Climate and anthropogenic controls on blue carbon sequestration in Hudson River tidal marsh, Pierront, New York

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Abstract

Tidal marshes globally are experiencing erosion with sea level rise. In order to adaptively plan for essential marsh preservation, we recognize the importance of the investigation of marsh archives for the perspective they provide toward resilience. Our objective in this study is to examine the relationship of tidal marsh carbon sequestration with both climate change and human impact throughout past centuries and millennia. A Hudson River marsh sediment core spanning the last 2000 years is analyzed for bulk loss on ignition (LOI), bulk density, sedimentation rate, carbon (C) and mineral flux, and x-ray fluorescence (XRF) analysis including lead, copper, titanium and potassium. We compare this record to previously established pollen and spore stratigraphy from the same site, along with an extensive macrofossil based AMS 14C chronology based upon both cores. Carbon accumulation generally follows sediment accumulation rates, which were higher than 200 g C m$^{-2}$ yr$^{-1}$ prior to 1500 years ago. Declines in carbon storage rate during the Medieval Warm Period (MWP) are linked to drought, fire, and charcoal, while lesser declines during the Little Ice Age (LIA) are linked to cooling and a shorter growing season. Subsequent human impact with marsh haying practices also led to carbon accumulation rate decline to 100 g C m$^{-2}$ yr$^{-1}$. Increases in C sequestration rates in recent decades may be attributable to nitrogen pollution of the estuary, invasive plants, and/or increased flooding, but the lack of mineral sediment threatens their stability. Ecosystem function is declining with the loss of foundational species, and the crisis is deepening for preservation of this habitat. We strongly recommend strategies for minimizing marsh loss.

1. Introduction

Tidal wetlands, including coastal and riverine marshes, seagrass meadows, and mangroves, are called ‘blue carbon’ wetlands. Though relatively small in areal extent they are among the strongest long-term carbon sinks per unit area because of continuous organic carbon (C) accumulation (Chmura et al 2003, Bridgham et al 2006). The factors that control the amount of C sequestered include vegetation type, productivity, decomposition, mineral import, tidal range, and human activities (Callaway et al 2012, Watson et al 2017a). The most recent State of the Carbon Cycle Report (SOCCR-2), Ch. 15 (Windham-Meyers et al 2018), estimates that In North America tidal wetlands remove roughly 27 ± 13 Tg C yr$^{-1}$ from the atmosphere as estuaries outgas 10 ± 10 Tg C yr$^{-1}$ to the atmosphere, and the net uptake by the combined wetland-estuary system is 17 ± 16 Tg C yr$^{-1}$. Major uncertainties in this key finding include minimal data available on burial, lateral flux, and estuarine outgassing measurements. As these tidal marshes are threatened with coastal inundation as sea level rises and storm frequency and intensity increase (Sallenger et al 2012), predictions of coastal marsh loss are up to 45% by the end of the century (Craft et al 2009). A striking recent multi-decadal analysis of aerial salt marsh extent in Rhode Island shows a loss of 17.3% in a mere 40 years (Watson et al 2017b). This loss of potential C sequestration is threatening because the upper meters of tidal marshes in urban regions such as Jamaica Bay, NYC
also sequester abundant heavy metals (Peteet et al 2018). The importance of preserving the integrity of New York’s marshes is critical for these reasons as well as for biodiversity, storm protection, water quality, and nursery habitat. Recent methodology that has proved to enhance our understanding of marsh preservation focuses on long-term sediment history reconstruction (Drexler et al 2009, Drexler et al 2011, Callaway et al 2012, Wigand et al 2014, Jones et al 2017, Peteet et al 2018), as declines in mineral contribution and nitrogen pollution have both been implicated in marsh instability.

