



# Are Tidal Salt Marshes Exposed to Nutrient Pollution more Vulnerable to Sea Level Rise?

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## Abstract

Over the past four decades, Long Island, NY, USA, has lost coastal wetlands at a rate of 4% per decade due to submergence. In this study, we examined relationships between the rate of tidal salt marsh loss and environmental factors, including marsh elevation, tidal range, and wastewater exposure through analysis of stable isotope ratios of marsh soils and biota. Our goal was to identify factors that increase vulnerability of marshes to sea level rise, with a specific emphasis on the potential role of poor water quality in hastening marsh loss. Our results suggest that wastewater exposure may accelerate loss of intertidal marsh, but does not negatively impact high tidal marsh resilience to sea level rise. And while marsh elevation and tidal range were statistically significant predictors of marsh loss, they similarly displayed opposite relationships among marsh zones. This study suggests that different functional zones of coastal salt marshes may not respond similarly to global change factors, and that elevation may be an important factor mediating eutrophication effects to coastal salt marshes.

**Keywords** Tidal marsh · Climate change · Wastewater · Nutrient pollution · New York · Long Island

## Introduction

Coastal wetlands are valuable ecosystems that provide habitat for numerous marine and terrestrial species, improve water

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quality, stabilize coastlines, attenuate coastal flooding, and sequester atmospheric carbon (Costanza et al. 1997; Kennish 2001). These important ecosystems are projected to decline by 10% to 45% in area by 2100 (Craft et al. 2009), due to rates of sea level rise (SLR) and submergence exceeding rates of elevation gain, a process that has been referred to as ‘marsh drowning’ (Orson et al. 1985; Kirwan et al. 2010). Coastal wetlands in the U.S. Mid-Atlantic region are particularly vulnerable to SLR due to local subsidence from isostatic readjustment following the last glaciation (Engelhart et al. 2009), as well as changes in pressure gradients between the Gulf Stream and coastal waters that are causing SLR acceleration (Sallenger et al. 2012). Marsh drowning was first described for coastal New York by Hartig and coauthors in 2002, where processes of interior pond formation, a widening of tidal inlets, and marsh edge slumping were found to be responsible for over 50% loss of marshlands between 1924 and 1999 in Jamaica Bay in New York City. Similar rates and patterns of loss have been observed for salt marshes in Rhode Island (Watson et al. 2017b), Cape Cod (Smith 2009), and Chesapeake Bay (Beckett et al. 2016), indicating that marsh loss due to submergence is widespread throughout the region.

The ability of tidal salt marshes to accumulate sediment and organic matter at rates that keep up with relative SLR can differ locally and is a function of plant biomass, mineral

sediment deposition, and organic matter formation (Kennish 2001; Langley et al. 2009; Kirwan and Megonigal 2013; Watson et al. 2014; Carey et al. 2017). Because sediment transport pathways to Long Island (NY) tidal marshes have been widely acknowledged to have been disrupted by anthropogenic development (Peteet et al. 2018), the role of autochthonous accretion is magnified. Aboveground growth of emergent wetland plants enhances sediment trapping and reduces erosion of the marsh platform (Kirwan et al. 2010). Belowground growth of emergent macrophytes leads to the accumulation of organic matter, thus increasing marsh elevation (Langley et al. 2009). Factors that affect plant productivity, such as nutrient availability, wetland soil texture, or chemical profile can thereby influence the ability of marshes to cope with SLR. In addition, tidal range can play an important role in marsh resilience to SLR. Marshes with a small tidal range experience stress from waterlogging and poor drainage (Stevenson et al. 1986), and higher tidal range marshes tend to accumulate more sediment (Kirwan and Guntenspergen 2010) and experience enhanced plant productivity (Morris et al. 2013a).

Over the past decade, a lively debate has focused on the effects of nutrient enrichment on salt marsh resilience to SLR. Evidence from long-term fertilization studies has shown that excess nitrogen and phosphorus in salt marshes can impede the accumulation of belowground biomass, as the plants alter their nutrient foraging strategies (Turner et al. 2009; Turner 2010). The decrease in belowground biomass can reduce peat stability, which in turn can increase soil erosion and marsh loss (Deegan et al. 2012; Wong et al. 2015). It was shown that excess nutrient loadings reduce the tensile root strength of emergent marsh plants, impacting their ability to withstand erosional forces (Hollis and Turner 2019). Furthermore, excess nutrients can be metabolized by the marsh soil microbial community, promoting the re-mineralization of organic matter and thereby reducing the soil volume and elevation (Langley et al. 2009). In addition to the direct effects of excess nutrients on marsh plant growth, enhanced nutrient availability can also lead to algal blooms and wrack deposits on the marsh surface that decompose rapidly leading to spikes increase marsh ammonia and sulfide levels (Watson et al. 2015). These elevated ammonia and sulfide levels can be toxic to marsh plants (van Katwijk et al. 1997), facilitate bank erosion and thus the conversion of tidal marsh to mudflats or open water (Kolker 2005; Wasson et al. 2017).

