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Sediment starvation destroys New York City marshes' resistance to sea level rise

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New York City (NYC) is representative of many vulnerable coastal urban populations, infrastructures, and economies threatened by global sea level rise. The steady loss of marshes in NYC's Jamaica Bay is typical of many urban estuaries worldwide. Essential to the restoration and preservation of these key wetlands is an understanding of their sedimentation. Here we present a reconstruction of the history of mineral and organic sediment fluxes in Jamaica Bay marshes over three centuries, using a combination of density measurements and a detailed accretion model. Accretion rate is calculated using historical land use and pollution markers, through a wide variety of sediment core analyses including geochemical, isotopic, and paleobotanical analyses. We find that, since 1800 CE, urban development dramatically reduced the input of marsh-stabilizing mineral sediment. However, as mineral flux decreased, organic matter flux increased. While this organic accumulation increase allowed vertical accumulation to outpace sea level, reduced mineral content causes structural weakness and edge failure. Marsh integrity now requires mineral sediment addition to both marshes and subsurface channels and borrow pits, a solution applicable to drowning estuaries worldwide. Integration of marsh mineral/organic accretion history with modeling provides parameters for marsh preservation at specific locales with sea level rise.

Jamaica Bay | marshes | sea level rise | sedimentation | mineral flux

Salt marshes are valuable for coastal protection, nursery habitat for fisheries, water filtration, biodiversity, and carbon sequestration, but loss of these critical wetlands and the services they provide (1, 2) is increasing worldwide. Ongoing losses such as those in the Mississippi River Delta are catastrophic, as Louisiana has lost over 2,000 ha of land since the 1930s (3). As the community realizes the long-term significance of these undervalued drowning ecosystems, recent studies have revised the 1997 value of coastal wetland ecosystem services by tenfold (4). Exposed to accelerated sea level rise (5, 6), pollution, and upriver dams, urban estuary marshes are in urgent need of investigation for the specific causes of their decline. Robust solutions to ensure their functioning survival require study of their sediment history. Specifically, reconstructing the sediment accretion history through time will allow us to quantify accretion rates and composition needed to keep pace with sea level rise (7).

We target New York City (NYC)'s Jamaica Bay marshes, remnant wetlands of this small and highly urban estuary that have been disappearing at an accelerating rate in recent decades (5, 6, 8) (Fig. 1). Situated along the Atlantic flyway, the wetlands are a renowned haven for 325 species of migratory and resident birds and are also valued for the horseshoe crabs, diamondback terrapins, and over 90 fish species (2). One of NYC's best defenses against coastal storms, the marsh edge erosion, both on islands and in island streams, is well documented with historical maps (6) (Fig. 1). Proposed reasons for urban marsh loss include the characteristic dredging of shipping channels (2, 8), rising sea level (5, 6), increased tidal range (9), and increased nitrogen pollution leading to declining root density (10). To learn how to restore marshes effectively, we focus on the complicated long-term urban history of the sediment accretion, examining the differing roles of inorganic and organic sediment fluxes, and their links to local and regional history. We then use this information to provide a roadmap for assessing past accretion rates for best restoration and preservation of these valued resources.

Jamaica Bay is an estuarine embayment. Rockaway Inlet, which is progressively shifting westward (11) (Fig. 1), provides Atlantic Ocean connection. Dense urban development, John F. Kennedy International Airport, and three large landfills surround the bay. Some fresh water enters the bay from four topographic watersheds, tidal currents bring additional Hudson River fresh water, and less than 10% is supplied by groundwater (12). However, the freshwater input to the bay is almost entirely anthropogenic, primarily wastewater effluent (13). Four large wastewater treatment plants (WWTPs) release fresh water to the bay, with the sewer sheds roughly mirroring the topographic watershed boundaries (14). Two smaller waste treatment plants also contribute effluent (15). The amount of fresh water coming into the bay today is 14.4×10^{14} L/y, including raw sewage overflow during heavy rains that is estimated to be 17.8×10^{13} L/y (16).

Historically, at least 18 tributaries entered the bay (Fig. 1), while only eight highly channelized streams remain (14). Recent

Significance

Worldwide, coastal marshes are facing extreme impacts, including urban encroachment, pollution, upriver dams, and sea level rise. Our research provides a method of sediment history reconstruction to understand the role of plant/animal (organic) and mineral (inorganic) matter in their growth and maintenance, including the effects of humans on the sediment burial. We find that, due to urbanization, these marshes have experienced a remarkable loss of mineral sediment and increase in organic sediment, significantly enhancing the risk of marsh loss with sea level rise by making them structurally weak. Future resilience depends upon active enrichment of mineral sediment in both borrow pits and marshes, ensuring the marshes outpace sea level rise, provide wildlife habitat, and retain polluted sediments beneath them.