We recognize the opportunity to link our previous published records of long-term climatic and human impact in Hudson marshes (Pederson et al 2005) with new calculations of tidal marsh C sequestration throughout millennial shifts in climate and century-scale human impact up to the present with more recent sediment cores from the same location. Linkage of the below-ground organic/inorganic components to climate change coupled with human impact have rarely been explored in a tidal setting (Drexler et al 2011, Jones et al 2017). We address this question using a paleoecological record in the upper sediments from brackish Piermont Marsh, NY which reveals climate impacts of the regional northeastern US Medieval Warming Period as well as the Little Ice Age and major human impacts in the estuary (Pederson et al 2005, Sritararat et al 2012). Utilizing marsh archives to understand how C dynamics have shifted with climate change and human impact will aid us in responding with solutions addressing pollution, dams, droughts, and floods as seas rise.

The eastern coast of N. America is a hotspot for tidal marsh carbon accumulation due to the presence of glacially-carved river systems. The Hudson is a prime example as a fjord containing deep organic deposits (Peteet et al 2006), as these freshwater and brackish wetlands are typically characterized by high rates of organic carbon burial (Mitsch et al 2013, Smith et al 2015). Studies of tidal river deposits have shown that the relative contributions of organic and inorganic matter vary over millennia (Drexler et al 2009, Drexler 2011, Jones et al 2017), depending on the relative contribution from freshwater discharge and tidal range as well as wind and wave activity (Leonard et al 1995, Fettweis et al 1998). The back-to-back 2011 tropical storms of Irene and Lee introduced a massive amount of new terrestrial-derived sediment to the Hudson estuary, but much of that material did not make it out to the ocean partly due to the trapping by the salinity intrusion and bottom salinity fronts (Ralston et al 2013, Nitsche and Kenna 2018).

2. Study site

Piermont Marsh, a coastal brackish marsh about 40 km north of New York City, lies on the western shore of the Hudson River. It is one of four sites federally protected by the National Estuarine Research Reserve (NERR) program, and is bounded on the western edge by Tallman State Park, which rises 100 m as part of the Palisades Sill (figure 1). The adjacent area was colonized by the Europeans around 1700 CE, and forest clearance is documented at this time and throughout the 1800s, with a signature of the resulting deforestation weedy ragweed (Ambrosia) signal in paleoecological records throughout the northeast (Pederson et al 2005). The Revolutionary War followed by farming, haying, tanneries, and then invasive species characterize the landscape. Reforestation in the twentieth century is matched by increased development adjacent to the river and in towns.

A 13.7 m sediment core was extracted from the northern portion of Piermont Marsh using primarily a modified Livingstone piston corer, and the upper 2.5 m was examined for both climate and human impact (Pederson et al 2005). Subsequently the site was visited in 2000 and an additional sediment core was extracted using the Dachnowski side-opening corer, which eliminated any compaction. This core was then used for additional analyses for this study, extending the record to 5 m which spans the last 2000 years.

The southern Hudson Valley experiences a mixture of continental and maritime climates. Mean temperatures for January and July in New York City are −0.4 °C and 25 °C, respectively, while mean annual precipitation is 1080 mm (www.ncdc.noaa.gov), Central Park Observatory) (Kunkel et al 2013).

The vegetation today is dominated by the invasive Phragmites australis (common reed), but 50 years ago when the marsh was only 66% covered by this grass, substantial meadows of Spartina patens and Distichlis spicata (native high marsh grasses) as well as Typha angustifolia (invasive) remained. The pollen, spore, and charcoal stratigraphic record of the upper 2.5 m of Piermont Marsh was published previously (Pederson et al 2005). The major features of this record are an increase in Pinus (pine), Carya (hickory) and charcoal during the Medieval Warm Period, which is indicative of drought, and increases in cooler, moister taxa, Picea (spruce) and Tsuga (hemlock), during the Little Ice Age.

We return to this record to measure the carbon shifts through these important climatic intervals of the last few millennia, followed by the human impact of the last few centuries.

3. Methods

3.1. Pollen, spores, and charcoal (1998 sediment core)

Our previous fossil stratigraphic analysis is presented here back to 2.5 m depth and spans from 650 AD to 1998 (Pederson et al 2005) using methods including standard treatment with HF, HCL, acetylation, and mounting in silicone oil (Faegri and Iversen, 1975,
Figure 1. Study site of selected core from which we analyze climate shifts and human impact in relation to carbon storage in the marsh. Nearby other Hudson River protected NERR marsh sites include Iona Marsh, Tivoli Bays, and Stockport Flats, as well as Jamaica Bay.