However, other studies suggest that nutrient enrichment can increase plant growth and the resilience of tidal salt marshes to SLR. Several nutrient enrichment studies documented enhanced marsh accretion associated with increased stem density, which boosts sediment

trapping (Morris et al. 2013a; 2014; Davis et al. 2017). Other studies have not found reductions in belowground biomass (Anisfeld and Hill 2011; Davis et al. 2017), or at least reported no negative effect on overall marsh accretion (Graham and Mendelssohn 2014). While Morris and co-authors (2013b) acknowledge that nutrients can stimulate microbial remineralization of organic matter, they argue that the effect on long-term marsh accretion is negligible, as microbes utilize labile organic matter, whereas only refractory organic matter significantly adds to the soil volume. Also, recent work has pointed at the importance of soil texture and organic content in mediating impacts of nutrient enrichment (Wong et al. 2015; Wigand et al. 2016). Finally, high wastewater inputs may expose coastal wetlands to toxicants completely apart from altered nutrient availability.

This study investigated the combined effects of nutrient enrichment and marsh elevation on the areal change of tidal salt marshes on Long Island, New York, from 1974 to 2008. Remote sensing-derived classifications of 39 estuarine wetlands were analyzed for multi-decadal trends in areal extent (Cameron Engineering and Associates 2015) and tested for relationships with marsh elevation relative to tidal datums and wastewater exposure as indicated by biota  $\delta^{15}\text{N}$  ratios (Watson et al. 2018). We hypothesized that low-elevation salt marshes would be disappearing more rapidly than high-elevation marshes, as previous work has suggested high inundation levels as a key driver of loss (Watson et al. 2017a). Because previous studies have suggested that nutrient exposure has triggered marsh loss or declines in soil organic matter elsewhere in New England (Deegan et al. 2012; Wigand et al. 2009), we further tested the hypothesis that salt marshes exposed to high wastewater levels were lost at higher rates. The aim of this study was thus to elucidate whether eutrophication was associated with marsh loss on Long Island, and how this relationship may interact with other important environmental factors, such as tidal range and marsh elevation.

## Materials and Methods

The study system of Long Island represents the largest Island of the conterminous United States, which stretches 190 km from its westernmost point in New York City north-eastward into the Atlantic Ocean. Two spines of glacial moraines are located close to the northern shore of western Long Island, which fork around Peconic Bay in the eastern part. An outwash plain stretches from the moraines towards the southern shore, where barrier islands and spits shelter several

embayments. Tidal ranges vary, with microtidal regimes of generally <1 m in eastern Long Island, 1–2 m on the western South Shore, and mesotidal (2–3 m) regimes on the northwestern coast. Tidal wetlands on Long Island range from fresh and brackish to saline, which are dominated by different plant communities. Typical fresh marsh species are *Typha angustifolia*, *Spartina pectinata*, *Peltandra virginica*, among others, while salt marshes host communities of *Spartina patens*, *Distichlis spicata*, and *Limonium carolinianum* at higher elevation and *Spartina alterniflora* at lower elevation. The invasive reed *Phragmites australis* is common in brackish portions of Long Island marshes. Soil composition at sampling locations included a significant sand textural component (12–22%, mean 16%) (Desianti et al. 2019, ESM1), and soil organic carbon ranged from 3 to 26% with an average of 11%, which translates to approximately one-third (35%) of the soils being classified as organic (Mocma 2005).