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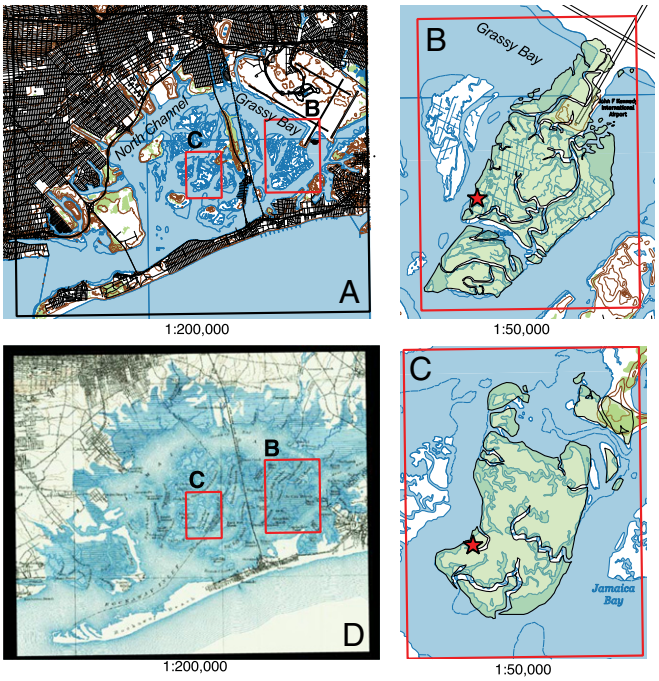

Fig. 1. Maps of the Jamaica Bay study area. (*A*) Jamaica Bay and environs at 1:200,000 scale, excerpted from four 7.5 min US Geological Survey (USGS) quadrangle maps published in 2016 ("Brooklyn, NY," "Jamaica, NY," "Coney Island, NY," and "Far Rockaway, NY"). Hydrographic units are in blue, topographic lines are in brown, natural areas are in green, and built structures are in black. (*B*) Jo Co and (*C*) Yellow Bar at 1:50,000 scale with 1897 marsh (green) overlain on the 2016 outline (white). Stars in *B* and *C* indicate core locations. (*D*) Jamaica Bay and environs at 1:200,000 scale, excerpted from the USGS "Brooklyn" 15-min quadrangle map, published in 1897. Blue hatching indicates salt marshes.

study of ^{234}Th and ^{210}Pb radionuclides in the water and bottom sediments indicates that, today, marine-derived sediment is an important component of the mineral sediment in waters of the bay (17).

It has been clear from maps that, over centuries (18) (e.g., Fig. 1), not only have the marshes that rim Jamaica Bay been completely destroyed due to urbanization, but the remaining island marshes are greatly diminished and fragmented. A study by Hartig et al. (6) proposed that sea level rise was contributing to this problem, but the sediment itself was not explored. Decreased root density (10) in the top 40 cm of cores from Black Bank and Big Egg, also in Jamaica Bay, supports the hypothesis of Deegan et al. (19) that nutrient increases may contribute to the marsh fragmentation.

We selected two sediment cores to investigate: a high marsh, Jo Co Marsh, in the eastern part of Jamaica Bay, vegetated with *Spartina patens* and *Distichlis spicata*, and a low marsh, Yellow Bar Hassock, in the west, primarily vegetated with *Spartina alterniflora* (Fig. 1). We use a multidisciplinary approach (*Materials and Methods*) to reconstruct the primary sedimentary history at Jo Co and use the sediments at Yellow Bar to ensure that our results are replicable across the bay. We pose three questions:

i) What is the accretion rate of Jo Co over the last several hundred years? We hypothesize that hardening of the shoreline, which cuts off sediment supply, has caused marsh accretion rates to decrease below that of sea level rise.

ii) What is the relative contribution of inorganic sediment flux (sand, silt, clay) to total accretion rate, and how does it compare with the organic matter burial? We hypothesize a greater decline in mineral matter due to streams that were channelized.

iii) Can we use pollution markers as age control points when building a history of accumulation, as radiocarbon calibration is too uncertain over this time interval? We hypothesize a clear anthropogenic signal of heavy metal concentrations as well as nitrogen enrichment, which we can tie to anthropogenic activities with known ages.

Historical Linkages

We produce a robust, detailed record of marsh accretion rate. Organic and inorganic sediment fluxes are calculated using loss on ignition (LOI), and an age model based on nine age–depth tie points over the past 350 y (Figs. 2 and 3 and Table 1). These tie points include markers of land use change, pollution by heavy metals and nitrogen, the effects of federal and local environmental legislation, and marsh restoration. Table 1 lists each tie point chronologically. The corresponding data from which the tie points are determined are shown in Fig. 2. Both ragweed (*Ambrosia*) pollen and charcoal are reliable indicators of landscape disturbance in the Hudson Valley (20, 21)—first by European settlers, around 1650 CE, and later by late 18th and early 19th centuries CE industrialization (8). In the Jo Co Marsh sediments, *Ambrosia* pollen first increases in concentration at 106 ± 2 cm core depth (Fig. 2, *Upper*). We assign this level an age of 1650 CE ± 3 y, the time at which Europeans settled and clear-cut forests for wood and agriculture, opening the landscape for disturbance taxa. Around this time, charcoal also began to increase in concentration. By 1698 CE, the Flatlands town on the western side of the bay had 300 residents (8). Later, in 1818 CE, a strong depression struck the young United States, slowing the economy. The downturn is possibly evident in the charcoal record as a decline in the charcoal concentration occurring at ~66 ± 2 cm core depth concurrent with a large decline in tree pollen. While we are not certain enough to use this level as an age–depth tie point, it does serve to support the surrounding tie points. Charcoal again rises in concentration with the resumption of the industrialization of New York in the years following the Depression, and remains high until about 24 ± 2 cm core depth, coincident with the passage of the Clean Air Act in 1963. Therefore, we assign the age 1963 CE to that depth. Using only disturbance indicators to assess sedimentation rate, we find that Jo Co Marsh accreted at an average of 2.6 mm/y over the past 350 y—a reasonable rate for coastal marshes in this region which range from 1 mm/y to 5 mm/y but cluster between 2 mm/y and 3 mm/y (22).

