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Contrasting decadal-scale changes in elevation and vegetation in two Long Island Sound salt marshes

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Abstract

Northeastern US salt marshes face multiple co-stressors, including accelerating rates of relative sea level rise (RSLR), elevated nutrient inputs, and low sediment supplies. In order to evaluate how marsh surface elevations respond to such factors, we used surface elevation tables (SETs) and surface elevation pins to measure changes in marsh surface elevation in two eastern Long Island Sound salt marshes, Barn Island and Mamacoke Marsh. We compare marsh elevation change at these two systems with recent rates of RSLR and find evidence of differences between the two sites; Barn Island is maintaining its historic rate of elevation gain (2.3 ± 0.24 mm yr⁻¹ from 2003 to 2013) and is no longer keeping pace with RSLR, while Mamacoke shows evidence of a recent increase in rates (4.2 ± 0.52 mm yr⁻¹ from 1994 to 2014) to maintain its elevation relative to sea level. In addition to data on short-term elevation responses at these marshes, both sites have unusually long and detailed data on historic vegetation species composition extending back more than half a century. Over this study period, vegetation patterns track elevation change relative to sea levels, with the Barn Island plant community shifting towards those plants that are found at lower elevations and the Mamacoke vegetation patterns showing little change in plant composition. We hypothesize that the apparent contrasting trend in marsh elevation at the sites is due to differences in sediment availability, salinity, and elevation capital. Together these two systems provide critical insight into the relationships between marsh elevation, high marsh plant community, and changing hydroperiods. Our results highlight that not all marshes in southern New England may be responding to accelerated rates of RSLR in the same manner.

Keywords

salt marsh; surface elevation change; sea level rise; sediment supply; salinity

Introduction

Salt marsh ecosystems are delicately situated at elevations in inter-tidal zones that allow for inundation at high tide and exposure to the atmosphere at low tide. Vegetation patterns,

biogeochemical function, and marsh structure are directly impacted by inundation regimes (Niering and Warren 1980; Howes et al. 1984; Kuhn et al. 1999) and even millimeter changes in water levels can directly alter many aspects of salt marsh ecology. For the past *ca.* 4000 years, New England salt marshes have generally kept pace with rates of relative sea level rise (RSLR) ($1\text{--}2\text{ mm yr}^{-1}$) (Redfield 1972). However, rates of RSLR are increasing globally, due to a combination of thermal expansion and melting ice (Nicholls and Cazenave 2010). The global average rate of SLR between 1970–2009 was $0.98 \pm 0.4\text{ mm yr}^{-1}$, but this global average masks variability at regional scales; along the Northeast seaboard of the USA, including New England, rates of RSLR are some of the fastest on Earth ($3.8 \pm 0.1\text{ mm yr}^{-1}$) (Sallenger et al. 2012).

In conjunction with experiencing faster-than-average increases in RSLR, New England rivers and estuaries have relatively low sediment loads compared to elsewhere in North America, resulting in tidal marshes that are organic-matter rich and sediment poor (Bricker-Urso et al. 1989; Roman et al. 2000; Weston 2013). Salt marshes with limited sediment availability are typically less resilient to rising sea levels (Kirwan et al. 2010; Mudd 2011), as these systems rely more heavily on belowground organic matter accumulation or expanding porespace to maintain their elevation (Wigand et al. 2014). Thus, New England salt marshes are experiencing co-stressors of accelerated rates of RSLR and limited sediment supplies (Morris et al. 2012), which makes their future patterns of elevation change fairly uncertain.

Understanding how marshes are responding to rising sea levels is a challenge because marsh elevation is controlled by numerous surface and subsurface factors, such as soil water content and porespace, organic matter accumulation (which reflects relative rates of primary production vs. decomposition), erosion, sediment availability, subsidence, and compaction, among others. Because marshes lie at the land-sea interface, processes occurring in both terrestrial and estuarine ecosystems have the ability to alter marsh elevation patterns. Thus, not only are marshes susceptible to changes in RSLR, but shifts in nutrient loading, sediment availability, and temperature can also directly alter marsh ecosystem processes (Valiela et al. 1976; Deegan et al. 2012; Wigand et al. 2014).

