# SEA LEVEL RISE AND SEDIMENT: RECENT SALT MARSH ACCRETION IN THE HUDSON RIVER ESTUARY

A Final Report of the Tibor T. Polgar Fellowship Program

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**ABSTRACT**

Salt marshes occupy a narrow elevation range within the intertidal zone. If they are to remain viable, marshes must rise at a rate commensurate with sea level. To understand the prospects for accommodating future sea level rise, this research asks whether vertical accretion in New York City salt marshes has kept pace with rising sea levels over the past two centuries, and how the resultant disparities have changed the flooding stress experienced by the marshes.

Sediment cores were retrieved from marshes on Staten Island, Jamaica Bay, and the Bronx, NY. Age-depth models were calibrated using multiple independent age markers; $^{210}Pb$, $^{137}Cs$, and total Hg content. Subsamples from depth increments were combusted to determine mineral and organic content. Water level loggers were deployed at each site and used to model historic tide data based on the 150-year tide data record for New York City.

These data show that marsh surface accretion has been variable in time and space, but has overwhelmingly lagged behind sea level rise over the past two centuries. This de-coupling has led to a substantial reduction in the elevation of the marsh surface relative to sea level, and has dramatically increased the frequency and duration of flooding experienced by the marshes, although there is evidence of a rebound of marsh accretion in response to increased flooding. Contributions of mineral and organic sediment deposition to total accumulation rates are examined within the context of changing inundation regimes. These results suggest that an uncertain future awaits many coastal wetlands in the northeastern US.

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## INTRODUCTION

As urbanization proceeded in the New York City region, salt marshes suffered substantial losses due to dredging and filling (Niering and Bowers 1961). Salt marshes that survived the urban expansion of the early twentieth century have since been protected from direct destruction, in recognition of the ecological services they provide, including carbon storage, storm surge mitigation, and the provision of habitat for commercially important fauna (Boesch and Turner 1984; Chmura et al. 2003). Although dredging and filling activities have largely ceased, marshes are still affected indirectly by human activities.

Accelerated sea-level rise and altered sediment availability are two important and enduring human impacts on coastal wetlands. Sea level rise records for the Hudson River suggest average rates of 1.3 $mm \cdot yr^{-1}$ from 4 kybp (thousand years before present) until the late 1800s (Engelhart and Horton 2012). During the last 150 years, the instrumental record shows that rates of sea level rise in New York City have averaged 2.8 $mm \cdot yr^{-1}$ (Donnelly et al. 2004; PSMSL 2013). In the coming century, the rate of sea level rise in the New York City region may increase by an order of magnitude or more (Horton et al. 2010). It is unclear whether the region's salt marshes will be able to accommodate dramatic increases in sea levels. Indeed, it is uncertain how marshes have responded to the moderately accelerated sea level rise observed over the past 150 years.

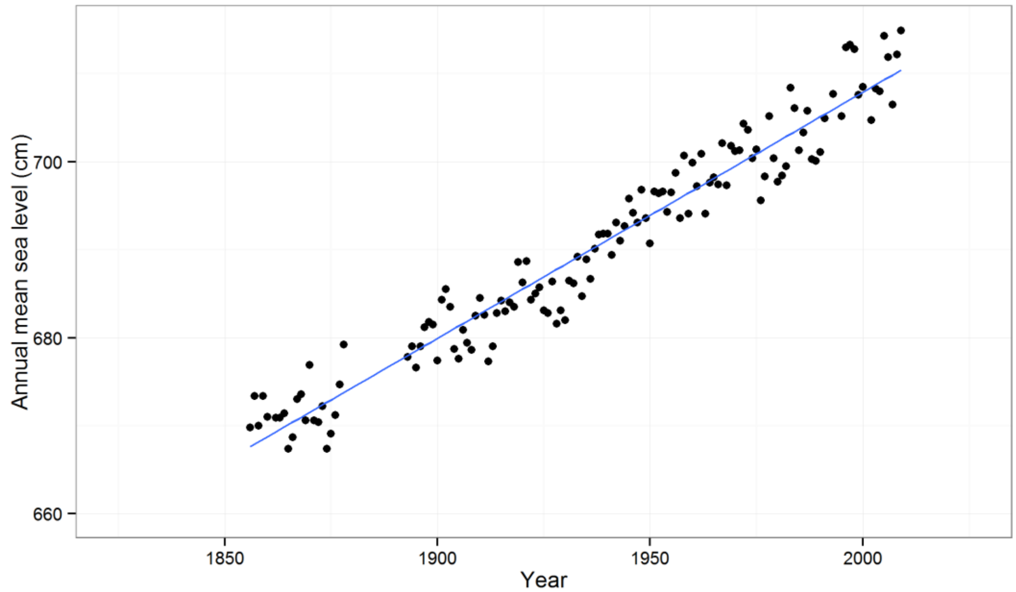



**Figure 1.** **Instrumental record of annual mean sea level in New York City, 1856-2012. Regression line slope is 2.8 mm·yr$^{-1}$ (Data source: PSMSL 2013).**

To avoid flooding stress and maintain their spatial extent, marshes must rise vertically to accommodate rising sea levels. This is accomplished through the capture of inorganic tidal sediment and the production of belowground organic material (Redfield 1972; Reed 1995). Many empirical models of marsh accretion treat belowground production as a constant (e.g., Morris et al. 2002; Temmerman et al. 2004), emphasizing the importance of sediment supplied by tidal waters.

Sediment supply to the Atlantic coastal zone has varied dramatically over time (Stevenson et al. 1985; Stevenson et al. 1988; Kirwan et al. 2011). Outside of the Hudson River Valley, European colonization led to extensive landscape clearing, erosion, and increased sedimentation in many coastal areas. This trend eventually shifted and sediment supply declined as forests re-grew and rivers were dammed, severing the link between watershed erosion and coastal deposition, a shift to which salt marshes may still be responding (Kirwan et al. 2011).

However, Hudson River tidal wetlands show a sedimentation pattern that bears little resemblance to broader trends in sediment supply. Prior to European settlement, sedimentation rates in Hudson River marshes varied from 0.5 $mm \cdot yr^{-1}$ in northern marshes to 3.0 $mm \cdot yr^{-1}$ in the southern Piermont marsh (Pederson et al. 2005; Sritrairat et al. 2012). Sedimentation rates appear to have declined with colonization (Peteet et al. 2007), only to reach historic highs in the last century – accreting as much as 7.8 $mm \cdot yr^{-1}$ (Sritrairat et al. 2012).