Marsh exposure to wastewater derived nutrient pollution was assessed through analysis of stable isotope ratios of estuarine biota and soils (Watson et al. 2018), as wastewater-derived dissolved inorganic nitrogen has a heavier nitrogen isotopic signature in comparison with marine-derived nitrogen sources (Cole et al. 2004). Collections of the Eastern mud snail (*Tritia obsoletus*) (50 site<sup>-1</sup>), Atlantic cordgrass (*Spartina alterniflora*) (5 green shoots site<sup>-1</sup> > 10 m distant) and soil cores (0–5 cm, 5 collections site<sup>-1</sup> > 10 m distant) were made at each study location and processed for stable carbon and nitrogen isotopes, which have previously been successfully employed as eutrophication indicators (Cole et al. 2004; Pruell et al. 2006). Soil and macrophyte material was also analyzed for nutrient stoichiometric ratios (molar C/N). Snails were analyzed as whole tissue samples. All samples were dried, milled and introduced into a Vario Cube elemental analyzer interfaced to an Isoprime 100 isotope ratio mass spectrometer (IRMS). Isotope ratios for carbon and nitrogen are reported in per mille notation as:

$$\delta^a X (\text{‰}) = \left[ \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 1000\text{‰}$$

where  $R$  is the abundance ratio of the less common ( $a$ ) to the more common isotope. All samples were analyzed in duplicate for stable isotopic and elemental composition with a mean difference between duplicates of 0.07 ‰ for  $\delta^{15}\text{N}$  and 0.1 ‰  $\delta^{13}\text{C}$ , and 0.7 for the C/N ratio (Watson et al. 2018).

As previous studies have found higher rates of marsh loss for low elevation marshes (Watson et al. 2014;

Cole et al. 2017), we generated an estimate of mean marsh elevation relative to mean high water at each study site. Digital elevation models (DEMs) with a 10-m resolution were obtained from the USGS 3D Elevation Program (U.S. Geological Survey and The National Map 2017). These elevation data were derived by light detection and ranging (LIDAR) surveys, conducted in April 2013, before the growing season for marsh plants on Long Island. The elevation bias introduced by overwintering salt marsh vegetation was evaluated using ground-based real time kinematic GNSS measurements and found to be within the error reported for the DEM, therefore we did not apply a vegetation-specific elevation offset (Fernandez-Nunez et al. 2017). To obtain marsh elevation statistics, we generated 1000 random points on all wetland areas that fell within a 2 km buffer around each of the sampling locations for eutrophication indicators. This sampling procedure allows for the exclusion of points that fall on features other than the marsh platform, such as tidal channels, upland, or roads. Mean elevations of each marsh are expressed relative to mean high water (MHW), utilizing the online vertical datum transformation of the National Oceanic and Atmospheric Administration (NOAA 2016).

Marsh loss at the 39 Long Island wetland sites was quantified by comparing past and recent aerial imagery. Changes in the areal extent of Long Island tidal wetlands, classified by vegetation type, were calculated based on analysis of high resolution aerial imagery (color or near-infrared imagery) collected in 1974 and 2005 or 2008 by Cameron Engineering and Associates (2015). Vegetation classes included intertidal marsh, tidal fresh marsh, high marsh, and *Phragmites* marsh. In this study, we investigate intertidal and high marsh only and adapt the classification laid out by the New York State Department of Environmental Conservation, with ‘intertidal marsh’ denoting lower elevation marsh dominated by *Spartina alterniflora* and ‘high marsh’ corresponding to higher elevation marsh dominated by *Spartina patens* and *Distichlis spicata*. The boundary between inter-tidal marsh and high marsh roughly corresponds with MHW, such that inter-tidal marsh is found below MHW and high marsh above MHW. To characterize change rates that were calculated for different time periods, loss rates were annualized. For each sampling station of eutrophication indicators, we generated a 2-km buffer, and intersected wetland extent polygons within this range to exclude wetlands far from indicator locations. Changes in the extent of intertidal marsh, high marsh, fresh marsh, and *Phragmites* were expressed as percent change relative to 1974. To avoid extremely small marsh areas skewing the results, the area of each class was only considered if it was greater than 1 m<sup>2</sup> at a

given site. The resulting relative change estimates for each wetland were used to test for relationships with eutrophication indicators and average marsh elevation.