Heusser and Stock (1984). A minimum of 300 pollen grains were counted per sample, and spores were tallied in addition. Pollen diagrams were constructed using Tilia (Grimm 1992). Charcoal pieces greater than 50 um \times 10 um (500 um^2) were counted along with pollen grains and exotic Lycopodium grains, and charcoal/pollen (C/P) ratios calculated.

3.2. Macrofossils (1998 and 2000 sediment cores)
Contiguous 4 cm intervals were washed using screens of 125 and 150 microns, and the residues picked in water at magnification of 20–60X. Identification relied on reference material in the extensive macrofossil collection housed at LDEO as well as various reference books (Martin and Barkley 1961, Montgomery 1977).

3.3. Loss-on-Ignition (LOI) (1998 and 2000 core)
Subsamples were taken at 4 cm intervals throughout the 1998 and 2000 cores following the methods of Dean (1974). This included burning at 550 °C for 2 h. LOI and bulk density measurements were multiplied to calculate ash-free bulk density. Carbon content was calculated from the ash-free bulk density by multiplying by 0.5 in sedge peat (Loisel et al 2014), as much of the peat is sedge (Schoenoplectus/Scirpus) prior to human impact.

3.4. XRF analysis (2000 sediment core)
XRF analysis utilized two methods:

(a) 2000 core—About 3 g of dried sediment at 4 cm intervals were analyzed for chemical composition using Innov-X Alpha Series (4000 XRF Innov-X Systems, Woburn, MA, Croudace et al 2010) following the protocols detailed by Kenna and Rothwell (2011). Each analysis included two 120 s measurements using the soil protocol.

(b) 2000 core—Prior to scanning, the peat core surface was smoothed. The core sections were scanned lengthwise along the center of the surface using an Itrax Core Scanner (Cox Analytical Systems, Molndal, Sweden) at LDEO (Croudace et al 2006). Analyses were performed using settings of 30 kV and 55 mA with a Mo tube, a step size of 2 mm and an exposure time.
of 30 s. Data were reported in counts per second (cps).

3.5. Total N and stable isotope N analysis (2000 core)
Using the same 4 cm intervals, dried and ground samples were sent in glass vials to Cornell where they were analyzed for %N and δ 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 N_2 in air.

3.6. Age control
Age is constrained with 28 AMS radiocarbon dated macrofossil remains along with tiepoints from XRF result of heavy metals lead and copper, and nitrogen isotopes (table 1). Age of each 1 cm increment of sediment is modeled using the ‘Bacon’ Bayesian age modeling software (Blauw and Christensen 2011). Sedimentation rates and derivatives are plotted with 75% confidence intervals where uncertainty is derived from the calibration of radiocarbon ages to the IntCal13 calibration curve.

4. Results and discussion

4.1. Fraction organic matter and bulk density (figure 2)
LOI representing the fraction organic matter shows the similar pattern obtained in the 1998 core for the top 2.5 m, ranging from around 10% at 5 m to over 50% upcore, with fluctuating values between 2 and 3 m depth. Bulk density shows the opposite pattern, with largest values at depth, declining values upcore, and similar fluctuation between 2 and 3 m depth.

4.2. Chronology and sedimentation rates (figures 3, 4)
The Bacon age model is shown in figure 3, using the tiepoints from table 1.

