2 (0.1)^{a}
Middle	4.3 (0.2)^{a}	4.2 (0.1)^{b}	0.1 (0.4)^{a}
High	3.6 (0.4)^{a}	3.3 (0.0)^{c}	0.3 (0.4)^{a}

[1] Surface accretion minus elevation change (I minus II); a positive value indicates shallow subsidence and a negative value indicates shallow expansion (Cahoon et al. 1995).

Table 3. Contribution of root zone processes to elevation change and shallow subsidence rates from 2004 to 2017. Comparison of accretion (I), elevation (II), and shallow subsidence or expansion (III), elevation change within root zone (IV), subsidence or expansion within the root zone (V), and shallow subsidence or expansion below the root zone (VI) compared among plant zones (lower case superscripts), and between SET and sRSET elevation change (upper case superscripts in column headings). Analysis among marsh zone was by ANOVA with $\alpha = 0.05$ for $n = 3$ independent rates. Tukey's HSD post-hoc test determined significance of individual pairs of means. Statistical significance between sRSET and SET elevation change within the same plant zone (treatment = elevation change measurement approach) was based on a paired, 2-tailed t-test with $\alpha = 0.05$ and $n = 3$. Lower case superscript letters indicate statistical differences within the column (among marsh zones) for each variable. Upper case letters in column heading indicate statistical difference between columns. Units of measurement are mm yr^{-1} for all variables Values are means with one standard error of the mean shown in parentheses.

	(I)	(II)	(III)	(IV)	(V)	(VI)
Marsh Platform Zone	Surface accretion	Elevation change^{A}	Shallow subsidence or expansion[1]	Elevation change within root zone^{B}	Subsidence or expansion within root zone [2]	Shallow subsidence or expansion below root zone [3]
Derived from…	Marker Horizon	SET	(I-II)	sRSET	(I-IV)	(IV-II)
Low	4.6^{a} (0.1)	4.4^{a} (0.2)	0.2^{a} (0.3)	5.1^{a} (0.2)	-0.4^{a} (0.4)	0.7^{a} (0.1)
Mid	3.2^{b} (0.4)	3.8^{ab}(0.2)	-0.6^{a} (0.6)	4.6^{ab} (0.5)	-1.4^{a} (0.8)	0.8^{a} (0.2)
High	3.1^{b} (0.2)	3.5^{b} (0.4)	-0.4^{a} (0.4)	3.5^{b} (0.3)	-0.4^{a} (0.4)	-0.0^{a} (0.5)

[1] Surface accretion minus elevation change (column III); a positive value indicates shallow subsidence and a negative value indicates shallow expansion (Cahoon et al. 1995).

[2] Surface accretion minus elevation change (column V); a positive value indicates shallow subsidence and a negative value indicates shallow expansion (Cahoon et al. 1995) within the root zone below the marker horizon.

[3] Shallow elevation change (sRSET) minus elevation change (column VI) a positive value indicates shallow subsidence and a negative value indicates shallow expansion. This zone is the portion of the soil profile between the base of the SET and the base of the sRSET (Fig. 2).

List of Figure Captions

Fig. 1 Location of the Upper Phillips Creek Marsh study sites relative to the East Coast of the United States. The positions of the low, middle (mid), and high zone sites on the marsh platform are indicated with white dots. Imagery from Google Earth, 2020

Fig. 2 Illustration of SET, sRSET, and MH installations. Roman numerals in drawing show portions of the soil profile referred to in Tables 2, 3, and 4. Figure redrawn from elements of Figures 6 and 7 in Lynch et al. (2015) and Figure 1 in Whelan et al. (2005). Not to scale

Fig. 3 Predicted relative mean sea level at Upper Phillips Creek marsh. Regression analysis in SPSS ver. 25 was used to determine the rate of sea level rise (solid line) and establish the 95% confidence limits of the trend line (blue lines). The error term of the predicted rate of relative sea-level rise (RSLR) rate is one standard error of the estimate. The datum for msl is VCR1 (see methods).