We hypothesized that inorganic sedimentation would decline more than organic. To determine whether mineral matter was terrestrial or marine, we compare percent inorganic sediment by LOI with parts per million concentration of Titanium (Ti), an indicator of terrestrial sediment (Fig. 2). Because LOI is in good agreement with [Ti], we conclude that most of the Jo Co and Yellow Bar mineral sediment is terrestrial in origin. Input of terrestrial sediment is strongly influenced by land use change, particularly that of European settlers and their descendants (20). Soon after the arrival of Europeans, as indicated by the *Ambrosia* rise in Jo Co at 106 cm, input of terrestrial sediment increased, until about 1819 CE (70 cm depth). From this time on, through two centuries and up until the restoration efforts of the last decade, terrestrial sediment input decreased, due to numerous dredging, damming, and hardening activities. Addition of inorganic sediment at Yellow Bar began in 2012 CE. This addition of sediment to the system is evident in the record of [Ti] at Jo Co as well, and begins at 4 cm in the ITrax data. We assign this level an age of 2011 CE ± 1 y, concurrent with restoration activities at Yellow Bar.

Geochemical signals provide additional tie points (Fig. 2 and Table 1), and the concentration of nitrogen in sediments,

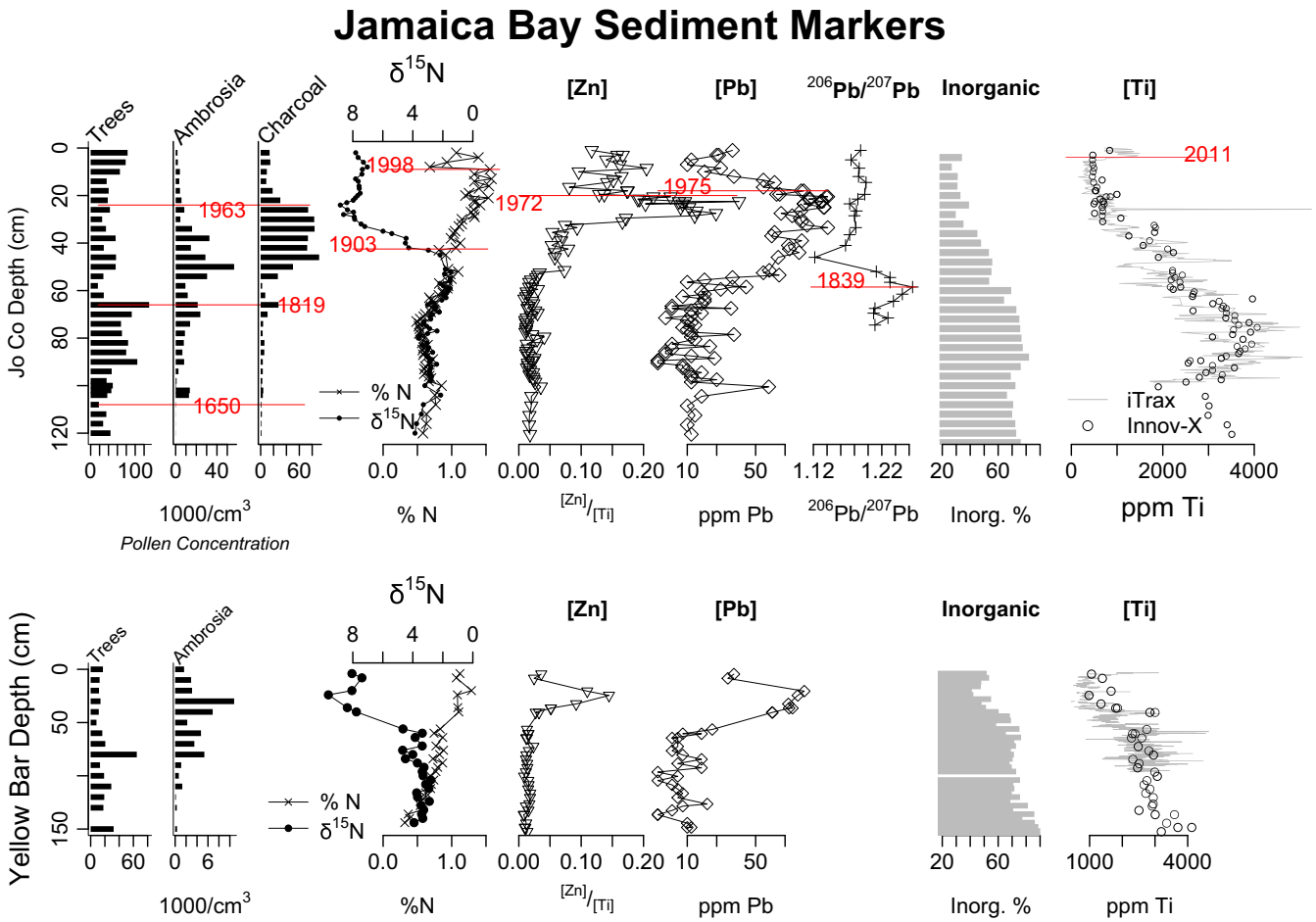

Fig. 2. Downcore results from (Upper) Jo Co and (*Lower*) Yellow Bar. (*Upper*, *Left* to *Right*) Arboreal pollen, *Ambrosia* pollen, and charcoal concentration (1,000 grains per cubic centimeter); nitrogen content (percent by mass of dry sediment) and bulk nitrogen isotopes (δ^{15}N ‰ vs. air); zinc/titanium ratio (parts per million/parts per million); lead isotope ratio (^{206}Pb/^{207}Pb); percent inorganic content by mass; and the concentration of titanium (counts per second) measured by iTrax (line) and Innov-X (parts per million, points). (*Lower*, *Left* to *Right*) Arboreal and *Ambrosia* pollen concentration (1,000 grains per cubic centimeter); nitrogen content (percent by mass of dry sediment) and bulk nitrogen isotopes (δ^{15}N ‰ vs. air); zinc/titanium ratio (parts per million/parts per million); percent inorganic content by mass; and the concentration of titanium and potassium measured by iTrax and Innov-X (as above).