| Tiepoint ID | Age  | Age ±  | Depth |
|-------------|------|--------|-------|
| Core Top    | −50  | 2      | 0     |
| Pb, Cu, As  | −25  | 1      | 14.5  |
| N           | 47   | 1      | 33.5  |
| Pb, Cu, As  | 100  | 3      | 54.5  |
| CAMS 87 074 | 145  | 40     | 82    |
| Ti, K       | 300  | 3      | 84.5  |
| CAMS 87 075 | 275  | 40     | 94    |
| CAMS 83 125 | 270  | 40     | 98    |
| CAMS 81 790 | 355  | 35     | 110   |
| CAMS 81 791 | 520  | 35     | 122   |
| CAMS 81 792 | 515  | 45     | 134   |
| CAMS 87 076 | 600  | 60     | 134.5 |
| CAMS 81 793 | 455  | 35     | 142   |
| CAMS 87 077 | 660  | 70     | 150   |
| CAMS 85 220 | 785  | 45     | 178   |
| CAMS 87 078 | 1035 | 45     | 186   |
| CAMS 81 794 | 1300 | 35     | 190   |
| CAMS 87 079 | 1030 | 40     | 194   |
| CAMS 80 963 | 1325 | 40     | 209   |
| CAMS 87 080 | 1210 | 40     | 215   |
| CAMS 80 964 | 1245 | 40     | 229   |
| CAMS 80 965 | 1490 | 45     | 257   |
| CAMS 87 081 | 1580 | 80     | 277   |
| CAMS 81 784 | 1750 | 35     | 346   |
| CAMS 80 966 | 1490 | 70     | 350   |
| CAMS 83 118 | 1355 | 40     | 394   |
| CAMS 80 967 | 80   | 60     | 402   |
| CAMS 81 785 | 1100 | 35     | 406   |
| CAMS 80 968 | 1850 | 40     | 445   |
| CAMS 80 969 | 1960 | 50     | 482   |
| CAMS 83 119 | 2035 | 40     | 486   |
| CAMS 83 120 | 1655 | 40     | 510   |
| CAMS 83 121 | 1425 | 45     | 550   |

3.5. Total N and stable isotope N analysis (2000 core).

−0.6. Age control
Age is constrained with 28 AMS radiocarbon dated macrofossil remains along with tiepoints from XRF result of heavy metals lead and copper, and nitrogen isotopes (table 1). Age of each 1 cm increment of sediment is modeled using the ‘Bacon’ Bayesian age modeling software (Blauw and Christensen 2011). Sedimentation rates and derivatives are plotted with 75% confidence intervals where uncertainty is derived from the calibration of radiocarbon ages to the IntCal13 calibration curve.

4. Results and discussion

4.1. Fraction organic matter and bulk density (figure 2)
LOI representing the fraction organic matter shows the similar pattern obtained in the 1998 core for the top 2.5 m, ranging from around 10% at 5 m to over 50% upcore, with fluctuating values between 2 and 3 m depth. Bulk density shows the opposite pattern, with largest values at depth, declining values upcore, and similar fluctuation between 2 and 3 m depth.

4.2. Chronology and sedimentation rates (figures 3, 4)
The Bacon age model is shown in figure 3, using the tiepoints from table 1.

The dated material selected from the macrofossils was pretreated with an acid-alkali-acid chemical digestion prior to combustion, graphitization, and measurement by accelerator mass spectrometry (AMS) at Livermore National Laboratory, Livermore, California. Dates were calibrated to the IntCal13 calendar age scale using Calib 7.10 (Stuiver et al. 2013) and reported as calibrated years before AD 1950. Figure 3 shows the rejected five erroneous younger dates at core breaks in the lower part of the profile (marked by an asterisk “∗” in table 1).

The sedimentation rate records large shifts from an average of 2 mm yr\(^{-1}\) about 2000 years ago to increasing rates up to 4 mm yr\(^{-1}\), then declines to less than 2 mm yr\(^{-1}\) between 1000 and the latter part of the 19th century. The uncertainty is large in this lower part of the record, driven by the age model, but is almost half from 1000 years ago to the late 1900s. In the very recent past, rates reach from 4–6 mm yr\(^{-1}\), with higher uncertainty. In contrast, the ash-free bulk density is more constant, ranging from 0.10 to 0.15 g cm\(^{-3}\), but generally highest between 500 and 1000 CE.

4.3. Paleocology, paleoclimate and human impact (figures 5, 6)
Pollen and spores, XRF results, organic/inorganic values, nitrogen values.