In addition to marsh elevation, marsh vegetation patterns are directly related to inundation regimes; even small differences in hydroperiods, that is the frequency or duration of tidal flooding over a specific time period, may alter sediment oxygen availability, nutrient availability, and redox potentials, all of which directly influence marsh plant species distributions (Giblin and Howarth 1984; Howes et al. 1984; Sundby et al. 2003). Traditionally, New England salt marshes exhibited classic zonation patterns (Miller and Egler 1950; Niering and Warren 1980), with *Spartina alterniflora* growing in the low marsh where high tides inundate twice each day. Moving landward from the low marsh, the high marsh platform is inundated less frequently than the low marsh and plant species diversity is higher; New England high marsh platforms are typically colonized by mosaic of *S. patens*, *Distichlis spicata*, *Juncus gerardii*, short form *S. alterniflora*, and a variety of forbs, with the abundance and distribution of these high marsh species varying widely among marshes.

Despite these well-documented patterns of salt marsh plant species zonation, evidence over the past several decades describes apparent vegetation shifts in New England (Warren and Niering 1993, Donnelly and Bertness 2001, Raposa et al. 2015). For example, in 1993 Warren and Niering described vegetation changes over four decades on the Wequetequock-Pawcatuck tidal marshes of Little Narragansett Bay, CT (including the Barn Island Marsh examined in this study), with a shift in high marsh dominants from *S. patens* and *J. gerardii* to species better adapted to wetter conditions, such as short form *S. alterniflora*, *D. spicata*, and some forbs. These changes reflected lower surface elevations and increased hydroperiods relative to more stable areas of the system (Warren and Niering 1993). Likewise, in two Narragansett Bay, RI salt marshes Donnelly and Bertness (2001) also document a rapid landward migration of low marsh *S. alterniflora* into the high marsh, which replaced *S. patens* vegetation, a trend which they attribute to RSLR. Moreover, in this Thematic Issue, Raposa et al. (2015) report recent alterations of marsh vegetation patterns in Narragansett Bay, RI where the ongoing replacement of *S. patens* by *S. alterniflora* is now being accelerated by recent dieback events.

The purpose of this study is to document recent decadal-scale changes in marsh elevation and vegetation species composition at two CT salt marshes in the context of increasing rates of RSLR. To do this, we used a twenty year (1994–2014) record of elevation and vegetation monitoring data from the high marsh of two salt marshes in Eastern Long Island Sound - Barn Island marsh off the coast of Little Narragansett Bay and Mamacoke Marsh located along the Thames River. Given the generally low sediment supplies in the region, and the already documented sensitivity of regional vegetation patterns to shifting hydroperiods, this dataset provides a unique lens to understand how tidal salt marshes are responding to multiple co-stressors over a relatively short time-scale (10–20 yrs) in southern New England.

Methods

Study Sites

This study was conducted on the high marsh of two salt marshes in eastern Long Island Sound (Fig. 1). The Barn Island marshes are a 115 ha salt and brackish tidal marsh complex that is part of the Barn Island Wildlife Management Area. These marshes front Little Narragansett Bay in Stonington, CT, at the eastern end of Fishers Island Sound. Mean tide range is 0.79 m and summer salinities typically range from 25 – 32 psu. The Pawcatuck River enters Little Narragansett Bay just east of these marshes and Wequetequock Cove to the west; the upland is bordered by *ca.* 295 ha of protected, undeveloped forest. Vegetation on the Barn Island marshes was detailed in 1950 (Miller and Egler 1950) and 1993 (Warren and Niering 1993), and consists of a mixture of high marsh vegetation types, including *S. patens*, *D. spicata*, short and intermediate form *S. alterniflora*, and a number of annual and perennial forbs.

The Mamacoke Marsh is a 1 ha marsh located in the Connecticut College Arboretum in Waterford, CT, on the Thames River, roughly 8 km north of the mouth. Mean tide range is 0.78 m and summer salinities typically range from 18 – 25 psu. The marsh connects western upland to Mamacoke Island, a 16 ha forested natural area. The western upland border is a railroad embankment constructed in 1858, behind which is *ca.* 50 ha of undeveloped forest.

Northern and southern intertidal borders face protected coves. Mamacoke Marsh vegetation was mapped in detail in 1958 (Niering 1961); similar to Barn Island marshes, vegetation consists of a mixture of high marsh vegetation types, predominantly *S. patens* on wide cove-front levees and short form *S. alterniflora* in a large central panne; Niering (1961) also identified smaller areas dominated by *D. spicata* and *J. gerardii*.

Sea Level

The NOAA tide gauge in New London, CT (station ID 8461490) near the mouth of the Thames River was established in 1938. The tide gauge is about 20 km west of Barn Island and 5 km south of Mamacoke Marsh. Sea levels in Little Narragansett Bay (Lefor et al. 1987) and other near-by Fishers Island Sound embayments (Steever 1972) closely track the New London tide gauge. Monthly water level data were downloaded from the NOAA COOPS web site (<http://tidesandcurrents.noaa.gov>) and used to calculate annual mean sea levels (MSL) from 1939–2013.