combined with its stable isotope ratio, is a strong indicator of wastewater input to Jamaica Bay. Below 42.5 cm core depth at Jo Co Marsh, sedimentary %N and δ^{15}N are inversely correlated. As denitrification in anoxic marsh sediment increases, nitrogen is removed from sediment, and the remaining sedimentary pool of nitrogen is enriched in the heavy isotope. Above 42.5 cm depth, however, this relationship changes dramatically. Both %N and δ^{15}N increase to values not observed previously. We interpret this change to be related to the concentrated wastewater effluent input into Jamaica Bay, beginning in 1903 CE with the opening of the Jamaica WWTP. Therefore, we assign the age 1903 CE ± 1 y to the depth 42.5 ± 1 cm at Jo Co. Toward the end of the 20th century, NYC began tertiary treatment of wastewater. This is evident in the sedimentary nitrogen record as a decrease in the %N without a change in δ^{15}N. NYC initiated tertiary treatment in 1998 CE and improved nitrogen removal techniques again in 2010 CE. Both of these improvements to the quality of WWTP effluent result in reduction in percent sedimentary nitrogen. We assign the depths 9 ± 1 cm and 4 ± 1 cm the ages 1998 CE ± 1 y and 2010 CE ± 1 y, respectively.

Wastewater in NYC is marked by heavy metals, and zinc (Zn) in particular. Over the course of the industrial age, the concentration of Zn in Jo Co Marsh sediments relative to the concentration of Ti increases dramatically. However, at a depth of 20 cm., Zn declines precipitously. We attribute this decline to the passage of the US Clean Water Act and wastewater treatment reforms that began in 1972 CE. Therefore, we assign an age of 1972 CE ± 1 y to the depth 20 ± 1 cm, the depth at which Zn concentration declines relative to Ti in Jo Co sediments.

Lead (Pb) is a heavy metal contaminant that is primarily deposited atmospherically. We use the ^{206}Pb/^{207}Pb isotope ratio to determine the provenance of atmospherically deposited lead in Jo Co Marsh sediments. The well-dated peak in ^{206}Pb/^{207}Pb ratio of sedimentary lead from Midwest lead smelting is recorded in anoxic sediments of a Rhode Island estuary that preserved annual laminations (23). The commonly accepted age for this peak is 1839 CE ± 1 y (23). We observe this peak in our sediments from Jo Co Marsh at 58.5 ± 2 cm. The concentration of Pb in Jo Co remains high throughout the industrial period, but rapidly declines at 18.5 cm. We attribute this decline to the phase-out of leaded gasoline and assign the depth 18.5 ± 1 cm an age of 1975 CE ± 1 y.

We have replicated most of our measurements (excluding charcoal and Pb isotopes) and find that depth profiles for all proxy data are similar at both Yellow Bar and Jo Co. Some small, elevation-related differences do exist. Jo Co, a high marsh, has a surface mineral content of about 30% compared with 40 to 50% in Yellow Bar, typical of lower-elevation marshes. Our resolution of measurements is not high enough at Yellow Bar to replicate