5. MWP (figure 5, 225–150 cm depth, 850–1350 CE, figures 5, 6)

Selected pollen, spore, and charcoal/pollen ratios first identified in Pederson et al. (2005) highlight the vegetational shifts key to identifying the MWP and the subsequent Little Ice age. Increases in pine and hickory along with a very large increase in charcoal/pollen ratio characterize the warmth and dry conditions of the site, and the large role of fire. We note the
increased *Ambrosia* profile in this interval up to 5% (figure 5) is possibly indicative of disturbance due to the fires. Also at this time, increased concentrations of potassium (K) and titanium (Ti), and low LOI values indicate increased supply of inorganic sediment to the site (figure 6). Nitrogen percentages (figure 5) are relatively high (~1.6% dry wt.) prior to European arrival, likely due to heavy bird usage and/or an increased marine influence.

5.1. **Little Ice Age** (figures 5, 6, 130–60 cm, 1400–1800, Lamb, 1982)
The decline of pine and hickory and the increased oak, hemlock, and traces of spruce and beech, northern hardwoods, indicate cool and moist conditions prevailing until about 70 cm. During the pre-Colonial interval (130–80 cm), the inorganic input to the site markedly declines, as indicated by decreases in K and Ti concentration. Disturbance as

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**Figure 2.** Fraction organic matter (LOI) and bulk density (g cm\(^{-3}\)) with depth from Piermont Marsh sediment core 2000.

**Figure 3.** Piermont 2000 core age model using 28 AMS dated macrofossils and bacon (Blaauw and Christen 2011).
Figure 4. Sedimentation rate and ash-free bulk density (AFBD) for Piermont Marsh. Sedimentation rate expressed in millimeters per year is displayed with 75% confidence intervals based on the results of the ‘Bacon’ Bayesian age model using AMS dated macrofossils and XRF tiepoints in figure 3 and table 1. AFBD is the concentration of organic matter in the marsh sediment as measured by loss-on-ignition and expressed in grams per cubic centimeter.

indicated by *Ambrosia* is minimal (figure 5). Subsequent shifts in Colonial forest clearance and farming greatly impact the pollen stratigraphy as well as the accretion rates. Nitrogen percentages fall to 0.6 in tandem with the *Ambrosia* rise and Ti increase, signifying disturbance to the watershed, while the isotopic δN-15 rise indicates the marked human impact.

5.2. European impact (figure 5, 80–0 cm, 1691–1998 CE) The decline in trees and sustained increase in *Ambrosia* marks the heavy disturbance signal up to the twentieth century, when it subsequently declines as reforestation spreads across the northeastern US. Approximately 1822 (60 cm depth) the rise in Pb, Cu and As signify the industrial era, with the decline at
1974 due to the federal rules for gasoline Pb phaseout. The rise in invasive Typha angustifolia is marked up to the twentieth century when a slight decline is paralleled by the increase in grass pollen, in large part the invasive Phragmites (Pederson et al. 2005). Further increased nitrogen in the estuary as denoted by the large increase in both nitrogen percentage and δN-15 isotope (figure 6), when the sewage treatment plant for Rockland County opened in 1968, and local Orangetown treatment expanded. Population increases and continued sewage in the estuary due to stormwater overflows continue to pose challenges to the marsh and the estuary today.

5.3. Carbon sequestration with climate and human impact
C burial in Piermont marsh varies greatly, ranging from 50 to almost 300 g C m$^{-2}$ yr$^{-1}$. The C sequestration in the lower portion of this core (0–500 yr CE) is very high (> 250 g C m$^{-2}$yr$^{-1}$) for tidal marshes, and close to maximum observed for those marshes in lower reaches of more southern estuaries (Krauss et al. 2018). However, the uncertainty is also high, driven by the uncertainty in the sedimentation rate from the age model. In contrast, during the MWP, the warm and dry climate was contemporaneous with very low carbon storage (figure 7) and very large increases in charcoal (figure 5), and low uncertainty.

Besides fire, the Hudson watershed reflects big declines in C sequestration due to the warmer soils which would have favored pine and hickory in the uplands, respired more carbon, and possibly resulted in less marsh production due to lower moisture at the site. Further evidence for the MWP drought is evidenced regionally by charcoal increases in other lower resolution cores from marshes (Sritrairat et al. 2012) and lakes in the Hudson Valley region (Maenza-Gmelch 1997, Menking et al. 2012). Drought is also detected in the Chesapeake Bay region (Brush 1986) and as far south as North Carolina (Stahle et al. 1988). Further, the large decline in C accumulation in the second half of the MWP is also paralleled by sites farther south in South Carolina’s rivers along the Atlantic coast. These wetlands have low C accumulation and are generally void of plant macrofossils during this interval, suggesting that the interval was largely erosional or that hydroperiods were shorter, allowing for more decomposition and less sediment delivery (Jones et al. 2017).