Elevation Change and Vegetation Measures

Our measurements directly quantify marsh surface elevation change: an integrated result of volume increase from belowground vegetation growth and sediment deposition, and loss from decomposition, subsidence, and erosion. There was no attempt to parse the separate contributions of these different processes to overall elevation change.

At Barn Island, surface elevation change was measured using a total of nine rod surface elevation tables (SETs) (Cahoon et al. 2002), all on the high marsh platform. Three SETs arrays were located at three areas within the Barn Island marsh complex, which we refer to as BI Array 1, BI Array 2, and BI Array 3. BI Array 1 SETs are located on marshland facing Little Narragansett Bay and less than 30 m from the intertidal zone. BI Array 2 is located within the 8 ha area that was the principal basis for Miller and Egler's model for New England salt marsh vegetation (Miller and Egler 1950). BI Array 3 SETs are distributed up a *ca.* 1 km tidal creek on a restoring marsh that had been diked and gated in 1946 and re-opened to tidal flooding in 1978 (Sinecrope et al. 1990). Within each array the three SETs span a distance of 500–1000 m, and the distance between the arrays ranged from 500–2000 m.

The nine SETs were established in the summer of 2002. SET elevations were surveyed to NGVD 29 using differential GPS by the engineering firm Malone and MacBroom¹. SETs were first read in May 2003; subsequent readings were made between mid-September and mid-October in 2004, 2005, 2008, 2010, and 2013, within three hours of either side of low tide. Each SET had nine pins and at each station pin height was measured with the arm locked in north, south, east and west positions. The mean of all 36 measurements was taken as the measure of elevation at each SET. Using linear regression, the mean elevation change of all three SETs in an array was plotted over time to provide a rate of elevation change that reflects the last ten years at Barn Island.

¹Malone and Macbroom, 99 Reality Drive, Cheshire, CT 06410

At Mamacoke Marsh, surface elevation change was measured using surface elevation pins (Fig. 2B). In April 1994 copper pipes (1.3 cm diameter) were pushed through the marsh peat (peat depth ranged from 0.2 m to 1.7 m) and then pounded into basal material to refusal, roughly another 1 meter further. Basal material consists mainly of submerged upland soils developed on glacial sand and gravel. The grid was based on a 15 × 15 m N/S oriented grid mapped by Niering in 1958 (Niering 1961) (Fig. 2A). Niering's 1958 origin point was relocated and pin locations set using a Lietz TM20c theodolite and Lietz survey quality meter tapes. All pins are located on the high marsh platform. A total of 36 pins were set, each cut 15 cm above the marsh surface. Elevations of cut pins were measured by leveling using a Lietz TM20c theodolite relative to NGVD 29 based on a USGS benchmark located just 10 m from the southeast corner of the marsh. Pins heights above the marsh surface were recorded in October of 1996, 2000, 2002, 2006, and 2014; heights of each pin were measured at the north, south, east, and west surfaces and the mean of the four values was calculated as the measure of elevation change at each pin. Similar to the SET methods, pin height measurements were consistently made within a few hours of low tide, as to limit the influence of tidal inundation in impacting our results (Nuttall et al. 1990; Paquette et al. 2004). Not all 36 pins were recovered in these measures; roughly one pin was lost each year. In total, 21 pins were recovered in 2014 and 15 pins were recovered consistently across all sampling dates, as some pins were not recovered in intermediate years. The 15 pins recovered consistently through all sampling events were used to calculate the rates of elevation change, although no significant difference in rates was observed if using just those pins recovered in 2014 or those recovered at each sampling event (Table 1).

Vegetation changes at the Barn Island SET sites were calculated from frequency of occurrence observations. During the initial (2003) and final (2013) SET readings, species present were recorded at each of the nine pin locations on each arm, following a protocol similar to the point-intercept method (Floyd and Anderson 1987), whereby any portion of a plant touching each pin was recorded as being present. The SET locations in each array were representative of vegetation along bayfront high marsh (Array 1), central high marsh (Array 2) and the restored impoundment (Array 3). Species frequencies, however, were quantified only within the reach of the SET arm.

At Mamacoke, vegetation was sampled across the entire marsh (Fig. 2A). Changes were calculated from percent cover observations; vegetation was sampled at each pin when pins were first measured in 1996 and last measured in 2014. At Mamacoke, all species present in a 30 cm diameter circle centered on a pin were recorded and their cover estimated visually. Differences in vegetation were determined using two-sample, two-tailed t-tests ($p = 0.05$). Statistical analysis was done using SPSS 17.0 and the Microsoft Excel statistical package with the Real Statistics Resource Pack.