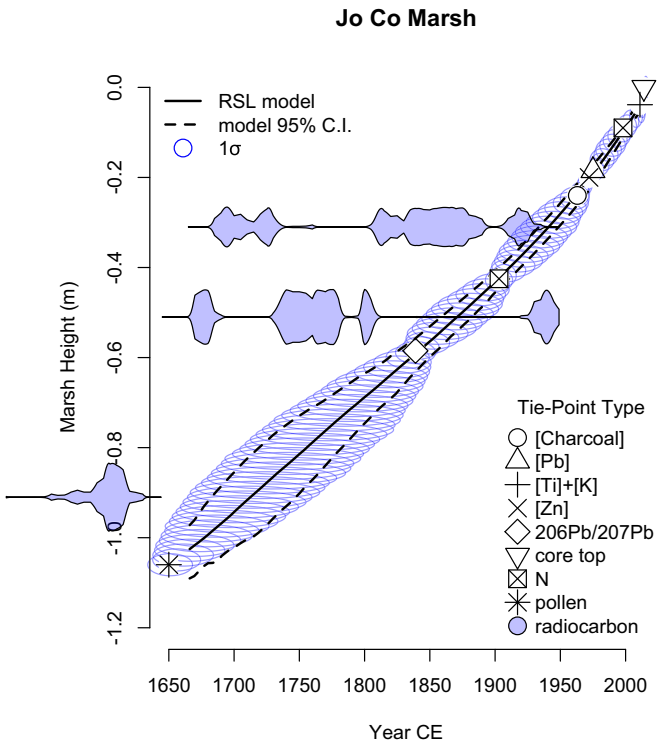

Fig. 3. Results of accretion rate modeling by the Bchronology package. Marsh height is given in meters below surface. Symbols indicate the tie points listed in Table 1. Blue ellipses indicate the width of the 1σ uncertainty around estimated height and age for each centimeter of marsh sediment. The solid line is the median estimated height/age relationship, and dashed lines indicate the 95% confidence interval around this line. Blue areas indicate the probability density of calibrated radiocarbon age for the three radiocarbon measurements (not included in the height/age model). RSL, relative sea level.

the age–depth relationships precisely, but we nonetheless conclude that the Jo Co measurements are representative of a basin-wide signal and not due to local effects, as illustrated by profiles at Yellow Bar.

In addition to our geochemical measurements tied to historical events, our accretion rate analysis includes accelerator mass spectrometry (AMS) radiocarbon measurements made on identified macrofossils (Fig. 3 and *SI Appendix*, Table S1). However, because the calibration curve for assigning calendar ages to radiocarbon dates is highly variable over the past few centuries, these AMS dates, while in agreement with the ages we determined from historical markers, add little precision to our accumulation rate estimates.

To test our hypothesis about marsh accretion, we use the nine age–depth tie points described above and displayed in Table 1, to construct an age–depth model (Fig. 3). Following the methods of Kemp (24), we used the Bayesian age modeling package "Bchron" for the R statistical computing environment (25–27). By this method, all of the age determinations were used to make a comprehensive age–depth model using a Markov Chain Monte Carlo simulation, with nonradiocarbon ages assumed to have a uniform probability distribution. Accretion rate of the marsh is found by calculating the first derivative of the resulting age–depth model (24, 26). By this method, we find that the accretion rate of Jo Co marsh was ~2.5 mm/y for the first 200 y of this record—from 1650 CE to 1850 CE. From 1850 CE to the present day, marsh accretion rate accelerates steadily to 5 mm/y (Fig. 4). This acceleration in marsh accretion of 0.017 mm/y^2 is approximately equal to that observed in marshes in Connecticut, New Jersey, and Pelham, NY (24, 28, 29), but exceeds sea level rise acceleration measured in Long Island Sound [0.006 mm/y (2, 24)]. Sea level rise at NYC's Battery tide gauge was 2.53 ± 0.51 during the 1890s CE and 3.38 ± 0.52 mm/y during the 1990s CE, an average change of 0.0085 mm/y^2.

Our original hypothesis was that the accretion rate would decline concurrently with shoreline hardening, but we find instead, surprisingly, that marsh accretion continues to exceed sea level rise, even as mineral sediment flux declines toward the present (Fig. 4). Using bulk density, LOI, and our age–depth model (Fig. 3), we calculated the flux of organic and inorganic matter at Jo Co. We find that overall accretion rate has accelerated since industrialization. While the flux of mineral sediment decreased, organic matter flux increased to compensate (Fig. 4). Either marsh plants have increased their growth rate or decomposition has slowed, allowing the marsh surface to keep pace with rising sea level. Our second hypothesis concerning inorganic decline toward the present is confirmed, and we focus on the historic reasons for this decline and the dangers that further erosion will pose for pollution with sea level rise.

From about 1650 CE until the late 1700s CE, Jo Co received increased mineral sediment as settlement of the region, including land disturbance for agriculture, resulted in destabilization of the upland landscape (Fig. 4). Historically, the mean depth of the bay was about 1 m, but today it is 5 m (30). Extended flooding, which was not present a century ago, now takes place over the tidal cycle (9, 14), and mean high water throughout the bay is higher today relative to a century ago by 0.4 m to 0.5 m (14). Early regional 1800s CE development and dredging resulted in a sustained decline in inorganic sediment, and dredging for oysters with power vessels accelerated the decline (8). Enormous loss of the rimming marshes through real estate development was coupled with the extensive dredging for shipping channels and infrastructure. These deep channels and borrow pits caused sediment to deposit in the low dredged basins, e.g., Grassy Bay and North Channel (Fig. 1), rather than on marshes. As urban development hardened surfaces, the original 18 streams entering the bay were channelized, diverting flow to sewage treatment plants, or were simply filled in, starving the water of suspended