The subsequent low C storage (50 g C m$^{-2}$ yr$^{-1}$) at Piermont during the Little Ice Age (LIA) and during the settlement period (late 1600s–early 1700s) almost reaches a similar effect to drought, possibly due to limits in productivity due to cooler summers and a shorter growing season. Uncertainty is again relatively low. A local Piermont diary (1829–1850) by Nicholas Gesner (Gerard 2015) remarks on the timing of first yearly frost dates occurring as early as August, while today Piermont rarely sees frost prior to mid-October. Winter ice may have negative effects on C accumulation by removing the marsh peat itself, enhancing export to the estuary. Further south along the Atlantic coast, the
Waccamaw and Savannah Rivers also reveal very little C accumulation during this interval (Jones et al. 2017).

Piermont marsh C storage recovers following the LIA to 200 g C m$^{-2}$ yr$^{-1}$, only to fall again to 100 g C m$^{-2}$ yr$^{-1}$ probably due to the extensive haying by local residents. Hay from the marsh was used as food for horses, bedding, and chinking houses. The subsequent increase in carbon accumulation in the early 20th century suggests that nitrogen fertilization may be affecting the recent C storage. The shift from Typha to Phragmites in much of the marsh may also be contributing to this increase. Alternatively, recent apparent C accumulation increase may be artificially inflated because it includes carbon which will be respired with burial (Bulseco et al. 2019). Similar increasing rates of C storage in recent decades in coastal salt marshes of Connecticut and New York (Hill and Anisfield 2015) as well as NYC indicated an average storage of 84 g C m$^{-2}$ yr$^{-1}$ from 1900–2012, which is significantly lower than our rates here in most recent decades (over 300 g C m$^{-2}$ yr$^{-1}$). However, Piermont is a brackish river tidal marsh, generally with higher rates of carbon storage than coastal salt marshes (Smith et al. 2015).

The large effects of climate shifts on the C sequestration in this brackish tidal marsh have large implications as climate warms (Vose et al. 2017) and the Hudson River experiences warming temperatures with eutrophication (Howarth et al. 2011) and potential future droughts. Predictions for climate change in the northeastern US include warming increases of about 1.4 C in the next few decades, and higher rates towards the end of the century (Vose et al. 2017). Along with predicted flashy increases in precipitation (Easterling et al. 2017), drought is of major concern as drier summers are predicted (Hayhoe et al. 2007, Pederson et al. 2013) and NYC has already endured six water emergencies since 1981 (NYC Department of Environmental Protection 2011).

Worldwide, marshes are known to be eroding and submerging due to increased sea level rise and diminished sediment delivery (Penland et al. 2001, Kearney et al. 2002, Hartig et al. 2002), and projections of marsh decline range from 10% to 50% (Kirwan and Murray 2008). While studies of the low marsh S. alterniflora suggest that marsh productivity of this species may increase with inundation as climate warms with warming or a longer growing season (Kirwan et al. 2009), it is not clear that this productivity will remain belowground with minimal

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**Figure 7.** Carbon accumulation flux (g C m$^{-2}$ yr$^{-1}$) and mineral flux (g C m$^{-2}$ yr$^{-1}$) for Piermont Marsh over the last 2000 years spanning the Medieval Warm Period (MWP) and the Little Ice Age (LIA) as well as human impact. Fluxes are expressed in grams per meter square per year with 75% confidence intervals based on the results of the ‘Bacon’ Bayesian age model. Note that the fluxes of mineral matter are multiplied by 0.1 to aid in visual comparison. The extents of Medieval Warm Period (MWP) and Little Ice Age (LIA) are marked with vertical lines in red and blue, respectively.
mineral supply (Wigand and Guntenspergen 2014) or because of concerns with carbon lability (Watson et al 2014, 2017b, Bulseco et al 2019). Additionally, submerged marshes may be below the optimum elevation for root growth, leading to marsh decline (Kirwan and Guntenspergen 2012).