It remains an open question whether marshes on the seaward end of the estuary reflect similar trends, and there is reason to suspect they may not. In highly developed coastal environments such as NYC, sediment supplied by coastal erosion may be severely limited by seawalls and other forms of shoreline hardening.

The present research explores two research questions:

(1) Are coastal marshes in NYC keeping pace with local rates of sea level rise?

(2) How have deposition rates of inorganic material (IM) and organic material (OM) changed over the twentieth century?

## METHODS

### Research sites

This research was conducted at three salt marshes in New York City: Saw Mill Creek on Staten Island, Pelham Bay Park in the Bronx, and Spring Creek Park, part of the Jamaica Bay wetlands complex in Queens (Fig. 2). In this report, references to Staten

Island, the Bronx, and Jamaica Bay refer, respectively, to these research sites. All three sites are owned and managed by the New York City Department of Parks and Recreation.

The Hudson River is the dominant local source of natural freshwater to the region. The Bronx marsh is separated from NY/NJ Harbor by Hell Gate and is near the Hutchinson River. Jamaica Bay receives nearly all of its freshwater inputs from four major sewage treatment plants, which collectively discharge approximately $10^6$ $m^3 \cdot day^{-1}$ into the Bay (Beck et al. 2009). The Staten Island marsh is adjacent to the Arthur Kill waterway, an industrialized shipping lane and the endpoint for a number of small rivers, although wastewater discharges (approximately $10^{5.7}$ $m^3 \cdot day^{-1}$) also make up a large proportion of the freshwater inputs to Arthur Kill (Burger 1994).

Salinity at the sites averaged 27 psu at the Staten Island marsh, and 32-33 psu at the Bronx and Jamaica Bay sites. Tidal range varies from ~1.4 m at the Staten Island site to ~1.5 meters at Jamaica Bay and ~2.1 m at the Bronx marsh. Vegetation at the Staten Island and Bronx sites is dominated by *Spartina patens* and *Distichlis spicata*, with a creekbank fringe of tall-form *Spartina alterniflora*. The Jamaica Bay site is dominated by tall-form *S. alterniflora*, with smaller patches of *S. patens* and *D. spicata*.

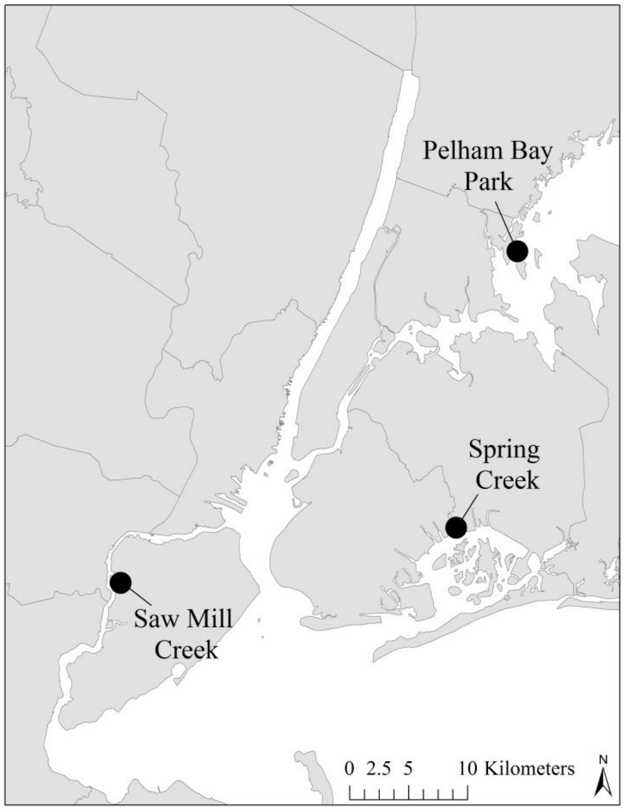



**Figure 2. Map of New York City region. Coring locations are indicated.**

**Sediment core retrieval**

At each site, exploratory coring was conducted to understand subsurface features and locate an area of peat that was without obvious physical or hydrologic perturbations. After finding suitable locations, sediment cores were collected from areas of high marsh (*D. spicata* or *S. patens*) with a coring tool made from 15 cm diameter PVC pipe. Sediment compression was quantified by measuring vertical displacement of the marsh surface following insertion of the coring tool.

Marsh surface elevations at coring locations were measured in National Geodetic Vertical Datum of 1929 (NGVD29) using surveying equipment. RTK-GPS was used to establish local benchmarks in NGVD29, and a total station was used to measure relative elevations within sites. Vertical accuracy of RTK-GPS, used to determine the absolute elevation of a benchmark at each site, is conservatively estimated at 25 mm. The total station used to measure relative elevations of coring locations, water level loggers, and benchmarks, has 2 mm vertical accuracy.

**Physical and chemical measurements**

In the laboratory, cores were sectioned into 1.5-2 cm intervals for physical and geochemical analysis. Each core section was weighed before and after drying to $60^{o}C$, and was then pulverized in a Spex 8000 ball mill. Sub-samples from each core section were re-dried and weighed at $60^{o}C$, $105^{o}C$, followed by combustion at $500^{o}C$ to determine organic content by loss on ignition. Mineral content was measured as the ash-free dry weight of a sample. Moisture content was determined by mass loss between field moisture and $105^{o}C$. Bulk density was measured as the moisture-free dry mass ($105^{o}C$) per unit volume for each core section.

Organic carbon ($C_{org}$) and total nitrogen content were measured on a ThermoFinnigan CHN analyzer following digestion with 6 N HCl. Total Hg content was measured using a Direct Mercury Analyzer (DMA80). Replicates, blanks, and standard reference material were run with every 10 samples for $C_{org}$, N and Hg analysis.

**Radionuclide activity**

Activity of $^{210}Pb$, $^{214}Pb$, $^{137}Cs$, and $^{7}Be$ were measured by gamma ray spectrometry using a low-background Ge detector. Activities were measured at energies of 46.5, 352.7, 661.7, and 477.2 keV, respectively, and corrected for detector efficiency and self-absorption. Dried, ground samples were sealed in 115 $cm^3$ cans and equilibrated for 21 days before analysis. This equilibration period allows supported $^{210}Pb$ ($^{210}Pb$ produced by in-situ decay of $^{226}Ra$, measured indirectly as $^{214}Pb$) to be distinguished from unsupported or excess $^{210}Pb$ ($^{210}Pb_{xs}$, the $^{210}Pb$ activity due to atmospheric deposition of $^{210}Pb$).