Table 1. Tie points used for accretion rate estimation

Depth, cm	Year CE	Event	Evidence
0 ± 1	2014 ± 1	Core extracted	Core top
5.2 ± 1	2011 ± 0.5	Yellow Bar restored	[Ti] (ITrax) local minimum
9 ± 2	1998 ± 1	Tertiary treatment initiated	% N local maximum
18.5 ± 2	1975 ± 1	Leaded fuel phased out	[Pb] (Innov-X) local maximum
20 ± 1	1972 ± 2	Clean Water Act passed	[Zn]/[Ti] (Innov-X) local maximum
24 ± 2	1963 ± 2	Clean Air Act passed	[Charcoal] local maximum
42.5 ± 1	1903 ± 1	Jamaica WWTP opens	δ^{15}N vs. %N relationship change
58.5 ± 2	1839 ± 1	Peak in Midwest coal burning	^{206}Pb/^{207}Pb peak
106 ± 2	1650 ± 3	*Ambrosia* rise	[Pollen] local minimum

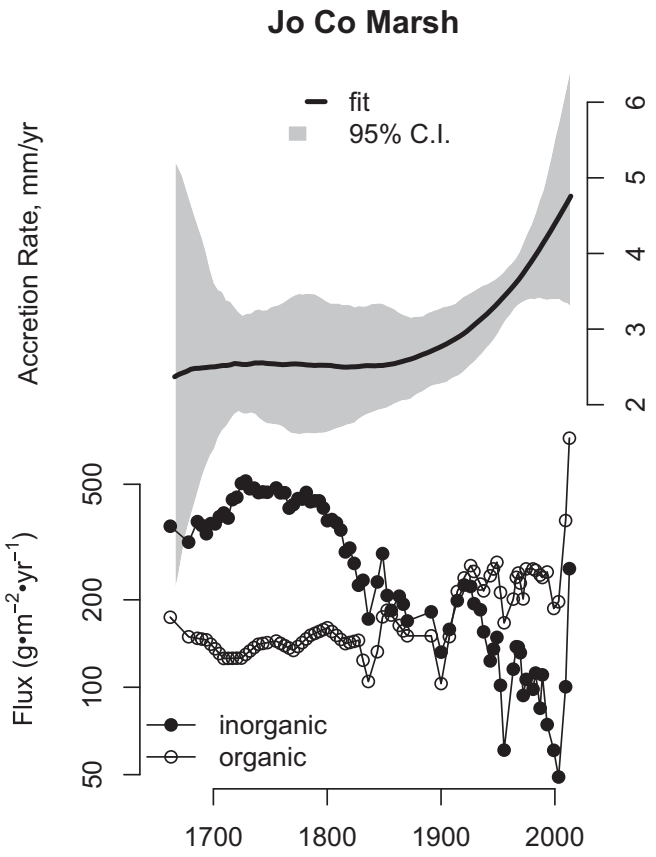

Fig. 4. (*Upper*) The estimated accretion rate for Jo Co. Heavy line is the median estimate, and the gray polygon encloses the 95% confidence interval around this estimate. (*Lower*) The flux of inorganic (filled symbols) and organic (open symbols) matter to Jo Co marsh sediment in grams per square meter per year. Note that the *y* axis is logarithmic.

sediment load and limiting the deposition of upland mineral sediment into the marshes.

This sediment decline has been noted as a major problem throughout coastal regions of the United States (31). The most vulnerable regions include the Mid-Atlantic States such as New York, where relative sea level rise is greater than many other regions, due to both reductions in fluvial transport (31) and reduced Atlantic overturning which then reduces sea level pressure, allowing sea level rise (32). Westward movement of Rockaway Spit has possibly further restricted deposition of marine-derived sediment to the marshes.

Degradation of marsh edges poses a secondary risk to estuaries by the release and resuspension of contaminated sediments. Increases in sedimentary Pb and Zn, as well as the peak in $^{206}Pb/^{207}Pb$, which has been linked to lead ore deposits from the Midwest (23), are evident at Jo Co and Yellow Bar. At the turn of the 20th century, local deliveries of ore to the National Lead Company added to the pollution. In 1906 CE, the bay was reported to have received 4,000 tons of ore and produced 3,800 tons of solder, tin, and lead, worth $1,250,000 (8). Today, this legacy of urban heavy metal contamination of estuarine waters may even exceed the continued contributions of wastewater, surface runoff, and groundwater sources (13, 33). The resulting contamination disposal can become a practical problem for estuarine managers, and requires serious planning, but, in healthy marshes, heavy metals are sequestered in place.

Despite a dramatic three-century decline in inorganic matter in both Jo Co (60%) and Yellow Bar (30%) (Fig. 2), the marshes show the surprising result of increased vertical accumulation rate over the last century (Fig. 4). We hypothesize that the increased growth could be a result of the anthropogenic addition of nitrogen. As many have noted, the carbon balance in marshes is a net result of both positive (plant growth) and negative (decomposition, erosion, subsidence, compaction) (34–36) elevational processes. While some fertilization experiments have resulted in increased aboveground biomass (7, 19), conflicting results have characterized a decline in belowground biomass due to increased decomposition in the face of increased belowground production and surface accretion (37).