This study and tree ring records documenting severe droughts throughout past centuries (Pederson et al 2013) indicate that C sequestration may decline as climate warms. The foundational high marsh species Spartina patens has been declining throughout southern New England (Niering and Warren, 1980, Donnelly and Bertness 2001) and is predicted to decline further with drought (Watson et al 2016). This has important implications for C storage, as S. patens habitats are associated with greater soil strength (by 35.3 psi, Wigand et al 2010) and thus presumably are more erosion resistant. The implications for biodiversity loss are large, because this species is associated with facultative fungal symbionts (vesicular-arbuscular mycorrhizae) that allow it to fix atmospheric nitrogen (Burke et al 2002) and thus provide benefits for co-occurring plant and animal species, including the vulnerable salt marsh sparrow. Thus, drought is a serious issue for further S. patens high marsh decline.

The Hudson Valley is facing more intense storms (Ralston et al 2013) along with additional sea level rise (Weston 2014), which will enhance inundation, leading to declines in low marsh Spartina alterniflora belowground production and subsequent marsh degradation (Watson et al 2017b). Higher inundation may also lead to fungal infection and herbivory contributing a combined role in plant mortality (Elmer 2014). Further human impacts including the continued spread of invasive species, nitrogen fertilization, and shifts in channelization (Collins and Miller 2011) will all impact both the quality and quantity of blue carbon in the marshes. Understanding the causes of blue carbon sequestration in marsh history provides keys to methods of preservation (McLeod et al 2011), but much remains to be understood. The nutrient balance for optimal marsh belowground C sequestration varies at the local scale (Watson et al 2017a, Bulseco et al 2019). Ongoing field and lab studies utilizing different species will aid us, as will more studies of marsh archives coupling paleoecological records with sedimentation and carbon assessments at various sites, both urban and rural.

To preserve marsh stability for a myriad of ecological and shoreline protection reasons, we advocate thin-layer mineral additions to replace the mineral supply that appears missing in both coastal (Petee et al 2018) and riverine marshes. Enhanced removal of nitrogen from wastewater is extremely important because of the documented increased organic matter decomposition with higher nitrogen (Watson et al 2014, Bulseco et al 2019) and the evidence for decreased root and rhizome production in several salt marsh species (Deegan et al 2012, Wigand et al 2014). Dam removal for future increased potential of mineral sediment is warranted, as well as preservation of new sites for tidal marsh encroachment.

6. Conclusions

(a) Sedimentation rates in a brackish Hudson River tidal marsh range from 1 to 6 mm yr$^{-1}$ over 2000 years, with an average of 2 mm yr$^{-1}$ and uncertainty highest in the lower part of the record. With sea level rise today over 4 mm yr$^{-1}$ at NYC, it appears the long-term record indicates marshes need enhanced mineral support.

(b) Carbon sequestration rates vary from highest prior to 1500 years ago at > 300 g C m$^{-2}$ yr$^{-1}$ to minimum rates of < 50 g C m$^{-2}$ yr$^{-1}$ in the MWP, during a major drought affecting both upland and marsh vegetation itself through fire.

(c) The LIA is marked by a marked decline to less than 100 g C m$^{-2}$ yr$^{-1}$, linked to a lower productivity due to colder temperatures, a shorter growing season, and possibly physical removal of the marsh peat with river ice.

(d) The farming impact of hay removal from the marsh which continued until the early 20th century appears to have resulted in substantial C decline as well, with most recent decades revealing large increases. These large increases may be due to the visible increases in estuary nitrogen enhancing productivity, regional Phragmites growth, and/or increased flooding of the marsh due to sea level rise. However, this may be temporary as the organic matter decomposes further.

(e) Climate adaptation strategies should include thin layer mineral deposition, potential dam removal for enhanced mineral sedimentation, enhanced nitrogen removal, and conservation of proposed locales for planned marsh migration.

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