$^{210}Pb$ has a half-life of 22.3 y, making it ideal for studying depositional processes over the past century. $^{210}Pb$ has limited utility in dating sediment older than about five half-lives, where less than 3% of initial activity is presently detectable.

To estimate sediment accretion rates, constant rate of supply (CRS) models (Oldfield and Appleby 1984) were applied to the $^{210}Pb_{xs}$ data. The sediment age, $t_x$, for each depth, $x$, is calculated as:

$$t_x = \frac{1}{\lambda} \ln \frac{Q_0}{Q_x} \quad (1)$$

where λ is the $^{210}Pb$ decay constant, $Q_0$ is the $^{210}Pb_{xs}$ inventory for the entire core, and $Q_x$ is the $^{210}Pb_{xs}$ inventory below depth $x$. Sediment accretion rates for a depth interval, $i$, are then calculated as:

$$r_i = \frac{x_i - x_{i-1}}{t_i - t_{i-1}} \quad (2)$$

CRS models assume that atmospheric supply of $^{210}Pb$ is constant, and as a consequence, variations in $^{210}Pb_{xs}$ activity between adjacent sediment layers reflect differences in sedimentation rates.

$^{137}Cs$ is an anthropogenic radionuclide derived from atmospheric nuclear weapons testing. Peak deposition occurred in 1963 and provides an unambiguous horizon of known age in sediments, suitable as an independent check on $^{210}$Pb-derived sediment dates (Appleby 2008). The deepest sediment layer with detectable $^{137}$Cs activity is sometimes used to indicate the 1954 horizon, when atmospheric nuclear weapons testing began. The 1954 horizon was not used in the present study because of high uncertainty. This uncertainty stems from the low initial $^{137}$Cs activity expected in a potential 1954 horizon combined with decay over the subsequent 60 years, which has reduced detectable activity to 25% of the initial level. As a result, 1954 $^{137}$Cs horizons are likely to exhibit an upward bias.

Hg concentrations offer an additional independent check on sediment dates. Peak Hg pollution occurred from approximately the 1950s-1970s in the NYC region (Varekamp et al. 2003). Hg peaks are less reliable than $^{137}$Cs because, while $^{137}$Cs reflects a global-scale signal, local industry and pollution trends can impart an undetected bias to Hg depth profiles.

Sediment accretion rates were then used to estimate mass accumulation rates:

$$MAR_i = r_i \times \rho_i \times [c_i] \quad (3)$$

where $MAR_i$ is the mass accumulation rate (g · cm$^{-2}$ · yr$^{-1}$) for a depth interval $i$; $r_i$ is the corresponding sediment accretion rate (cm · yr$^{-1}$), $\rho_i$ is sediment bulk density (g sediment · cm$^{-3}$), and $[c_i]$ is the concentration of a constituent of interest (e.g., g C · g$^{-1}$ sediment).

## Hydrology

Water levels were measured by deploying pressure transducers (Solinst® Levelogger LTC) at each of the three marshes. Transducers recorded pressure, temperature, and conductivity at 6 minute intervals for at least two months at each site. Pressure measurements were corrected for atmospheric pressure to yield water depth measurements, and these were verified by manual field measurements. Surveying techniques were used to convert water depths to elevations in NGVD29.

# RESULTS

## Bulk density and organic matter profiles

Bulk density profiles (Fig. 3) show that these marshes generally have low density peat, consistent with field observations. The Bronx and Jamaica Bay cores have spikes in sediment density, although the depth of the peak varies from 9 cm in the Bronx to 34 cm in Jamaica Bay. Bulk density in the Staten Island core is homogenous.

Organic matter (OM) depth profiles (Fig. 3) were less variable than bulk density profiles. All three cores have slight subsurface increases in OM, followed by gradual declines with depth. In the Bronx and Staten Island cores, OM content subsequently rises again deep in the core. In the Bronx core, OM content near the base of the core is even higher than near the surface. These observed OM profiles are consistent with field observations of abundant OM throughout the cores, including fibrous rhizomes readily identifiable to species even at the base of the sediment cores.

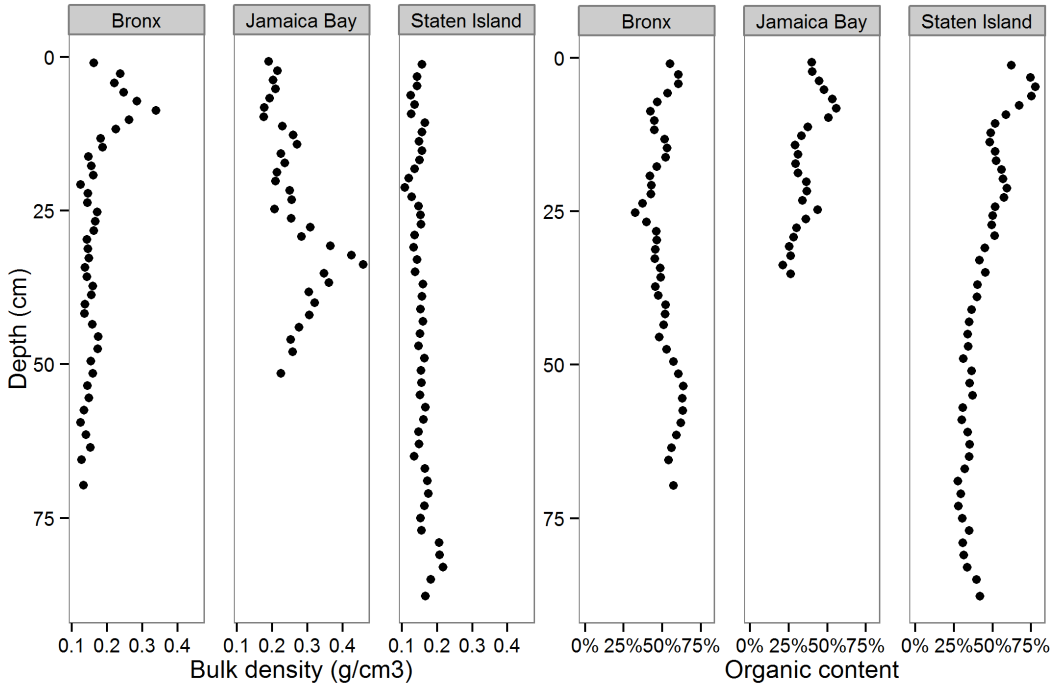



**Figure 2. Depth profiles of bulk density (left side) and organic matter concentration (right side).**

### Elemental analysis

All of the cores exhibited two distinct peaks in organic carbon ($C_{org}$) content in the top 25 cm (Fig. 4). Peaks ranged from 25% - 40% $C_{org}$ by mass. $C_{org}$ content declined to 15-20% at depth in the Staten Island and Jamaica Bay cores, but in the Bronx core the $C_{org}$ concentrations deep in the core were comparable to levels observed in the near-surface peaks.