Results

Sea Level Rise

The long-term (1939–2013) record of RSLR based on annual average MSL at New London is $2.6 \pm 0.17 \text{ mm yr}^{-1}$ ($R^2 = 0.76$) (Fig. 3). Around 1980, RSLR began to accelerate along the Northeast coast of the US (Sallenger *et al.* 2012, Boone 2012), and this acceleration is

apparent in the long-term record of MSL at New London. For example, from 1939 to 1979 the rate of RSLR at New London was $1.9 \pm 0.34 \text{ mm yr}^{-1}$ ($R^2 = 0.46$), while from 1980 to 2013 the rate more than doubled to $4.7 \pm 0.54 \text{ mm yr}^{-1}$ ($R^2 = 0.71$) (Fig. 3).

Marsh Surface Elevation Change

At Barn Island, average rates of elevation change based on the three SET arrays at each site were always positive and ranged from $1.9 \pm 0.49 \text{ mm yr}^{-1}$ (at BI Array 3, the restoring marsh) to $2.8 \pm 0.26 \text{ mm yr}^{-1}$ (at BI Array 1, the site closest to the bay) (Table 1, Fig. 4). Averaging the rates at all three SET arrays ($n=9$) together produces a mean rate of elevation gain at Barn Island of $2.3 \pm 0.24 \text{ mm yr}^{-1}$ from 2003–2013. This average rate of elevation change of the high marsh platform at Barn Island closely matches the long-term (1939 – 2014) rate of RSLR at New London (2.6 mm yr^{-1}), but is only half the current (1980–2013) rate of RSLR.

Similar to Barn Island, the rate of elevation change at Mamacoke based on the mean of all pins recovered at each sampling date ($n=15$) over the initial ten years (1994 and 2006) was positive and strongly linear ($2.8 \pm 0.21 \text{ mm yr}^{-1}$, $R^2=0.98$) (Fig. 5). Based on measurements made in 2006 and 2014, however, the rate of elevation gain at Mamacoke more than doubled to $6.7 \pm 0.11 \text{ mm yr}^{-1}$ (Table 1). Nevertheless, not all of the pins showed the same rates of elevation change between 2006 and 2014, as values ranged from 1.3 to 16.1 mm yr^{-1} across the marsh (mean = 6.7 mm yr^{-1}). There was no consistent spatial pattern in the location of the pins that showed unusually high or low rates, as both were found throughout the study area. This variability in elevation change rates during the 2006–2014 period was unique to this sampling period, as data from the sampling dates prior to 2006 did not show such a large range (error bars, Fig. 5).

The variability in rates of elevation change observed across Mamacoke cannot be explained by absolute differences in the surface elevations found throughout the marsh, as there was no significant relationship between marsh surface elevation in 1994 and overall gain in elevation at each pin in 2014 ($R^2 = 0.01$, $p = 0.67$). Although pins dominated by *S. alterniflora* had slightly lower elevations (72.6 cm) in 1994 compared to those pins dominated by *S. patens* (76.3 cm), mean rates of elevation change at pins dominated by *S. alterniflora* (9.2 cm) was not different than those dominated by *S. patens* (9.4 cm) ($p = 0.89$). In addition, it is important to point out that elevation change rates were not different when the 20 year data set was limited to just those 21 pins recovered in 2014 or those pins recovered intermittently throughout the study ($R^2 = 0.99$, $p < 0.001$).

Relating the Mamacoke elevation increase to rates of RSLR, we see a similar pattern to that at Barn Island during the first decade of measurements; between 1994–2006 rates of elevation change at Mamacoke ($2.8 \pm 0.21 \text{ mm yr}^{-1}$) approximated the long-term record of RSLR ($2.6 \pm 0.17 \text{ mm yr}^{-1}$), but were much smaller than the 1980–2013 rate of RSLR at New London (4.7 mm yr^{-1}). However, based on our measurements taken in 2006 and 2014, it appears that the rate at Mamacoke has more than doubled, to be nearly one third higher than RSLR. Although the values represented by each of the sampling dates are based on 15 unique pin height observations, we recognize that Mamacoke data from the last decade

showed large variability and is limited in representing just the two end-members of this time period.