A partial least squares regression (PLSR) approach was used to determine the relationship between trends in marsh extent and marsh wastewater exposure, marsh elevation, as well as tidal range. This method has the advantage to be robust against collinearity of input variables and is suitable for datasets with many variables but few observations, as individual predictor variables are split into latent variables (components), each describing as much covariance between the predictors and observations as possible. The number of components to include in the model is selected to minimize the root mean square error after cross-validation and maximize how much of the variance of the response variable is explained. In order to aid variable selection for PLSR, the relative importance of each variable is assessed by calculating variable importance in the projection (VIP) metrics. The VIP score indicates what fraction of the variance captured by latent variables is explained by each predictor variable, with  $VIP > 1$  signaling high importance. Correlation matrices and hierarchical cluster analysis performed using between-groups linkage served as an initial indicator for the selection of meaningful parameters. These were individually regressed with marsh areal trends and incorporated into multiple regression analyses. The statistical analyses were performed in R version 3.3.2 (R Core Team 2017).

## Results

Stable isotope and stoichiometric ratios of soils and biota displayed a wide range of values across the 39 Long Island wetlands analyzed for this study (Supplemental Material). There was a clear gradient in eutrophication indices between the wetlands of densely populated western Long Island and those of Shelter Island Sound and Peconic Bays in the east. Higher  $\delta^{15}\text{N}$  values were found in western than eastern Long Island wetlands were found in soils ( $7.8 \pm 0.3\text{‰}$  vs  $5.1 \pm 0.4\text{‰}$ ), *Spartina* ( $9.4 \pm 0.5\text{‰}$  vs  $7.0 \pm 0.5\text{‰}$ ), and snail tissue ( $11.5 \pm 0.4\text{‰}$  vs  $9.5 \pm 0.4\text{‰}$ ) (mean  $\pm$  SE) demonstrating higher levels of wastewater exposure (Watson et al. 2018).

Overall, 13% of the 8480 ha Long Island marshes investigated by this study were lost over the 34-year time period, which reflects a loss rate of 32 ha per year. The overall relative change in marsh area from 1974 to 2008 varied considerably, with the highest areal loss occurring at Northport (64%) and the largest areal gain at Fishers Island West Harbor (54%). Eleven wetlands changed less than 10% and 26 wetlands lost more than 10% in area over the 34-year time span. LiDAR-derived

average elevation relative to MHW for the Long Island wetlands was 0.12 m below MHW, ranging from  $-0.77$  m MHW (Fishers Island East Harbor) to 0.52 m MHW (Hutchinson River). The tidal range for these marshes averaged 1.3 m but varied from 0.35 to 2.2 m across the east-west gradient of Long Island, with more westerly sites having a larger tidal range and more easterly sites having a lower tidal range ( $r^2 = 0.46$ ,  $p < 0.001$ ).