Nitrogen content was slightly elevated in the top ~10 cm of all cores. Staten Island had the highest surface N concentration, nearly 3% N by mass. As with $C_{org}$, N declines with depth in the Staten Island and Jamaica Bay cores, but in the Bronx N content returned to levels seen at the marsh surface.

Hg showed subsurface peaks of 0.5, 11.4, and 2.3 ppm in the Bronx, Staten Island, and Jamaica Bay, respectively. Surface concentrations ranged from 0.1-2 ppm in the cores. Although background levels were not reached in the Jamaica Bay core, the other cores both declined to 0.02 ppm at depth.

Quality control data are presented in Table 1. Standard reference materials were consistently very close to expected values, and replicated samples showed close alignment. Replicates include samples duplicated within and among instrument runs, and reflect data quality on both scales.

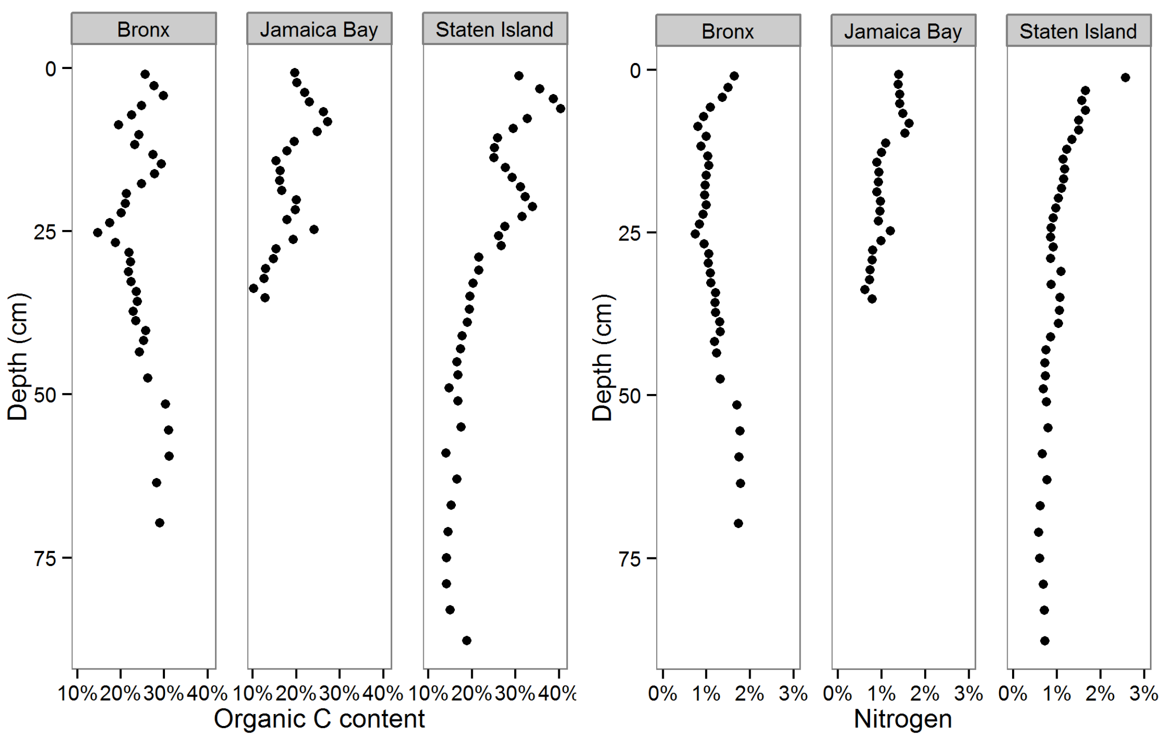



**Figure 3. Organic carbon (left three panels) and nitrogen (right panels) depth profiles.**

| Element | Standard reference material recovery | Coefficient of variation between replicates |
|---|---|---|
| C | 99 ± 0.3% (63) | 1 ± 0.1% (39) |
| N | 100 ± 0.7% (63) | 1 ± 0.1% (39) |
| Hg | 102 ± 2% (128) | 5 ± 1% (68) |

**Table 1. Quality control data for chemical analyses. Values reported are means ± 1SE (sample size in parentheses). Replicates include inter- and intra-run replicates.**

## $^{210}$Pb, $^{137}$Cs, and sediment accretion rates

The $^{210}Pb_{xs}$ inventories for the Jamaica Bay and Bronx marshes were comparable to inventories from elsewhere in the region (Cochran et al. 1998) and those expected from local atmospheric deposition atmospheric $^{210}$Pb deposition (530 ±100 mBq·cm$^{-2}$; Table 2; Turekian et al. 1983). Staten Island's $^{210}Pb_{xs}$ inventory was 41% lower than the atmospheric inventory.

In all cores, $^{210}Pb_{xs}$ declined to undetectable levels within 30 cm of the surface (Fig. 5). The Bronx core had a roughly log-linear decline whereas the other cores have significant departures from log-linearity (Fig. 5).

| Site | Marsh surface elevation (m NGVD29) | Marsh surface elevation (m rel. to mean high water) | $^{210}Pb_{xs}$ inventory ($mBq \cdot cm^{-2}$) | Percent of expected $^{210}Pb_{xs}$ inventory |
|---|---|---|---|---|
| Bronx | 1.598 | 0.106 | 439 | 82% |
| Staten Island | 1.287 | 0.007 | 317 | 59% |
| Jamaica Bay | 1.102 | -0.017 | 563 | 106% |