Fig. 4 Marsh surface change expressed as (A) elevation above mean sea-level (NADV88) measured by SET, (B) surface accretion measured as materials accumulated over marker horizons and (C) root-zone accretion measured by RSET. Measurements were made semi-annually from August 1997 for elevation and surface accretion, and from August 2003 for root-zone elevation, until March 2009. After March 2009 measurements were made annually. Symbols represent the mean of three replicates in each zone; low (circles), middle (open, downward triangle), and high (squares). Standard error bars are shown

Fig. 5 Tidal flooding index for the low, middle, and high zones of the marsh platform during each year that the SETs were measured. Each point is the mean number of tides per month for replicate SETs in each zone (n = 3) during the interval between successive measurements. Standard error bars are shown

Fig. 6 Monthly (A, top panel), and growing season and annual (B, bottom panel) precipitation (mm) from 1997-2017. For reference, the annual average precipitation is shown for the period between 1961-1990 in the bottom panel. Precipitation data are for the Melfa, VA, airport and were obtained from https://www.wunderground.com/history/daily/us/va/onancock/KWAL

Fig. 7 Soil organic matter profiles adjacent to elevation benchmark pipes. A. Roots are abundant over feldspar (white) marker layer (left side of photo). Note rhizome below the marker layer (bottom center of photo). B. Depth profiles of the average soil organic matter content each marsh zone. Samples were collected adjacent to each of the SET installations. Symbols represent the mean of three replicates; error are one standard error of the mean

Figure 1:

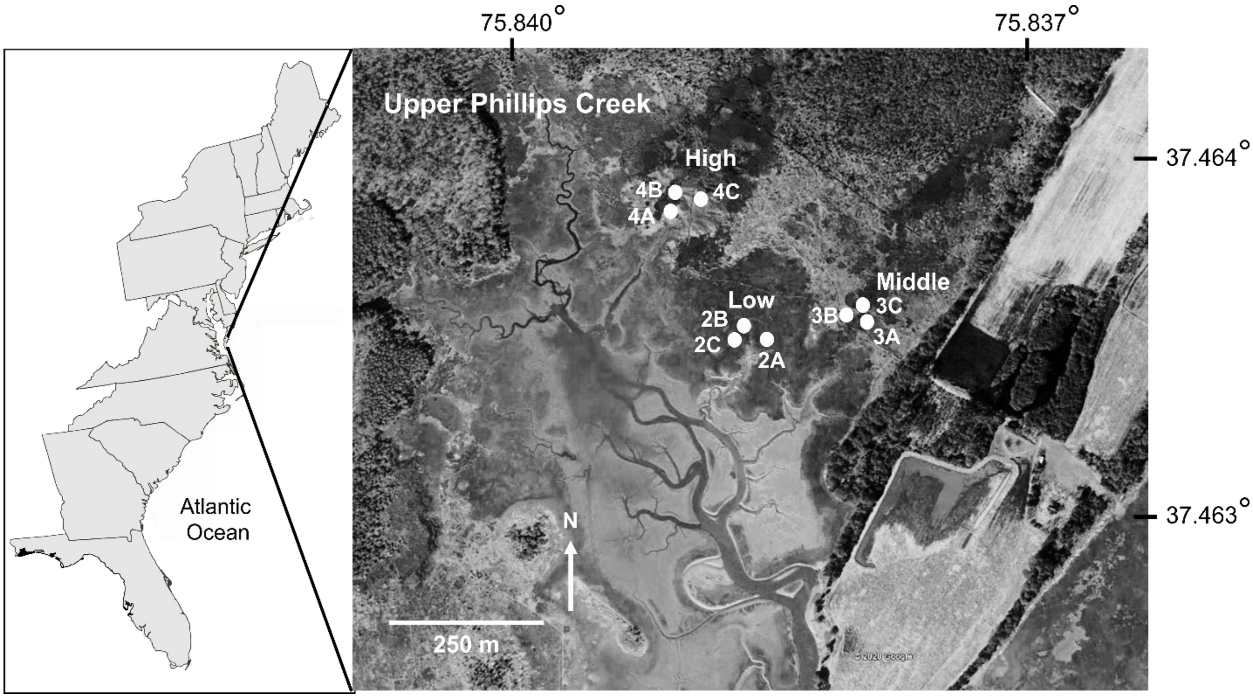

75.840°
75.837°
37.464°
37.463°
Upper Phillips Creek
High
4B
4C
4A
Middle
Low
3B
3C
2B
3A
2C
2A
Atlantic
Ocean
N
250 m