Vegetation Patterns

When Barn Island vegetation was initially recorded in 2003 for this study, *S. patens* was the most common species found on the marsh, with a 51% frequency of occurrence at the SET arrays (Fig. 6). However, by 2013 short form *S. alterniflora* became the dominant plant species on the marsh, occurring 61% of the time, with *D. spicata* also occurring much more frequently (44% of the time compared to 31% in 2003). Despite these changes, the only statistically significant difference in frequency of species occurrence at Barn Island between 2003 and 2013 was the increase in *S. europea* from zero to 44% (Fig. 6).

Based on the 1996 pin measurements, Mamacoke Marsh was dominated by *S. patens* (62 – 66 mean % cover) and short form *S. alterniflora* (15 – 16 mean % cover), with the balance of cover by water and open peat (4 – 6 mean % cover), and lesser amounts of *D. spicata*, *J. gerardii*, forbs, sedges, and the upper border shrub *Iva frutescens*. At the 21 recovered pins in 2014, we found no significant differences in mean cover between years for any of these dominant plant species (Fig. 7).

Discussion

The methods we use here (SETs and pins) enabled us to quantify marsh surface elevation change at different systems and at different scales. These methods do not measure accretion or erosion, as our measurements include all surface and subsurface processes that influence distance between the marsh surface elevation and the base of the pin or SET. Unlike radionuclide dating methods, such as ^{210}Pb or ^{137}Cs , our methods allow us to quantify changes in surface elevation rates at much shorter timescales, on the order of years to decades. Although they do not allow us to differentiate the relative roles of organic matter, inorganic matter (i.e. sediment), and porespace, they provide a measure of elevation change, which ultimately allows us to understand if the marsh surface is keeping pace with RSLR.

Over the long term marsh elevations must track changes in relative sea levels if the marshes are to survive. In New England, accretion rates often closely track surface elevation change (e.g., Wigand et al. 2014), resulting in many studies quantifying marsh accretion to understand how marshes are keeping up with SLR. For example, in Southern New England several historic studies have documented high marsh accretion rates as being roughly the same rate as RSLR (Bricker-Urso et al. 1989; Orson and Howes 1992; Orson et al. 1998). In fact, the Orson et al. (1998) study measured accretion rates at Barn Island marsh and found the high marsh to accrete by roughly 2.2 mm yr^{-1} , which was similar to the long-term rate of RSLR at that time. The acceleration of the RSLR rate in recent decades makes our findings on elevation changes in these two marshes relevant to understanding if the organic-rich, sediment-poor marshes in this region are able to continue to keep pace with RSLR.

With this in mind, our data shows two contrasting signals of current marsh vertical growth patterns, with one marsh (Barn Island) not keeping pace with the current rate of RSLR and the other marsh (Mamacoke) exhibiting surface elevation changes that may allow it to

maintain its elevation in light of rising seas. For example, elevation increases at Barn Island ($2.3 \pm 0.17 \text{ mm yr}^{-1}$) average 2.4 mm yr^{-1} lower than the current (1980–2013) rates of RSLR, arguing that this system is not keeping pace with recent RSLR. If this pattern continues, the Barn Island marshes may be lost to submergence in the future. Conversely, surface elevation changes at Mamacoke marsh, albeit a trend based on limited data, indicate accelerating rates of elevation rise over the past eight years, with average rates ($6.7 \pm .11 \text{ mm yr}^{-1}$) 2.0 mm yr^{-1} higher than current rate of RSLR.

Vegetation patterns at the two sites reflect the observed patterns of elevation relative to sea level. In 1993, Warren and Niering documented a shift in marsh vegetation at Barn Island reflecting a wetter marsh platform over four decades since Miller and Egler's initial survey (1950). Our recent vegetation data from this current study reinforce that finding, with a trend of increasing presence of species that tolerate wetter conditions (*S. alterniflora* and *D. spicata*) (Fig. 6). These shifts in species importance at the SET arrays are consistent with observations of vegetation changes on the Barn Island marshes made by one author (RSW) over the past four decades. In addition, the significant increase ($p = 0.04$) in the frequency of occurrence of *S. europaea*, a marsh colonizer species, (Chapman 1940) reflects the more open conditions on the marsh, which is also documented by increasing the presence of mud, or bare patches (Raposa et al. 2015) (Fig. 6). The rates of elevation increase reported here for the three SET arrays at Barn Island ($1.9\text{--}2.7 \text{ mm yr}^{-1}$) are lower than the rate of RSLR by several mm yr^{-1} , a pattern that is consistent with these vegetation observations. Contrary to Barn Island, vegetation patterns at Mamacoke Marsh are unchanged from almost 20 years ago (1996 vs. 2014) (Fig. 7). Except for the slight loss of *J. gerardii* stands at the north and south marsh edge, and an increase in *S. patens* in the area mapped as *D. spicata* by Niering, the general vegetation pattern today is very similar to that of 1958 (Niering 1961) (Fig. 2A). The lack of shift in vegetation community composition at Mamacoke indicates that this marsh may be keeping pace with current rates of RSLR, the same signal we found in our measures of elevation change.