**Table 2. Selected characteristics of sediment cores and $^{210}Pb$ profiles.**

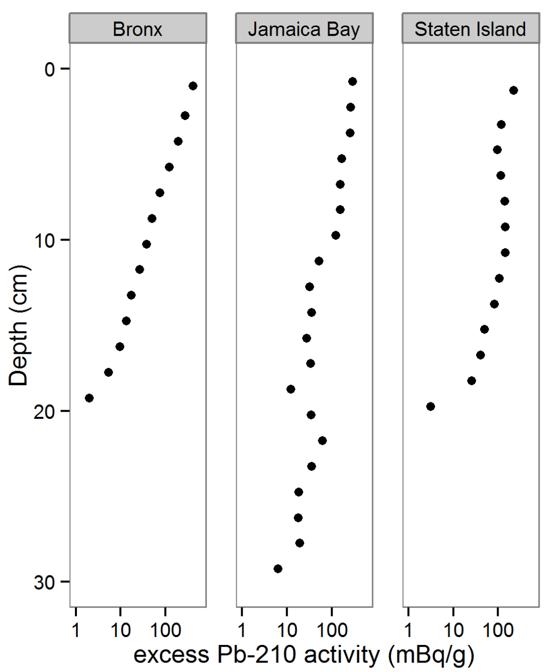



**Figure 4. Depth profiles of $^{210}Pb_{xs}$ activity. Note log scale x-axes.**

As an independent check on CRS accretion estimates, the 1963 $^{137}Cs$ peak was compared to the $^{210}Pb$-derived estimate for the 1963 layer. All cores showed excellent agreement between the two estimates. Peak Hg concentrations in the sediment profiles of the Bronx and Staten Island marshes also occur during the 1950s-1960s, within the expected date range (Varekamp et al. 2003). Based on the elevated Hg concentrations observed at the Staten Island and Jamaica Bay sites, local point sources of Hg are believed to be important at these sites and the chronology of Hg contamination may not reliably reflect the regional trend, despite the apparent alignment at Staten Island.

The CRS models show that accretion rates have varied spatially and temporally (Fig. 6). All three marshes accreted sediment at a rate of 0.5-1 $mm \cdot yr^{-1}$ from the late nineteenth century until approximately 1950, when Jamaica Bay began experiencing a sustained period of enhanced accretion. Accretion at Jamaica Bay peaked at 8.8 $mm \cdot yr^{-1}$ around 1950, and subsequently remained between 2.5-5 $mm \cdot yr^{-1}$. Sediment accretion at the Bronx marsh slowly increased to 1.7 $mm \cdot yr^{-1}$ while the Staten Island marsh experienced a period of enhanced accretion from 1985-present.

Bulk sediment mass accumulation rates (Fig. 6) reflect the same patterns observed in sediment accretion rates. This similarity appears due to the relatively small variations in bulk density compared with those in sediment accretion rates.

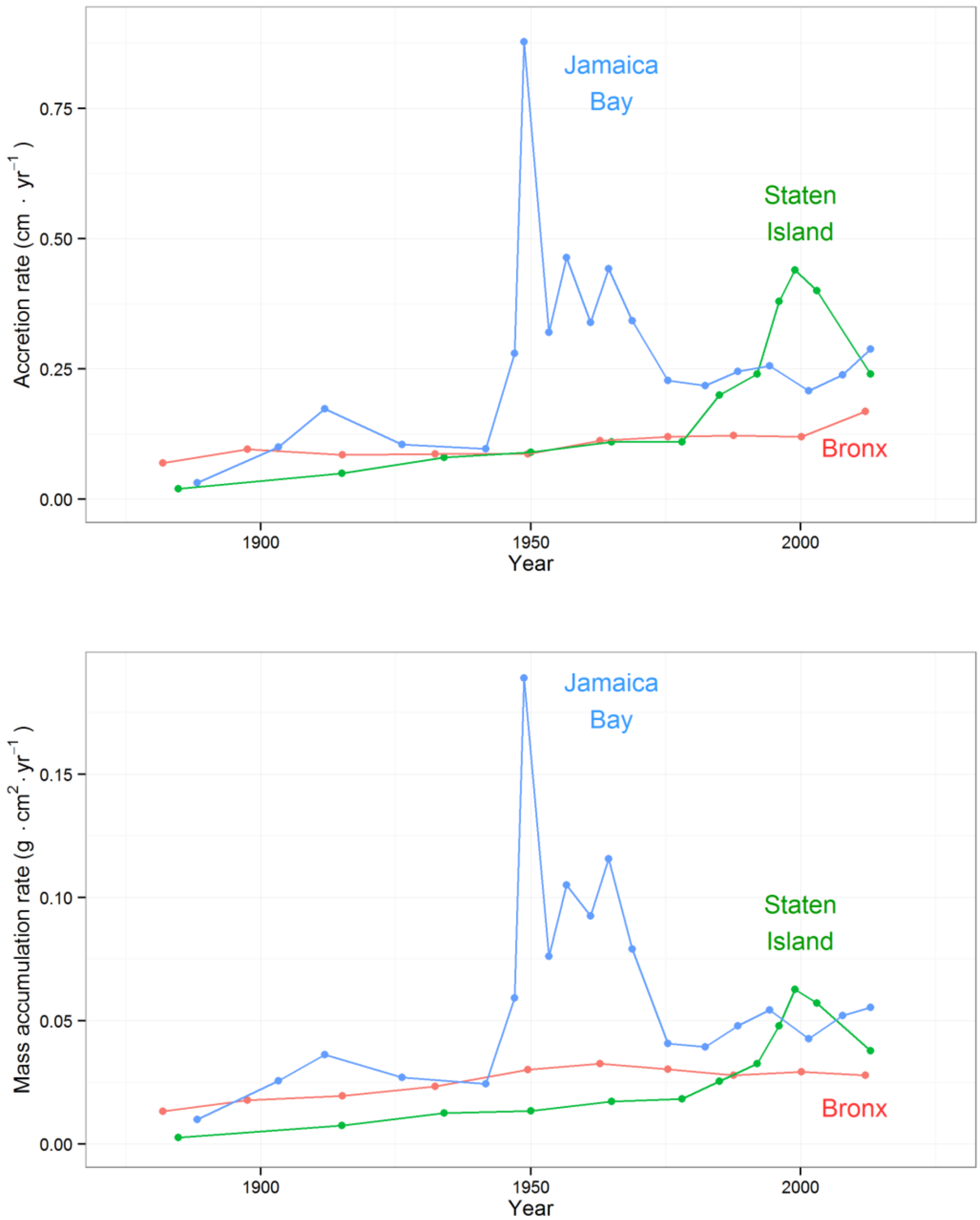
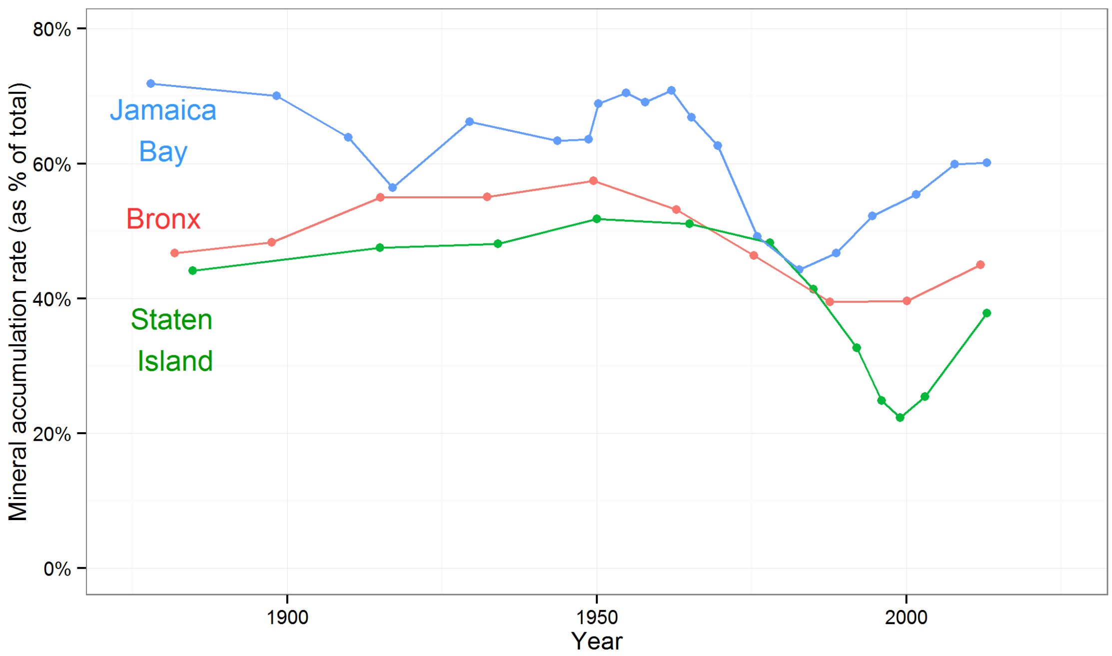