Figure 2

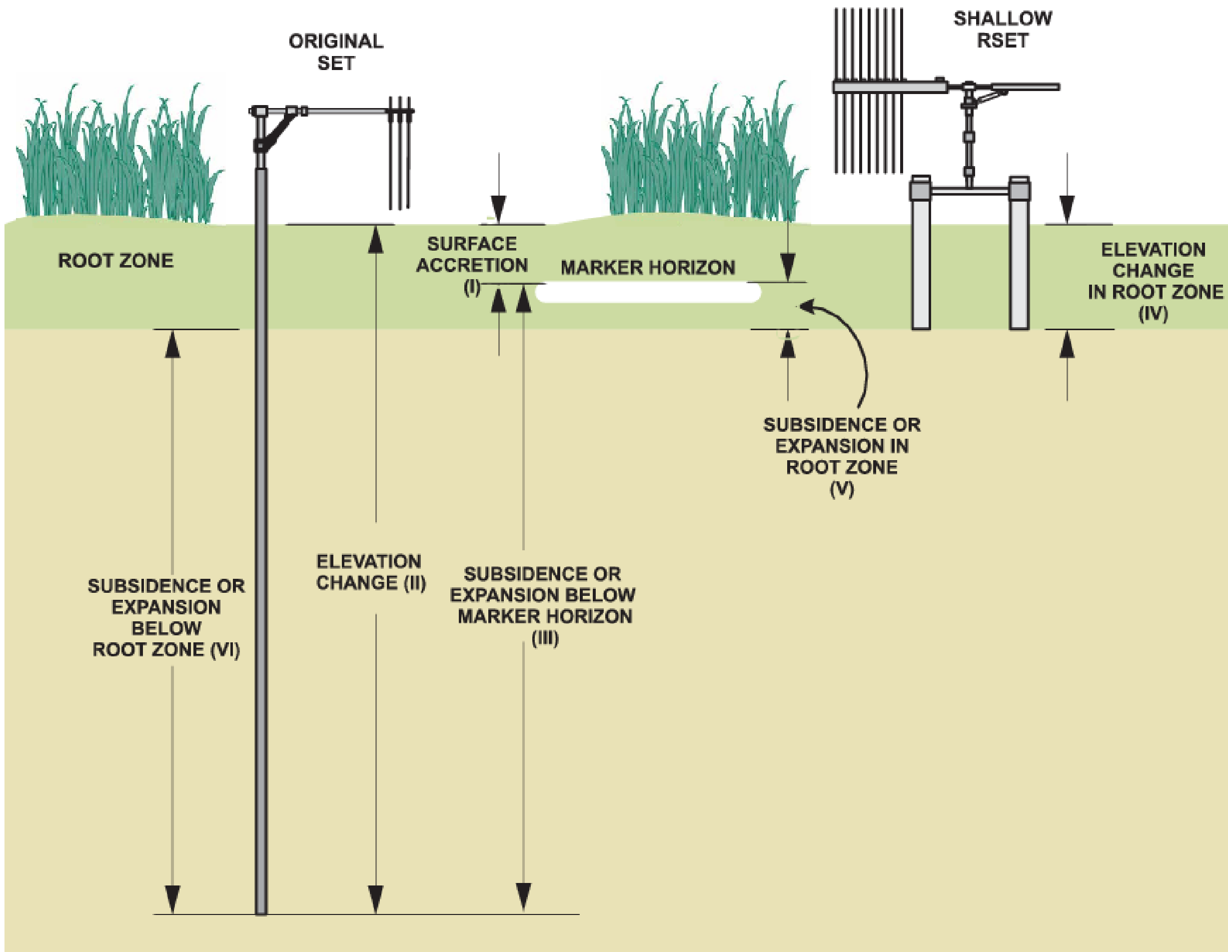

ORIGINAL
SET
SHALLOW
RSET
ROOT ZONE
SURFACE
ACCRETION
(I)
MARKER HORIZON
ELEVATION
CHANGE
IN ROOT ZONE
(IV)
SUBSIDENCE OR
EXPANSION IN
ROOT ZONE
(V)
SUBSIDENCE OR
EXPANSION
BELOW
ROOT ZONE (VI)
ELEVATION
CHANGE (II)
SUBSIDENCE OR
EXPANSION BELOW
MARKER HORIZON
(III)