The contrasting signals of elevation change at these two sites leads us to wonder why these marshes appear to be behaving so different over relatively short timescales. Below we propose several hypotheses to explain the apparent divergence in surface elevation changes at the two marshes during the past decade.

Elevation Capital

Differences in 'elevation capital', or the elevation of the marsh platform within the tidal frame, is a critical factor in determining how processes controlling marsh surface elevations will respond to higher sea levels (Cahoon and Guntenspergen 2010). In general, marshes with greater elevation capital should be better positioned to sustain greater plant production and favor efficient peat formation over a longer period than marshes lower in the tide range, although both may be losing elevation at the same rate relative to sea level rise (Cahoon and Guntenspergen 2010; Watson et al. 2014). Thus, we hypothesize that higher elevation capital at Mamacoke is at least in part responsible for the higher rates of vertical elevation change observed at this site.

To investigate this, we turn to flood frequency data collected in 1998 by Bellet (1999), where high marsh flooding regimes were determined at Mamacoke and at two locations within the Barn Island system, one at the BI Array 1 and another at BI Array 3 over the 1998 growing season (May 1 to September 30) (Bellet 1999). Microrelief transects were established at all three areas and elevations measured on one meter square grids, with 500–800 points measured on each transect. Elevations were determined relative to local mean lower low water (MLLW) and local benchmarks were set to MLLW by measuring tide heights with “tide sticks” (Smith and Warren 2007) at spring tides during the growing season. Mean flooding frequency values, calculated for each grid point as the percentage of seasonal high tides that reached or exceeded that elevation, were then averaged over all the high marsh points on each transect; Mamacoke and BI Array 1 were flooded by 24% of growing season high tides. BI Array 3, in contrast, was flooded by 57% of high tides. Thus, the array with the lowest gain in surface elevation (BI Array 3 at 1.9 mm yr^{-1}), had the highest flooding frequency, indicating less elevation capital at this section of the Barn Island system. However, flooding frequencies were not different between BI Array 1 and Mamacoke, which is curious considering that these two areas had drastically different rates of elevation change (2.7 vs. 6.7 mm yr^{-1} for BI Array 1 and Mamacoke, respectively). Thus, differences in elevation capital at these sites cannot fully explain our results.

Sediment Availability and Hurricane Activity

Mamacoke Marsh is located on the Thames River, 8 km upstream of the mouth, while Barn Island Marsh is located on the coast and exposed to more open estuarine water. Sediment loads are typically higher in rivers compared to open estuarine waters due to riverine drainage of terrestrial landscapes. Thus, we hypothesize that its location along a river and higher sediment availability may be a factor contributing to the larger gain in surface elevation at Mamacoke Marsh. This hypothesis is supported by Stevenson et al. (1986) who found higher rates of vertical accretion on riverine marshes compared to higher salinity marshes in Maryland and Georgia due to proximity to sediment availability at these sites.

Sediment availability at our CT sites may also have been impacted by the occurrence of several major hurricanes which struck the study sites during the study period (Cahoon 2006; Turner et al. 2006; Turner et al. 2007). In August 2011 and October 2012, the Northeast Coast of the US experienced Hurricane Irene and Hurricane (“Superstorm”) Sandy, respectively. This hurricane activity may be an important contributor to the increase in accretion rates observed at Mamacoke Marsh during the past decade. For example, Orson et al. (1998) found evidence of a large jump in accretion rates at Barn Island following Hurricanes Carol and Dianne in the 1950s. Although it is curious that there are no similar increases in recent 20 year record of accretion at Barn Island, the location of Mamacoke Marsh along the river may explain the difference; heavy inland precipitation accompanied Hurricane Irene, dropping over 25 cm of rain in parts of New York and Connecticut (NOAA Service Assessment 2012). This extensive precipitation no doubt mobilized sediments, which were eventually carried by flooding rivers into marine systems. Higher sea levels in combination with higher sediment availability have been shown to result in increasing marsh accretion rates in some instances (Morris et al. 2002; Kirwan and Mudd 2012). Thus, the location of Mamacoke Island on the shores of the Thames River could explain why

hurricanes, particularly Irene, potentially played more important a role in Mamacoke Island accretion compared to Barn Island.