**Figure 5.** **Rates of vertical accretion (top) and bulk sediment mass accumulation (bottom), over time.**

Mineral accumulation has varied over time in its contribution to total accumulation (Fig. 7). None of the marshes have experienced a simple linear trend with time; each has oscillated between mineral and organic dominance. In all cores, the past

15-25 years have been a period of increasing mineral dominance, preceded by a 30-40 year period where mineral accumulation declined relative to organic material.



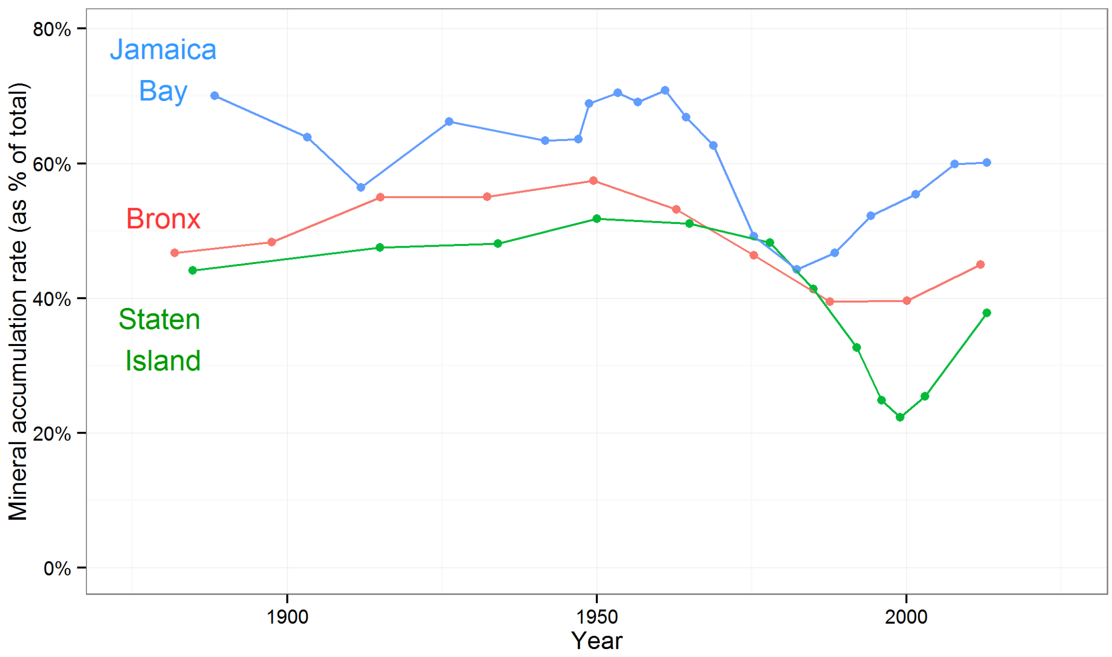




**Figure 6. Mineral accumulation rates as a proportion of total accumulation rates.**

**Hydrology and marsh accretion balance**

Water level loggers captured 89 tidal cycles in Jamaica Bay, 120 in Staten Island, and 256 in the Bronx. These water level data were used to generate estimates of flooding duration and flooding frequency for each marsh, and to examine how those parameters vary with elevation. Water level data are used to estimate flooding of the marsh platform; the area of the marsh where sediment cores were taken and elevations measured.

The percent of time that a given elevation spends submerged is referred to as its flooding duration. This metric was calculated from the empirical cumulative distribution function (ECDF) for the full record of 6-minute water level measurements (Fig. 8). Using these datasets, the three marshes surveyed in the Bronx, Staten Island, and Jamaica Bay are submerged 8%, 11%, and 17% of the time, respectively.

Flooding frequency, the percent of high tides that flood a given elevation, was generated by isolating high tide heights from the period of water level logger deployment. Local high tide heights were correlated with data from nearby harmonic NOAA stations; the Battery, NY was used for Staten Island and Jamaica Bay, and the Bridgeport, CT NOAA station was used for the Bronx. The linear models relating local high tides to those at nearby NOAA stations were all highly significant ($p < 10^{-16}$) and had strong explanatory power ($R^2 > 0.94$). The resultant relationships were used to model local high tides over the entirety of 2012 (the most recent full calendar year of tidal data).