Figure 3

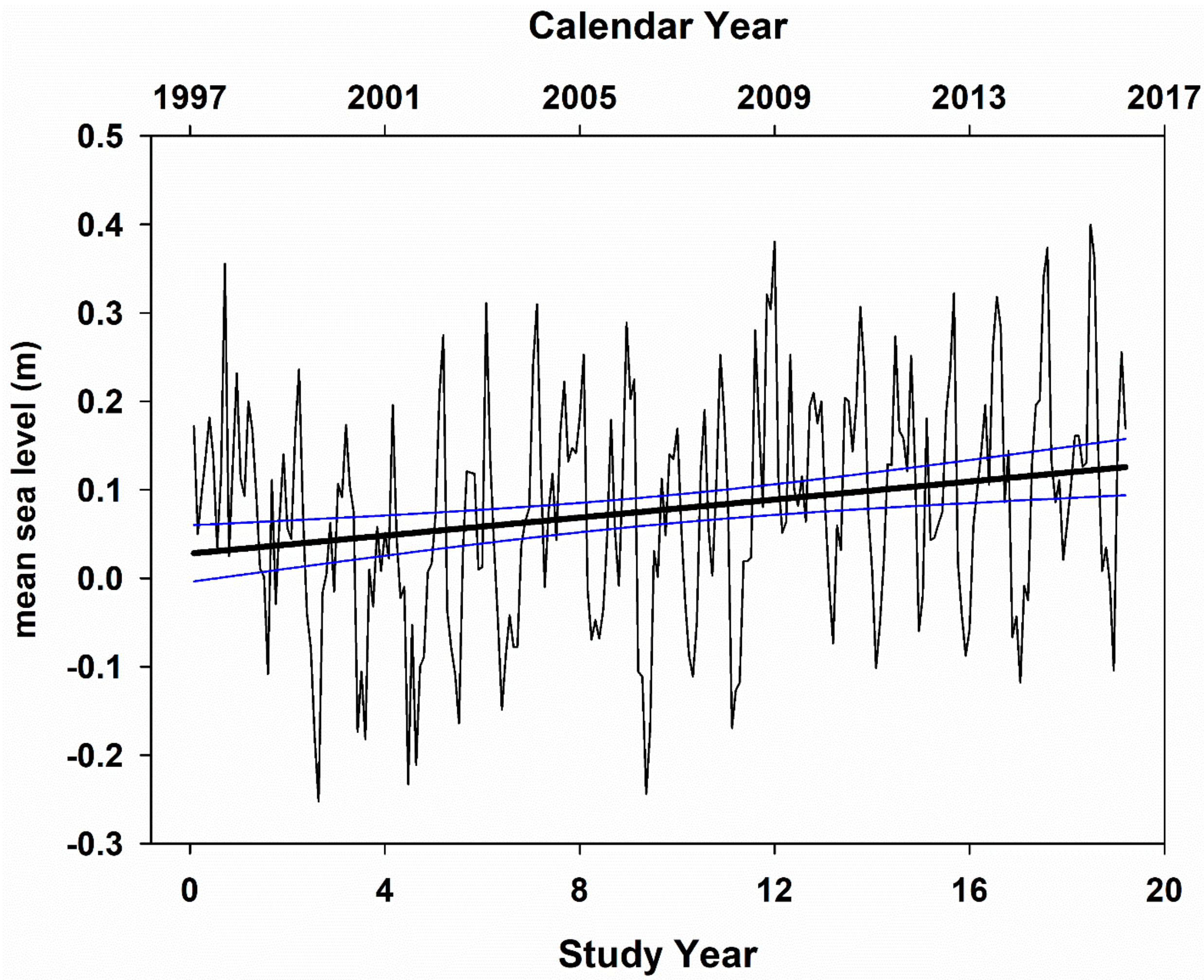

Calendar Year
1997
2001
2005
2009
2013
2017
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
mean sea level (m)
0
4
8
12
16
20
Study Year