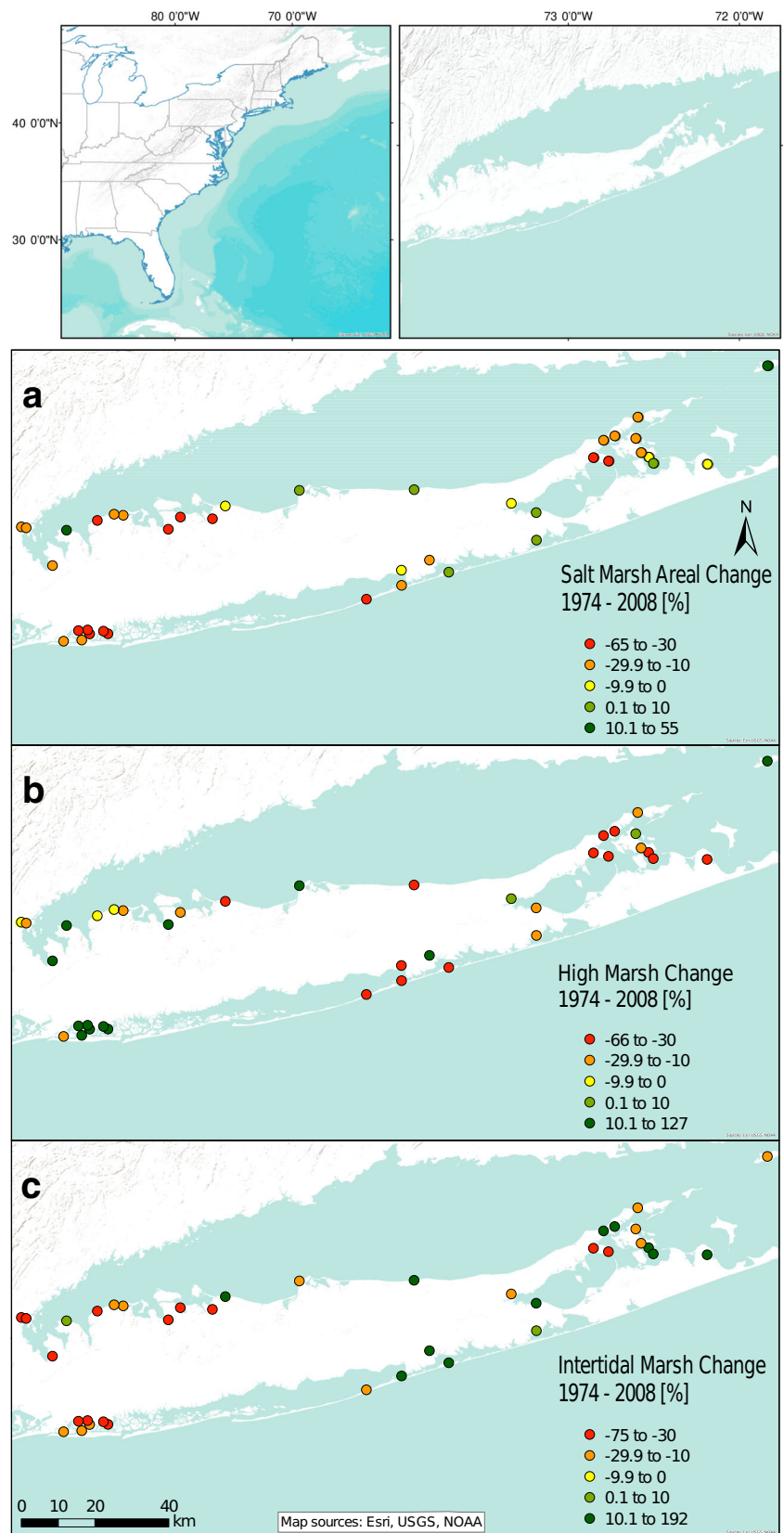
Biplots and a correlation matrix revealed a number of significant relationships, especially between the  $\delta^{15}\text{N}$  of soil, macrophytes and snails, and position along the west to east gradient in population density and wastewater pollution (Figs. 1, 2 and 3). When the 39 tidal wetlands were analyzed collectively, no significant relationship was found between the relative areal change, tidal range, marsh elevation or stable isotopic ratios of soils, plants, or snails, as indicators of wastewater exposure. However, trends in areal marsh cover became apparent when high marsh and intertidal marsh were analyzed separately. Regression analysis indicated that there is a statistically significant relationship between soil, macrophyte, and snail  $\delta^{15}\text{N}$  and the percent loss of intertidal marsh, with higher rates of intertidal marsh loss in areas exposed to higher wastewater inputs. Conversely, lower rates of high marsh loss were found in areas exposed to higher wastewater inputs. Similar trends were found for tidal range, where tidal range and high marsh loss rates were inversely correlated, while for intertidal marsh, marsh loss was positively correlated with tidal range. There was no significant effect of mean marsh platform elevation above MHW and the rate of high marsh loss, but lower marsh platforms saw more rapid rates of intertidal marsh loss.

PLSR analysis (Table 1) showed a relationship between the loss of intertidal marsh area, eutrophication indices, and marsh geomorphology. Four components described 66% of the variation in intertidal marsh loss, with high variable importance in projection (VIP) and positive regression coefficients for marsh elevation and *S. alterniflora*  $\delta^{13}\text{C}$ , and negative regression coefficients for tidal range and eutrophication indices (*T. obsoletus*  $\delta^{15}\text{N}$ , *T. obsoletus*  $\delta^{13}\text{C}$ , *S. alterniflora*  $\delta^{15}\text{N}$ ). A PLSR model for high marsh area change explained 50% of the variation in observations and high VIP values for tidal range and eutrophication indicators (soil  $\delta^{15}\text{N}$ , soil N, *S. alterniflora*  $\delta^{15}\text{N}$ , *T. obsoletus*  $\delta^{15}\text{N}$ ).