These year-long high tide datasets were used to calculate mean high water (MHW) and flooding frequency as a function of elevation (Fig. 8). MHW was simply the average of all high tides in the dataset. The ECDF of each high tide dataset characterized the relationship between elevation and flooding frequency. These data show that in 2012, the three marshes in the Bronx, Staten Island, and Jamaica Bay were flooded by 32%, 50%, and 53% of high tides, respectively.

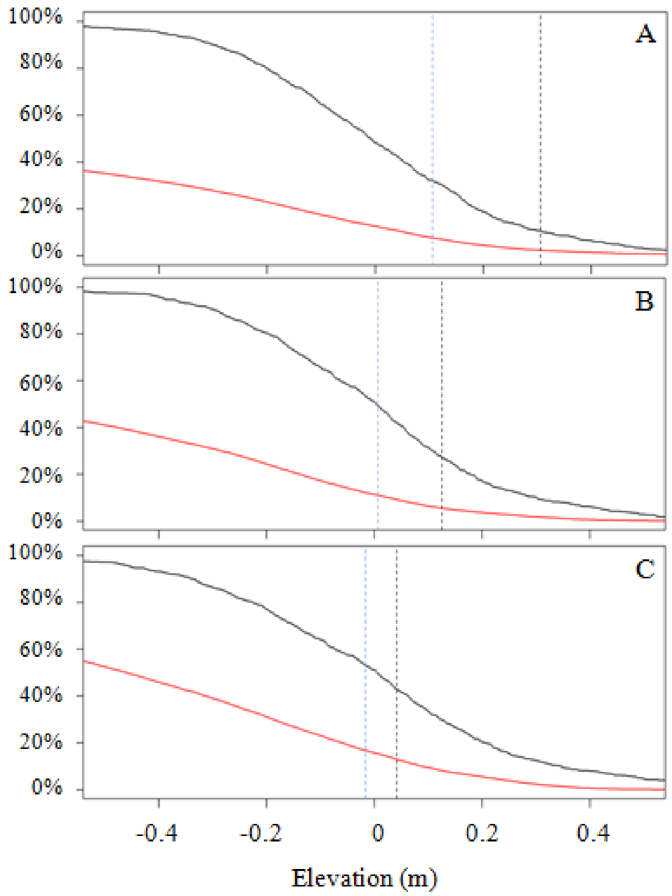



**Figure 7.** **Relationship between vertical elevation and flooding frequency (black curves) and duration (red curves). Vertical elevations are relative to site-specific MHW in 2012. Black vertical lines show relative marsh surface elevations in 1900; blue vertical lines show relative elevations in 2012. Panel A: Bronx; panel B: Staten Island; panel C: Jamaica Bay.**

The *relative marsh surface elevation* is defined as the difference between the elevation of the marsh surface and local mean high water (Table 2). The marsh platform in the Bronx had the highest relative elevation, sitting 11 cm above current MHW (Fig. 8). At Staten Island and Jamaica Bay, marshes were substantially lower, just 0.7 and -1.7 cm relative to current MHW.

Annual mean sea level (MSL) data from NOAA's tide station at the Battery, NYC (1856-present) were used to characterize the rate of relative sea level rise. These trends include both eustatic sea level rise and region-wide subsidence following deglaciation. The MSL trend over the entire period of record (2.8 $mm \cdot yr^{-1}$) was used to estimate the elevation of MHW in the past. MHW data were not directly used to characterize rates of relative sea level rise because MHW data began being recorded in 1920 and do not cover the full period of $^{210}Pb$ data. During periods where both MSL and MHW were recorded, the two datums increase at identical rates.

The elevation of MHW at some time in the past, $MHW_{t2}$, was calculated as:

$$MHW_{t2} = MHW_{t1} - \left(rslr \cdot (t_1 - t_2)\right) \qquad (4)$$

Where $MHW_{t1}$ is the mean high water elevation (m) at time point 1; *rslr* is the rate of relative sea level rise (assumed constant at 0.0028 $m \cdot yr^{-1}$); and $t_1$ and $t_2$ are time points of interest (units of years). Historic relative marsh surface elevations were calculated by comparing the vertical position of MHW (calculated from equation 4) with the vertical elevation of the dated core section corresponding to the time point of interest.

Although Jamaica Bay was the only marsh found to presently be below MHW, all sites have experienced declines in relative marsh surface elevation over time (Fig. 9). In Jamaica Bay, the period of rapid accretion starting around 1950 (Fig. 6) occurred shortly after the marsh surface fell below MHW, and allowed the marsh to temporarily recover to an elevation just above MHW. Similarly, accretion at Staten Island began accelerating as the elevation of the marsh platform approached MHW in the 1980s. In the Bronx, the marsh surface elevation has not yet approached MHW, and accretion rates have remained low.

The declines in relative marsh surface elevations have led to corresponding increases in flooding frequency and duration at all sites. Between 1900 and 2012, study sites in the Bronx and Staten Island experienced an approximate doubling of the frequency and duration of flooding. The Jamaica Bay site, already a relatively wet system in 1900, became ~25% wetter by 2012 (Table 3; Fig. 8).