Figure 4

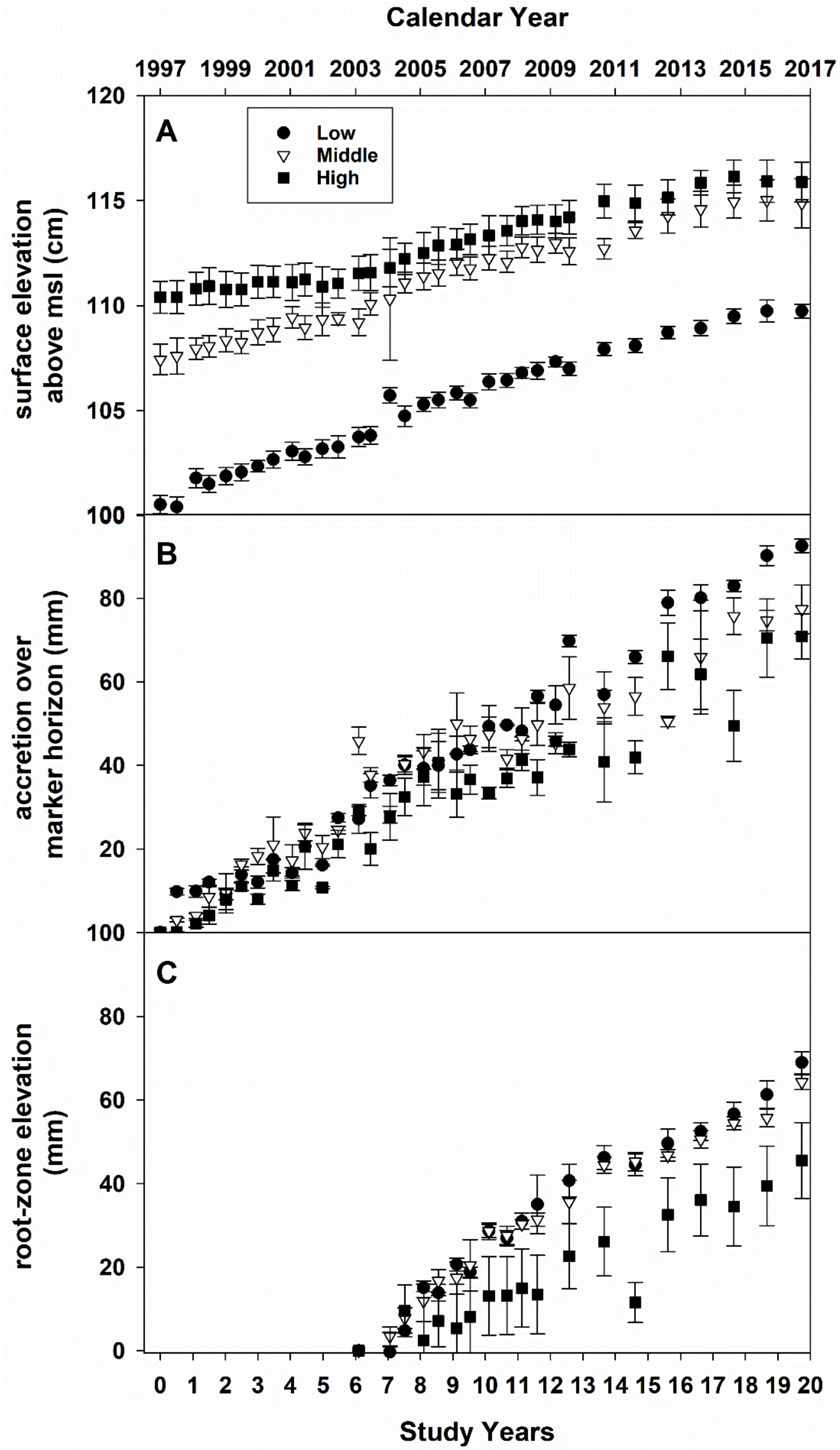

Calendar Year
1997 1999 2001 2003 2005 2007 2009 2011 2013 2015 2017
A
Low
Middle
High
surface elevation above msl (cm)
120
115
110
105
100
B
accretion over marker horizon (mm)
80
60
40
20
100
C
root-zone elevation (mm)
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Study Years