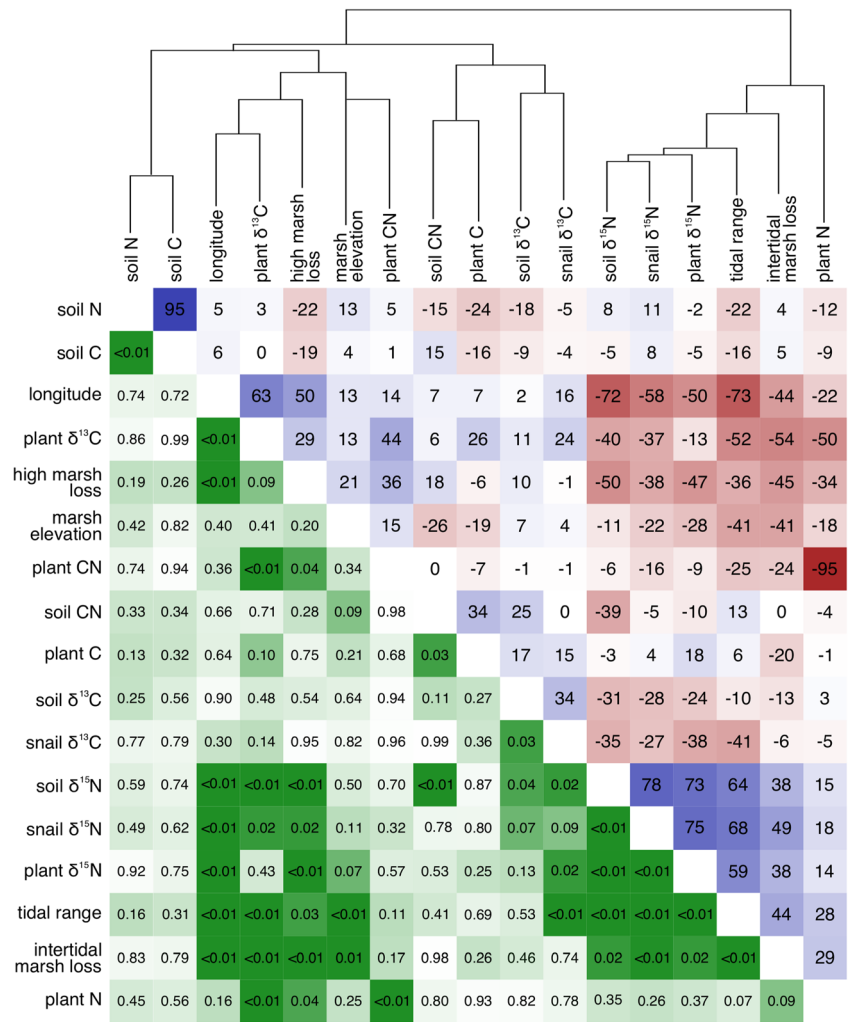
## Discussion

While the long-term average rate of Long Island tidal marsh loss was found to be 13% or  $0.4\% \text{ a}^{-1}$ , considerable variability

**Fig. 1** Percent change in (a) overall marsh areal extent for study sites from 1974 to 2008; (b) Percent change in high marsh extent; (c) percent change in intertidal marsh extent



**Fig. 2** Correlation matrix showing correlation coefficients ( $r \times 100$ ), with positive correlation coefficients in blue and negative correlation coefficients in red, and  $p$  values in green, with darker values indicating significant correlations and lighter green values indicating non-significant correlations. Order of variables was determined by hierarchical cluster analysis