In order to test this hypothesis, we collected three sediment cores from Mamacoke Marsh in October 2014 at pin locations that represented the range of elevation changes observed at this site. We analyzed cores for sediment grain size with a particle sizing instrument (Malvern Hydro 200S/Mastersizer 2000) and sediment organic content. Sediment organic content was estimated using loss-on-ignition (LOI), by combusting sediment at 500°C for 4 hrs. Sediment grain size analysis reveals that all three cores were dominated by silt grains, but in Core 1 we also found a sand deposit near the surface (at 2–4cm depth). This Core 1 also had the highest overall elevation increase (15.4 cm) compared to the other two cores, which did not show evidence of sand deposition. While these data are limited to only three cores, it supports the hypothesis that recent sand deposition on the marsh may be responsible for the higher overall rate of elevation gain observed at Mamacoke compared to Barn Island. The data from these cores also helps to explain the variable rates of elevation change at Mamacoke observed across the 21 pins recovered in 2014, as one core contained sand deposits, while the others did not.

Based on our LOI measurements, the average percent organic matter (OM) was similar among the three cores (63 – 73%). However, OM content was not uniform throughout the cores, with peaks in OM (90%) found at 1.5–2.5 cm depth in Cores 1 and 2. These two cores were dominated by *S. patens* and are at higher elevations on the marsh platform. Core 3, which was taken in the short form *S. alterniflora* zone of the marsh, had OM peak (90%) at 4.5 cm depth. This elevated OM content throughout the marsh peat supports the idea that belowground organic matter accumulation (e.g., root/rhizome production) is critical in marsh elevation maintenance at this site, in addition to sediment availability.

Salinity differences

Salinity levels at the two study sites are different, with Mamacoke marsh typically experiencing salinities of 18–25 psu and Barn Island experiencing salinities of 25–32 psu. Although some studies have found no trend in accretion or surface elevation change rates and salinity (Nyman et al. 1990), lower salinity tidal marshes generally tend to exhibit higher rates of elevation increase relative to more saline marshes (Hatton et al. 1983; Stevenson et al. 1986; Craft 2007). For example, in an examination of 51 marshes throughout the conterminous US, salinity was significantly inversely related to vertical accretion rates (Craft 2007). The significantly lower rates at higher salinity marshes is hypothesized to be due in part to more sulfate availability in saltier marshes, which serves as a terminal electron acceptor, increasing decomposition rates in these systems (Craft 2007). In addition, high sulfide concentrations, which increase in water-logged saline marshes, can be toxic to many organisms and has been associated with a decrease in above- and below-ground biomass and nutrient uptake, which may contribute to less accretion and organic matter accumulation (King et al. 1982; Koch and Mendelssohn 1989; Koch et al. 1990). Furthermore, elevation increase rates may be higher at lower salinity marshes because they are typically further up in a watershed and thus, have more land-based sediment sources available to them.

However, the idea that salinity is playing a role in the differences observed in the two sites does not explain why these differences were not observed during the first decade of the study. It is possible that the co-occurrence of multiple stressors to these marshes is leading to our observations. In addition to the recent hurricane activity, atmospheric carbon dioxide (CO₂) concentrations are also increasing. In 1994, the average global CO₂ concentrations was 359 ppm, while in 2013 the value was 396, an increase of >10%. Increasing atmospheric CO₂ availability has the potential to increase plant biomass production when light, nutrients, or water are not limiting (Norby and Luo 2004; Bernhardt et al. 2006). For example, Langley et al. (2009) examined how marsh surface elevations would respond to higher CO₂ concentrations across marshes with various salinities, finding that under intermittent flooding conditions, freshwater marshes would respond favorably to increases in CO₂ concentrations by increasing below ground biomass production to allow for maintenance of marsh elevation. However, as salinity increased, Langley et al. (2009) showed a different signal, specifically that higher CO₂ concentrations associated with decreasing accretion rates under intermittent flooding regimes. Thus, lower salinity marshes may be better able to maintain their elevations than those exposed to higher salinities, although other factors such as hydroperiods, sediment availability, and soil biogeochemistry no doubt play a crucial role.