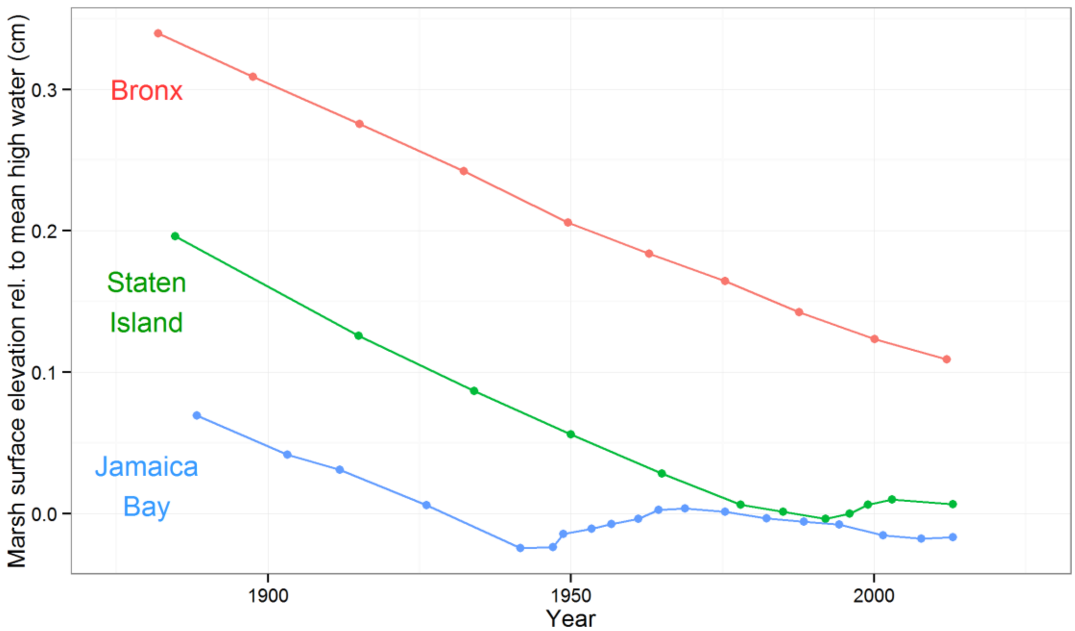



**Figure 8. Relative elevation of marsh surface, 1880-present.**

| Site | Flooding frequency 1900 | 2012 | Flooding duration 1900 | 2012 | Absolute change Frequency | Duration |
|---|---|---|---|---|---|---|
| Bronx | 11% | 32% | 3% | 8% | 21% | 5% |
| Staten Island | 27% | 50% | 5% | 11% | 23% | 6% |
| Jamaica Bay | 43% | 53% | 13% | 17% | 10% | 4% |

**Table 3. Changes in hydroperiod between 1900 and 2012.**

## DISCUSSION

Research question (1) asks whether marshes in NYC are keeping up with sea level rise. At all sites, the relative marsh surface elevations have declined over the past century, indicative of accretion deficits. Integrating over the past century, these marshes have not risen at the same rate as sea levels. Losses in relative elevation have resulted in dramatic increases in the frequency and duration of tidal flooding.

But while the marshes have failed to maintain their initial relative elevations, there are some positive signs. Marshes in Staten Island and Jamaica Bay lost enough relative elevation to fall below MHW, but they subsequently began accreting at a rate that allowed them to remain at the same level as MHW. The marshes have not recovered or begun gaining ground against rising sea levels, but they may be in equilibrium. One caveat to this interpretation is related to the sea level rise estimates used. The 2.8 $mm \cdot yr^{-1}$ average derived from the 150 year tide record at the Battery may mask slightly higher rates of sea level rise in recent years, although shorter time series have much higher uncertainties. If sea level rise has recently accelerated above 2.8 $mm \cdot yr^{-1}$, these marshes would have continued on a trajectory of accretion deficits and increased flooding.

The data presented in this study are generally consistent with those from other marshes in the region. Cochran et al. (1998) found that high marsh accretion rates in six western Long Island Sound marshes approximated or were significantly lower than the rate of sea level rise, and also observed recent accelerations in marsh accretion. A Narragansett Bay high marsh also had an accretion rate that is slightly lower than the rate of sea level rise used in this study (Bricker-Urso et al. 1989). In Delaware, local rates of sea level rise also approximate or exceed marsh accretion rates (Church et al. 1981; Ward et al. 1998).

Some previous research has suggested that, generally, the northeastern US is an area where salt marsh accretion is safely in excess of rates of sea level rise (Stevenson et al. 1985; Reed 1990). This is inconsistent with the data reported in the present study and noted in the preceding paragraph. These incongruous results are likely due to different foci; the present study is focused on accretion of the marsh platform of non-riverine marshes. Low marsh accretion rates tend to be higher than on the marsh platform, although in the northeastern US the low marsh zones tend to be marginal and very limited in spatial extent (i.e., not representative of the system as a whole). Similarly, marshes along river margins tend to have higher accretion rates than marshes exposed to the more diffuse sediment supply of the coastal zone (Ward et al. 1998).

For marshes that are not keeping up with sea level rise, two extreme outcomes are possible. One possibility is that the process forms a negative feedback loop and self-regulates (Reed 1990; FitzGerald et al. 2008); greater flooding leads to increased sediment deposition and the marsh surface accretes rapidly enough to maintain or increase its relative elevation, resulting in a stable system. A second possibility is that marshes are unable to capture enough sediment to sufficiently increase their accretion rate. In this case, the high marsh community would transition to a *Spartina alterniflora* monoculture, which may continue to submerge until conditions become too stressful to support vegetation. These trajectories are complex, but the supply of tidal sediment to a marsh is an important determinant of a system's resilience to sea level rise (Kirwan et al. 2010).

Research question (2) asked how deposition of mineral material on the marsh surface has changed since 1900. Trends in mineral deposition can best be described as variable and bi-directional. The proportion of total accumulation attributable to mineral sediment is lower than it was in the middle of the twentieth century, but is also substantially higher than it was twenty years ago.

To an extent, especially at the lower, wetter sites (Jamaica Bay and Staten Island) the variations shown in Fig. 7 may be associated with greater tidal flooding. These variations may also reflect broader changes in sediment dynamics and nearby land uses. Similarities between cores in the trends and the timing of inflection points (Fig. 7) suggest that landscape-scale factors are important drivers of mineral sediment availability. Determining specific regional-scale drivers of changes in sediment availability would be a useful extension of this work, and would raise the possibility of managing the watershed and harbor in ways that might help preserve coastal ecosystems.

## CONCLUSION

Sediment cores from three marshes in NYC were used to create a detailed record of marsh response to sea level rise and changes in rates of mineral sediment deposition. During the past century these marshes have all lost elevation relative to sea level. This has altered flooding regimes at the sites, and changes in hydroperiod were quantified.

Marshes that fell below MHW began accreting rapidly and were able to maintain their relative elevations as a result. This demonstrated ability to respond to sea level rise is encouraging, but is not decisive proof that these systems are entirely resilient. Threshold rates of sea level rise may exist, and more work on sediment supply and ecosystem-scale vegetation and geomorphological changes will help discern the true resilience of these systems in the face of sea level rise.

The magnitude of sea level rise projections suggest that sea level rise is an existential threat to salt marshes. As projections of accelerated sea level rise become increasingly confident, coastal resource managers will benefit from an understanding of how marshes respond and what interventions might increase their viability. The present work contributes to this understanding and suggests that the fate of NYC salt marshes is not a foregone conclusion.

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