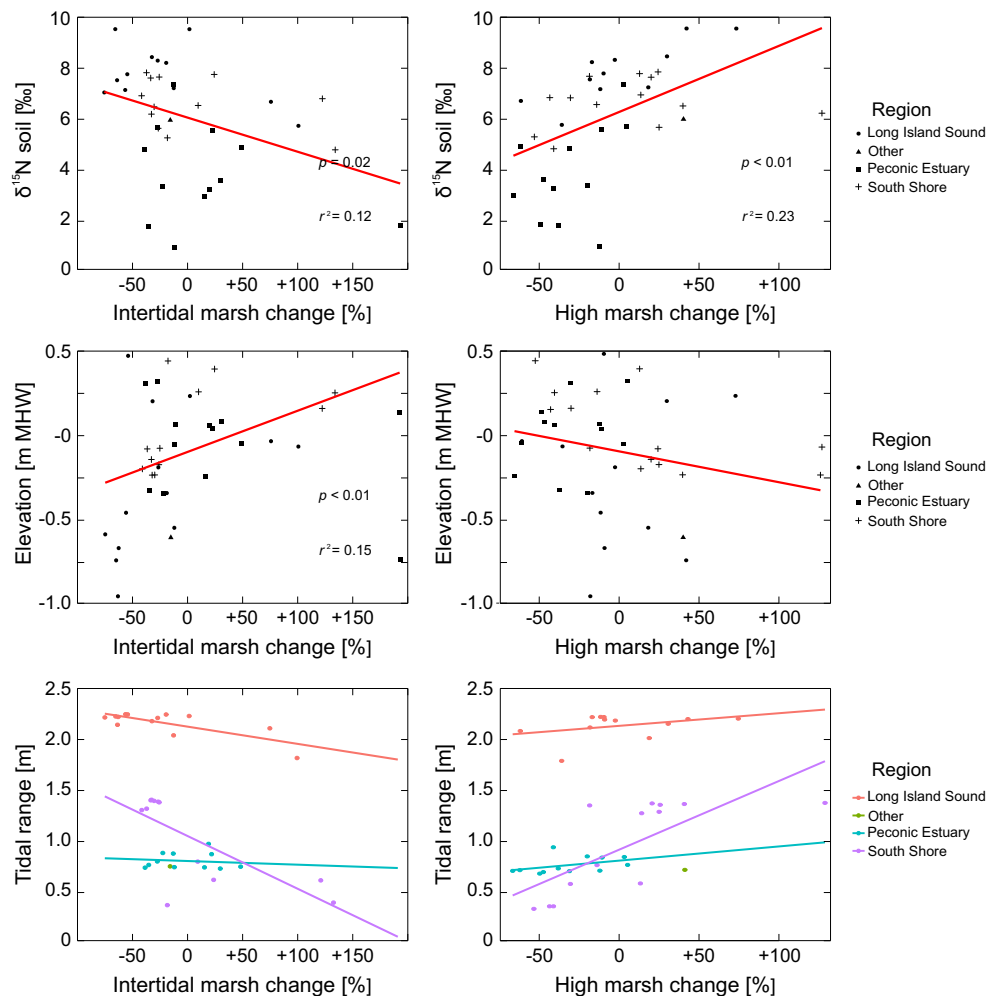


was found between sites, allowing examination of environmental factors that may promote or protect wetlands from drowning associated with SLR. Previous studies have identified multiple factors that promote marsh drowning, including accretion deficits, droughts leading to hypersalinity, and plant stress leading to reduced rates of organic matter production and peat formation (Carey et al. 2017). The areal change of an individual marsh over time is likely a response to a combination of factors and the observed change across Long Island sites is not expected to be uniform (Carey et al. 2017). While individual relationships between marsh area change and environmental predictors were modest, we were able to account for over half of site-to-site variability in marsh loss ( $r^2 > 0.5$ ) considering exposure to wastewater in concert with tidal range and marsh elevation. While wastewater constituents other than nutrients may affect marsh health, their analysis is outside the scope of this study, hence the following discussion focuses on wastewater nutrients.

In contrast to previous studies, which largely report nutrient inputs as having positive or negative effects on

wetlands (Turner et al. 2009; Morris et al. 2013b), our results instead suggest that exposure to wastewater tended to decrease vulnerability to SLR among high marsh, and yet increase vulnerability to SLR for intertidal marsh. We thus suggest that nutrient over-enrichment may have opposing effects on high and low elevation marshes. While we did not directly test the mechanisms through which nutrient enrichment promotes marsh loss in low marshes, previous work has suggested several mechanisms that might account for this difference. First, coastal estuaries exposed to high wastewater inputs tend to support nuisance blooms of opportunistic macro algae, especially species of *Ulva*, and large wrack deposits often accumulate along the low marsh, which can disturb the growth of marsh plants (Sfriso et al. 1992; Hartig et al. 2002; Newton and Thornber 2013; Wasson et al. 2017). However, these wrack deposits are often limited to the low marsh or the marsh edge, and thus only negatively affect low marsh.

**Fig. 3** Empirical relationships between observed changes in the extent of inter-tidal and high marsh with  $\delta^{15}\text{N}$ , as an indicator of wastewater exposure, mean marsh elevation relative to MHW, and with tidal range, which varied by water body



Second, in addition to physical effects of algal blooms, the increase in labile organic matter inputs associated with eutrophication may fuel enhanced rates of sulfate reduction in nutrient enriched marshes. Sulfate reduction and organic matter mineralization are a coupled process in anoxic marine sediments. High levels of sulfides are more likely to affect low marsh negatively, as high marsh soils are often well oxygenated and not prone to anoxia and sulfide accumulations (Wigand et al. 2016).