Figure 5

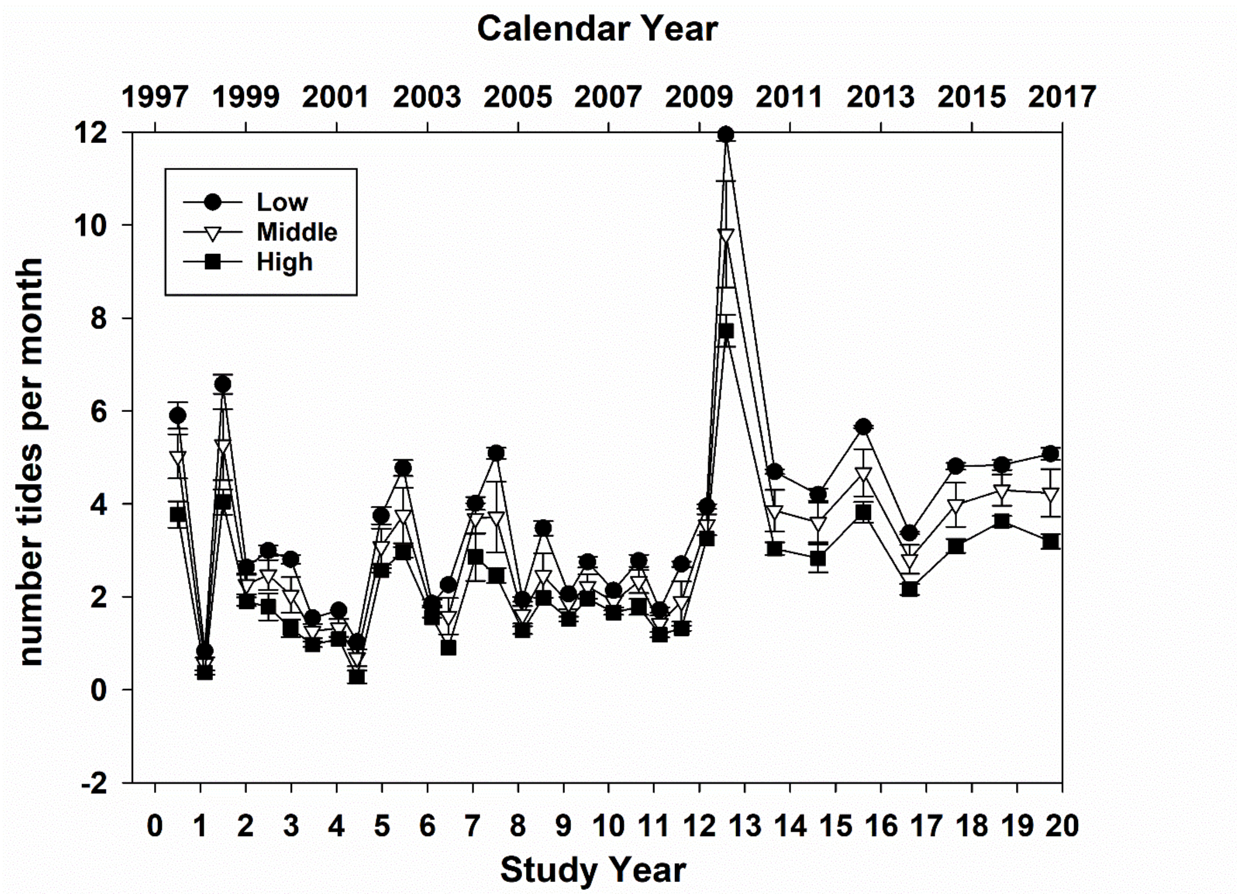

Calendar Year
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
12
10
8
6
4
2
0
-2
number tides per month
Low
Middle
High
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Study Year