Declines in root density, increased porosity, and higher soil respiration were noted in Jamaica Bay's compromised marshes compared with stable Jo Co (10). However, accretion rates were similar in these two marshes. Other studies indicate an increase (38, 39) or no difference (36) in belowground growth with fertilization. Indeed, accretion and elevation change increased in plots that had been fertilized by nitrogen and phosphorus in nearby Guilford, CT (36).

Conclusions

Intense fertilization by wastewater-derived nitrogen in Jamaica Bay has led to increased organic marsh content and increased vertical accretion rate, compensating for the loss in mineral matter over the last two centuries. Enhancing accretion, as well, may be sea level rise, as flooding and increased flooding duration has been associated with enhanced marsh accretion, as more suspended organic sediment is available with flooding and enhanced aboveground growth provides better trapping (34, 36) of that organic sediment. Our measurements of $\delta^{13}C$ throughout the sediments indicate a stable salt marsh grass (C-4) signature, supporting the fertilization hypothesis. A study of 14 marshes in Connecticut and New York has recently documented an increase in organic sedimentation regionally as flooding increased with sea level rise (22). It is possible that increased algal and other marine fauna could be contributing to this accretion rate increase, while flooding also erodes marsh edge sediment. Ironically, the negative effects of high sewage influx into the bay may have compensated for the decrease in sediment supply and, in the highest marshes such as Jo Co, temporarily preserved the remaining marshland.

Sea level rise projections have identified the northeastern US coast as a "hot spot" (32) where increasing storm frequency will cause more severe flooding (40, 41). Marsh degradation not only removes a protective barrier but also threatens natural habitat and adds toxic heavy metals to the environment. However, defining the causes for the degradation in Jamaica Bay provides a path for solutions, so that these marshes can continue to provide these critical services.

Following methodology such as that utilized in the Mississippi delta (42), some success has been achieved in Jamaica Bay (2) by spraying marsh surface with a swing-ladder dredge of sediment from channels, followed by plantings starting in 2006 CE. However, recent challenges include some compaction, erosion, and subsidence, as well as finding sediment deemed "clean" enough (43). Studies in the Netherlands and the United Kingdom have relied on this fine-sediment spraying to successfully increase marsh elevation, finding that perennial plant colonization fostered more sediment trapping and positive feedback for positive sediment budget (44). Some of these projects have utilized a "trickle-charging" technique (45) rather than spraying. Sediment mounds are deposited with a bottom-opening barge. The mounds are then eroded away by tidal action and waves, slowly introducing fine-grain sediment to the tidal flow. Introduced sediment is then subsequently deposited in the upper intertidal zone. While initial observations are promising, long-term success has not been fully documented.

The continuous addition of fine sediment to marshes has shown some success in Jamaica Bay and elsewhere, but this site presents some additional challenges. Because the bay is channeled, sediment, when added to the system, tends to collect in dredged navigational channels and other lows, like the Grassy Bay borrow pit, as well as on marsh surfaces. Sediment fill is likely needed in these locations in order for sprayed fine sediment to remain on the marshes themselves, just as in Wax Bay Delta, LA, where marsh restoration was successful when dredged channels were filled in (46).

This conclusion is supported by Anisfield et al. (47), who found that high sediment availability is a prerequisite for marsh stability as sea level rises. The organic sediment supply increase in Jamaica Bay appears to be compensating for the inorganic sediment starvation for the moment, but this benefit likely will decline as NYC improves nitrogen removal from wastewater. The addition of mineral sediment is now critical for marsh stability, thereby protecting natural habitat, its associated ecosystem services, and prevention of heavy metal erosion into the estuary, a strategy applicable to urban sites worldwide. While each marsh is different, historical sediment fluxes, reconstructed by our method, can be used as benchmarks for future mineral additions. Other authors, e.g., Morris et al. (7), have developed models to define sediment fluxes necessary to achieve a steady-state marsh surface. Our methods provide an essential parameterization and ground truth for such models, necessary for each individual site.

Materials and Methods

Peat cores of 2 m to 3 m depth were extracted in 2014 CE from the western side of Jo Co and Yellow Bar (Fig. 1) using a side-opening 1-m Dachnowski peat corer, eliminating the possibility of compaction. After wrapping and refrigeration, they were sampled at 4 cm for LOI, X-ray fluorescence employing two different methods (dried Innov-X Alpha Series and wet Itrax), and total N and stable isotope N analysis. Pollen, spore, and macrofossil analyses were performed at 4-cm intervals at Jo Co and 10-cm intervals at Yellow Bar. Details are provided in *SI Appendix*.