Additionally, a recent study of extractable nitrogen and biomass in Long Island marshes found higher levels of above-ground biomass and lower levels of belowground biomass in marshes with increasing levels of extractable nitrogen (Aldred et al. 2017) consistent with the classical explanation of reduced belowground growth where nutrient levels are abundant. This shift in productivity pattern associated with nutrient exposure may have different effects on high and low marsh vegetation, which typically support different growth forms of *Spartina alterniflora* (Howes et al. 1986), and in the high marsh may result in shifts from low productivity to high productivity species (Bertness et al. 2002).

Finally, coastal wetland marsh zones may vary in nutrient exposure based on their tidal height. Plants that are flooded frequently may be more exposed to exogenous nutrients, while exposure values for infrequently flooded high marsh are likely more modest (Wigand et al. 2014). As recent reports have documented reduced tensile strength in *S. patens* roots associated with elevated nutrients (Hollis and Turner 2019), this could translate into reductions in root tensile strength, affecting primarily the low marsh. Lastly, other – potentially toxic – constituents of wastewater may also alter plant health, and exposure to such toxicants may also scale with tidal height.

In addition to examining effects of wastewater exposure on tidal salt marsh vulnerability to SLR, this study also examined relationships between marsh loss and tidal range and marsh elevation profile. Similar to our findings on wastewater enrichment, we found different relationships between marsh loss and predictor variables (tidal range, and marsh elevation), depending on whether the focus was intertidal marsh or high marsh. While numerous previous studies have highlighted the vulnerability of low elevation and low tidal range marshes

**Table 1** Number of latent variables, coefficient of determination (Model  $R^2$ ), and root mean square error of prediction (RMSEP) for PLSR models of the percent areal change of intertidal marsh and high marsh

Model statistics	Inter-tidal marsh areal change (Model 1)		High marsh areal change (Model 2)	
Latent variables	4		3	
Model $R^2$	0.66		0.50	
RMSEP	39.21		33.29	
<i>Predictor statistics</i>	correlation	VIP	correlation	VIP
Elevation (m)	+	1.08	X	X
tidal range (m)	–	1.20	+	1.09
soil $\delta^{15}\text{N}$	–	1.00	+	1.37
soil N (%)	–	0.92	+	0.94
soil C (%)	–	0.92	+	0.82
<i>T. obsoletus</i> $\delta^{15}\text{N}$	–	1.14	+	1.20
<i>T. obsoletus</i> $\delta^{13}\text{C}$	+	0.69	+	0.77
<i>S. alterniflora</i> $\delta^{15}\text{N}$	–	0.88	+	1.04
<i>S. alterniflora</i> $\delta^{13}\text{C}$	+	1.20	X	X
<i>S. alterniflora</i> C (%)	+	0.69	X	X
<i>S. alterniflora</i> N (%)	X	X	+	0.71
<i>S. alterniflora</i> C/N	X	X	–	0.71
high marsh areal change (%)	–	1.12	X	X
intertidal marsh areal change (%)	X	X	–	1.14

Direction of correlations and VIP of predictor variables show significant positive associations (+) between wastewater exposure and high marsh change, and negative associations (–) between wastewater exposure and intertidal marsh change. A VIP > 1 indicates a strong influence of the predictor on latent variable of the PLS. Absence of correlation is denoted by (X)

to SLR (Stevenson et al. 1986; Watson et al. 2014; Kearney and Eugene Turner 2016; Ekberg et al. 2017), our work suggests more broadly that coastal salt marshes may support two biogeochemically distinct zones – essentially a higher marsh oxidized zone, and a more reducing low marsh zone that respond differently to environmental forcings. Because few studies have discriminated trends in high marsh and intertidal marsh zones separately, this potential relationship may have been obscured.

## Conclusions

From 1974 to 2008, the 39 Long Island salt marshes investigated in this study show differing trends in areal extent, with an overall loss of 13%. The factors making salt marshes more susceptible to SLR differed between marsh zones. In *S. alterniflora*-dominated intertidal marsh, low elevation, large tidal range, high soil carbon, and high wastewater exposure were associated with higher rates of marsh loss. In contrast, large tidal ranges, high soil carbon, and high wastewater exposure in the *S. patens*-dominated high marshes on Long Island were associated with resilience to SLR. Collectively, this work highlights the importance of considering functional

differences between intertidal and high marsh vegetation when considering vulnerability to SLR, or other interacting anthropogenic stressors.

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