Conclusion

Our measurements of high temporal resolution elevation changes at two marshes over one to two decades provides a unique lens to understand shifting marsh structure over the short-term. Despite being located in the same region of Southern Connecticut, the two marshes studied here show different signals in of elevation change. For the first decade of measurements, rates on both marshes were similar (2-3 mm yr⁻¹) and closely matched the local long-term rate of RSLR. However, after 2006 a divergence in rates was observed, with rates of elevation change at Mamacoke Marsh appearing to double between 2006 and 2014, which is different than the signal observed at Barn Island during the same period. We hypothesize that the location of Mamacoke marsh along the river plays an important role in its accelerated rate of elevation gain. Specifically, we suggest that increased sediment availability, especially during major storm events, combined with lower salinities and potentially higher elevation capital at Mamacoke, may lead this marsh to be more resilient to rising sea levels, although more measurements are needed to determine if this trend holds true in the future. Our results indicate that not all salt marshes in this region may respond uniformly to changing site conditions, providing further evidence of an uncertain future for the sediment-poor marshes along the coast of New England.

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Figure 1.
Map of study sites in southern Connecticut, USA

Figure 2. Schematic of Mamacoke Marsh

A) pin grid locations and vegetation zonation with position indicated of the corners of the permanent 15 × 15 m quadrats, adapted from Niering (1961) **B)** elevation pin method, where copper pins (1.3 cm diameter) are pushed through marsh peat (0.2 m to 1.7 m depth) into upland basal material to refusal, another ~1 meter deeper than bottom of marsh peat.

Figure 3. Annual average sea level at New London, CT

Sea level data is from the NOAA New London, CT tide gage. Open circles indicate sea levels from 1939–1979 ($y=0.0019x - 2.33$, $R^2=0.46$) and filled circles indicate sea levels from 1980–2013 ($y=0.0047x - 7.91$, $R^2=0.71$). Dashed trend line represents entire dataset ($y=0.0026x - 3.53$, $R^2=0.76$).

Figure 4. Elevation change at Barn Island (2003–2013)

Each point represents the marsh elevation (mm) at all three SETS at each site ($\text{Avg} \pm \text{SE}$). Black circle represents Array 1, white circle represents Array 2, and gray circle represents Array 3. Rates of elevation gain were strongly linear ($y=2.34x - 4684$, $R^2=0.89$ across all three sites).

Figure 5. Elevation change at Mamacoke Marsh (1994–2014)

Filled circles represent marsh elevation (cm) across the 15 pins consistently recovered at each sample date (Avg $\pm$ SE). Between 1994 and 2006, rates of net vertical accretion were strongly linear ($y=0.28x-562$, $R^2=0.98$). After 2006 rates more than doubled ($y=0.67x-1339$). Combined across all years (solid line), the rate of elevation increase was 4.2 mm yr^{-1} ($y=0.42x-843$, $R^2=0.94$).

Figure 6. Frequency of Vegetation Occurrence at Barn Island Marsh Sites

Bars represent mean ($\pm$ SE) frequency of occurrence of dominant species of vegetation in 2003 and 2013 across the nine SETs. Sa = *Spartina alterniflora*, Sp = *S. patens*, Ds = *Distichlis spicata*, Jg = *Juncus gerardii*, Se = *Salicornia europaea*. Statistically significant changes were only observed for *S. europaea* ($p=0.04$).

Figure 7. Vegetation Cover at Mamacoke Marsh

Bars represent mean ($\pm$ SE) percent cover of dominant species of vegetation in 1996 and 2014 at the 21 pins recovered in 2014. Sa = *Spartina alterniflora*, Sp = *S. patens*, Ds = *Distichlis spicata*, Jg = *Juncus gerardii*, If = *Iva frutescens*. There are no significant differences between years for any species ($p > 0.05$).

Table 1
Surface elevation change (Avg $\pm$ SE) at each salt marsh

Rates of elevation gain are reported for various time periods at Mamacoke Marsh using data from 15 pins that were recovered at all sampling dates throughout the study. Italics indicate rate using all pins recovered at each sampling date (range of 36 pins in 1994 to 21 in 2014, with some pins not recovered in intermediate dates but later found in 2014). Rates for one period (2003–2013) are reported for Barn Island due to the consistent rates and shorter period of measure at this site.

Rates of Elevation Change		
Mamacoke Marsh		
Specific Period (yr)	mm yr ⁻¹	R ²
1994–2006	2.8 $\pm$ 0.21	0.98
	<i>3.0 $\pm$ 0.05</i>	<i>0.99</i>
2006–2014	6.7 $\pm$ 0.11	NA
	7.0 $\pm$ 0.11	<i>NA</i>
1994–2014	4.2 $\pm$ 5.2	0.94
	4.4 $\pm$ 0.54	<i>0.94</i>
Barn Island Marsh (2003–2013)		
SET Site	mm yr ⁻¹	R ²
BI Site 1	2.7 $\pm$ 0.06	
BI Site 2	2.4 $\pm$ 0.07	0.98
BI Site 3	1.9 $\pm$ 0.16	0.91