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Supplementary Information for

Starving New York City Marshes with Sea Level Rise – Nature versus Nurture

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Supplementary Information

Field Sampling and core acquisition

Yellow Bar was cored in 2000 using a Livingstone piston corer at the eastern edge of the marsh in *S. alterniflora* to a depth of 2.5 m. In 2014, several duplicate peat cores were extracted from the western edge of Yellow Bar Hassock (40° 36.437' N, 73° 50.839'

W) to a depth of 2 meters. Also in 2014, cores to a depth of 3 meters from the western side of Jo Co (40° 36.841' N, 73° 47. 991' W) were retrieved using a 1-meter length Dachnowski "Russian" peat corer. This device retrieves sediment with a sharp, horizontally rotating blade, eliminating the possibility of compaction. Cores were wrapped in polyvinylidene chloride film and aluminum foil and transported to LDEO Core Repository, where they were refrigerated at 4°C prior to analysis. For this study, the upper 1.20 cm of peat were analyzed at Jo Co, and the upper 1.5 m at Yellow Bar Hassock.

Core sampling, loss-on-ignition (LOI) and x-ray fluorescence (XRF) analysis

The 2000 Yellow Bar core was subsampled at 10 cm intervals for pollen analysis in the upper 1.5 m. The 2014 cores for Jo Co and Yellow Bar were split and photographed before subsampling at 4 cm intervals from both sites for loss-on-ignition, pollen and spores, macrofossil and hand-held XRF analysis. LOI was determined for each sample following the procedures of Dean[1] where the samples were dried overnight at 100°C to estimate moisture content and then burned at 550°C for 2 hours to burn off the organic content. Percentages for inorganic/organic content downcore are presented in Fig 2. Inorganic remains were primarily silt, but also contained some clay and sand.

X-ray fluorescence of the cores were performed using two methods:

1) About 3 g of dried sediment was analyzed for chemical composition using Innov-X Alpha Series (4000 XRF Innov-X Systems, Woburn, MA) following the protocols detailed by Kenna et al.[2] Each analysis included two 120 s measurements using the soil protocol.

2) Prior to scanning, the peat core surface was smoothed. The core sections were scanned lengthwise along the center of the core surface using an Itrax Core Scanner (Cox Analytical Systems, Mölndal, Sweden) at the Lamont Doherty Earth Observatory. Analyses were performed using settings of 30 kV and 55 mA with a Mo tube, a step size of 2mm and an exposure time of 30 seconds. The data were reported in counts per second (cps) [3,4]

Pb isotopes were analyzed using a Perkin-Elmer NexION 350D ICP-MS. EPA 3050B, Acid Digestion of Sediments, Sludges, and Soils, was the protocol used for the extractions of heavy metals from solids. The GFAA/ICP-MS method in this protocol is recommended for Arsenic, Beryllium, Cadmium, Chromium Cobalt, Iron Lead, Molybdenum, Selenium, and Thallium.

Pollen spore, and charcoal analysis

Wet sediments were processed using standard techniques of KOH treatment, filtration using 150 and 7 micron screens, and standard HCl, HF, and acetolysis [5] including repeated centrifugation, and final alcohol dehydration and silicone oil mounts. Exotic *Lycopodium* spores were added to calculate pollen concentration [6] and identification at 400X was based on pollen identification keys[5] and LDEO reference collections.

A minimum of 300 pollen grains were counted per sample, and percentages presented as part of the pollen and spore sum. Selected taxa are displayed here. Charcoal on the slides were counted with the pollen, excluding samples less than 50 microns to avoid mineral pieces that might be confused with charcoal.

Macrofossil analysis

10 cm^3 of wet samples were screened between 500 and 250 microns using water. Sieve remains were suspended in water in a petrie dish and examined for identification using the reference collection at LDEO under a microscope at 40x, then refrigerated. Selected identified remains were utilized for AMS C-14 dating.

AMS Radiocarbon Dates

Identified macrofossils selected for accelerator mass spectrometry (AMS) dating were sent to Lawrence Livermore or UC Irvine for dating. Radiocarbon dates were calibrated to calendar years using the CALIB program, version 7.1[7].

Total N and stable isotope N analysis

Dried and ground samples were sent in glass vials to Cornell where they were analyzed for %N and N-15 analyses using standard methods and mass spectrometry. Samples were analyzed via combustion analysis on Carlo Erba NC 2500 Elemental Analyzer (Italy) coupled to a Thermo Scientific Delta V Isotope Ratio Mass Spectrometer (Germany). The nitrogen isotope ratio of the peat is expressed as a part per thousand (per mil) difference from the composition of a recognized reference material, which by convention is N2 in air[8].

Table S1: AMS Radiocarbon Dates

Lab Number	Site	Depth Range (cm)	Material Dated	fraction modern	±	$\Delta^{14}C$ (‰)	±	^{14}C Age (BP)	±
UCIAMS-170489	Jo Co	30-32	*S. patens* and *Distichlis* leaves	0.955	0.002	-15.081	1.69	120	15
UCIAMS-170490	Jo Co	50-52	*S. patens* and *Distichlis* leaves	0.979	0.002	-20.886	1.68	170	15
UCIAMS-170491	Jo Co	90-92	*Distichlis* crowns	0.985	0.002	-44.128	1.64	365	15
UCIAMS-170492	Yellow Bar	51.5-52.5	*Distichlis* leaves	0.971	0.002	-28.709	1.80	235	15
UCIAMS-170493	Yellow Bar	67.5-68.5	*Distichlis* leaves	0.973	0.002	-27.027	2.29	220	20

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