Figure 6

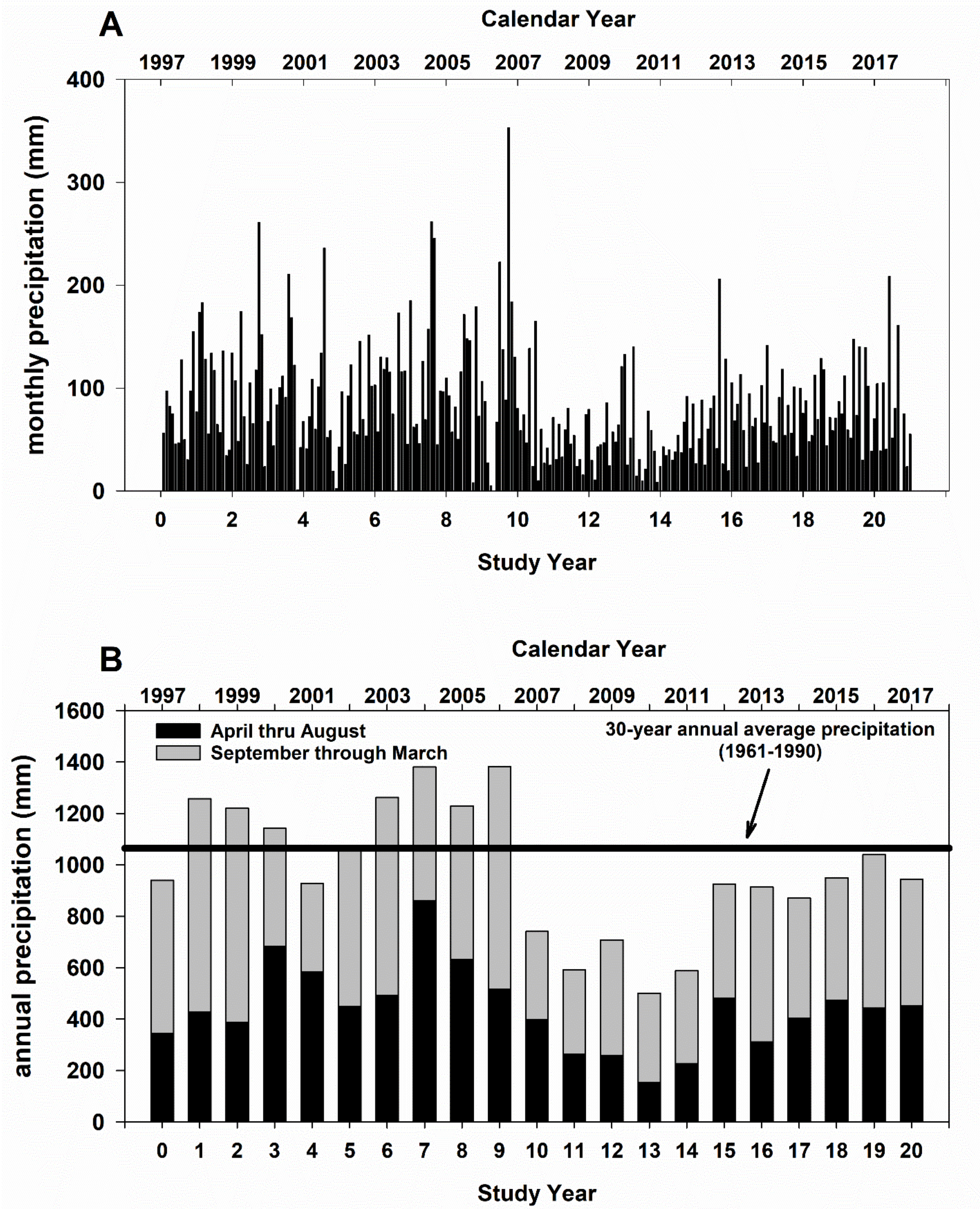
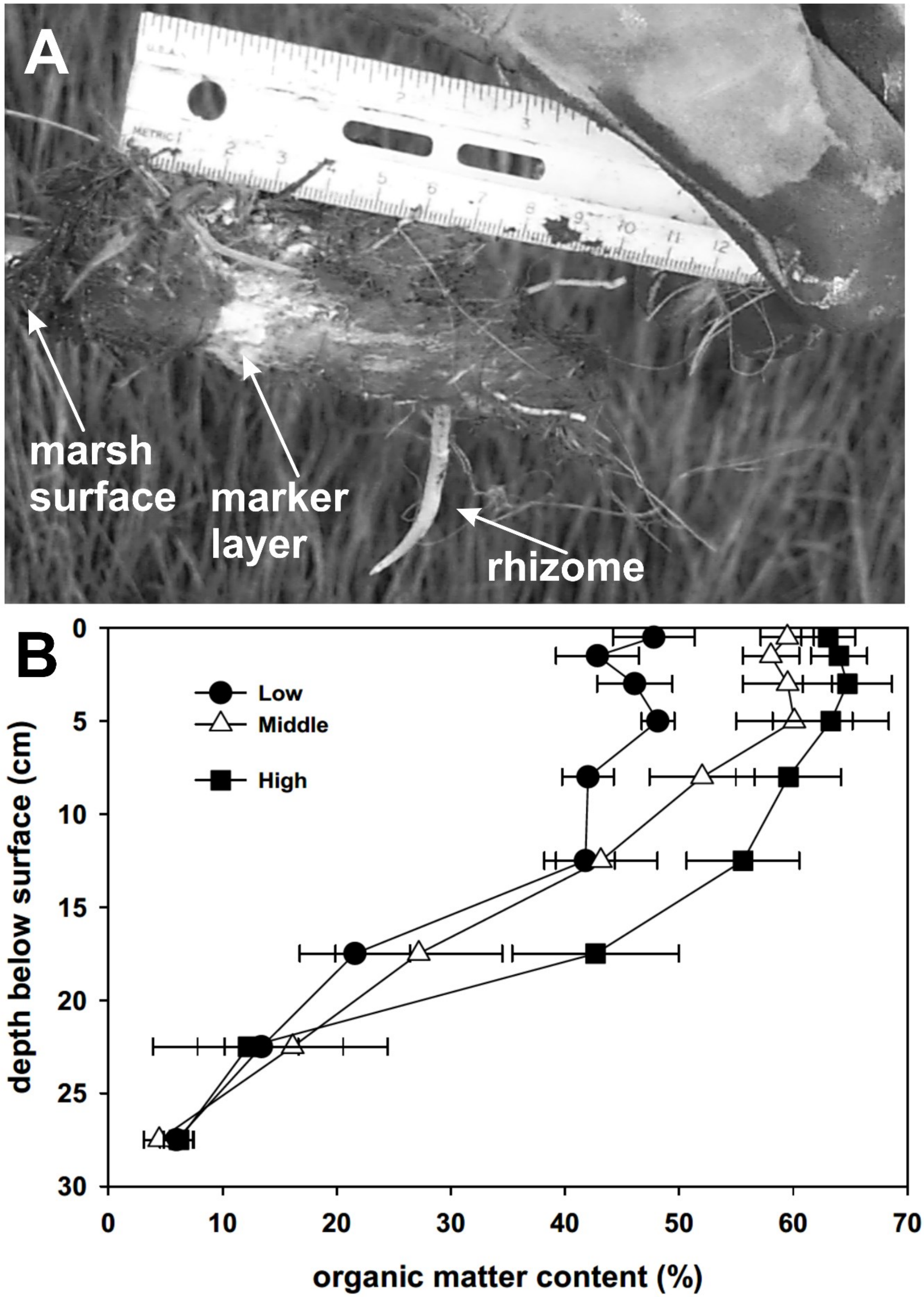

A
Calendar Year
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
monthly precipitation (mm)
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
20
Study Year
B
Calendar Year
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
annual precipitation (mm)
1600
1400
1200
1000
800
600
400
200
0
April thru August
September through March
30-year annual average precipitation
(1961-1990)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Study Year

Figure 7:


A
marsh surface
marker layer
rhizome
B
Low
Middle
High
depth below surface (cm)
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
organic matter content (%)