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Importance of quantifying the full-depth carbon reservoir of Jamaica Bay salt Marshes, New York

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ABSTRACT

Constraining uncertainty in the global carbon cycle requires valid assessment of both surface and stored carbon in marine and coastal ecosystems (Blue Carbon) as well as terrestrial carbon (forests, peatlands, and soils) [Pendleton et al., 2012]. Quantifying the global carbon stock of coastal salt marshes, potentially the most efficient carbon-burying ecosystems in the world per area, is a key area of further research in both of these fields Pendleton et al., 2012. One of the largest challenges is that despite the fact that salt marshes often sequester carbon several meters deep, nearly all estimates of salt marsh carbon stocks consider only the upper 1 m of sediment (Windham-Myers et al., 2015) [54]. This is particularly concerning because coastal wetlands are increasingly at risk due to climate change, sea level rise, and anthropogenic disturbance and destruction (Deegan et al., 2012) [15]. Using full-depth measurements from marsh cores, we estimate the carbon stock of five salt marshes in the highly urbanized estuary of Jamaica Bay, New York and argue that partial-depth measurements can underestimate carbon stocks. These estimates use calculated carbon content and probe depth data of these marshes collected between 2000 and 2019, applying this data across the full area of the marsh obtained from satellite imagery. Carbon density measurements are then multiplied by the full-depth volume of the marshes to create an estimate of total carbon stock. In addition to calculating present-day estimates, we compare our carbon stock estimates to historical Jamaica Bay imagery to calculate historical carbon stocks and carbon loss. The carbon stock estimates presented here show a 95% carbon stock loss between 1885 and 2019 in Jamaica Bay and highlight the severe underestimation of carbon stocks without full-depth calculations. These findings have important implications for disappearing salt marshes with regard to the global carbon cycle and the incorporation of belowground carbon into global climate models. The findings are increasingly relevant for advocacy efforts aiming to conserve these marshes with sea level rise.

Introduction

Carbon storage in coastal ecosystems

The discussion on anthropogenic climate change is often focused on fossil fuel emissions. Yet often ignored, approximately 30% of global emissions come from the destruction of natural ecosystems [24,29]. Even within the realm of ecosystem destruction, research primarily focuses on terrestrial deforestation. Coastal wetlands, however, contain much more carbon per unit area than forests, but receive relatively little attention [30]. In recent years, interest in the carbon stored in coastal and marine ecosystems has brought greater attention to carbon-dense stocks like salt marshes. The degradation of these coastal ecosystems is currently estimated to release up to 1.02 Pg of carbon dioxide annually [34]. Quantifying human impact on coastal wetlands, as well as the extent of their carbon sequestration, is critical to filling knowledge gaps in our understanding of the global carbon cycle, the foundation of climate change mitigation and adaptation efforts. Key uncertainties in this quantification include the spatial extent, depth, and carbon content of coastal wetlands. Using a full-depth carbon stock estimation of Jamaica Bay salt marshes as a case study, we demonstrate the way conventional approaches can significantly underestimate carbon stocks.

Coastal wetlands (salt marshes, mangroves, and seagrasses) cover between 0.3 and 1.2 million km^2 globally [8,30]. Salt marshes sequester between 43 and 55 times more carbon per unit area than terrestrial forested ecosystems despite making up a smaller portion of the earth’s surface, burying carbon-rich layers of peat over thousands of years [30]. Economic valuation recently has assessed that tidal wetlands are 15 times more valuable than lakes and rivers, almost 47 times more valuable than grass and rangelands, and 51 times more valuable than forests

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per unit area [9]. Due to their immensely important ecosystem services, tidal wetlands rank as the second more valuable ecosystem per unit area after coral reefs. Despite the important roles that they serve, wetlands have historically been and are still being lost to rising sea levels, anthropogenic disturbance, damming, eutrophication, and drainage. In the contiguous 48 states of the United States, 60 acres of wetland were lost every hour between 1780 and 1980, resulting in a 53% loss of wetland area in this time period alone [13]. Due to accelerating sea level rise and continued anthropogenic disturbance, the area of intertidal marshes specifically declined 1.4% from 2004 to 2009[12]. Holmquist et al. [23] estimate that between 43% and 48% of the existing contiguous US wetland area, almost entirely located in watersheds along the Gulf of Mexico and Mid- Atlantic coasts, is subject to both vertical and lateral limitation [23]. While many of the valued "services" of coastal wetlands are acknowledged, the magnitude of the associated impacts on the carbon cycle remain unclear.

Anthropogenically induced climate change, beginning with industrialization, is well-documented [38,28,56]. However, large uncertainties still exist in the global carbon cycle and the implications these shifts may have on a changing climate. Salt marsh loss from rising sea levels can rapidly remobilize carbon that took thousands of years to sequester. Associated positive feedback loops can accelerate marsh loss, contributing further to the climate emergency [41]. The ability of carbon loss to overpower rates of carbon sequestration is illustrated by radiocarbon dating showing that up to 250 years' worth of accumulated peat has been lost in as little as 30 years of salt marsh die-off [10]. Coastal wetlands are distinctly affected by climate change-induced sea level rise and hotter air temperatures, which increase carbon and methane emissions, render them uninhabitable to certain species, and cause the loss of environmental benefits, such as water filtration [51,31]. When sea level rise causes declines in carbon stocks, carbon-dense coastal ecological communities, such as mangroves or salt marshes, shift to less carbon-dense communities, like sea grasses [27]. As the effects of climate change and anthropogenic disturbance continue, wetlands may transition from net carbon sinks to net carbon sources [10].

Peat depth is a key variable that determines the total volume of carbon stored in salt marshes. Satellite imaging may be used to determine bathymetry of water in coastal areas. However, neither this method nor sonar can detect the depth of peat below the surface in salt marshes. Thus, salt marsh depth must be probed manually, a difficulty which has contributed to limited understanding of the full depths of salt marshes and the implications these depths have on the global carbon cycle. In many marshes, carbon is stored several meters deep, but most studies of carbon in wetlands include only analysis of the top 50 cm [8] or at most 1 m [22]. This is further affirmed by the van Ardenne et al. [2] assessment that their study was the first full-depth carbon stock estimate of salt marshes and that using the full depth dramatically changes carbon stock estimates [2]. Submergence of wetlands caused by sea level rise endangers the large stocks of C that are stored within coastal soil. Deeper (>50 cm) organic matter stocks can be vulnerable to mineralization, especially following submergence and wetland erosion, and it has been suggested that total carbon and organic matter is highest between 50 and 100 cm [42]. Without precise data for wetlands, these critical carbon reservoirs remain excluded from earth system models, such as NASA GISS ModelE-2.1, NCAR CCM3 and others. Policies that could value and protect wetland carbon sequestration further require accurate measurements of these carbon stocks. Furthermore, the IPCC's chapter on emissions management in coastal wetlands uses estimates from a study that acknowledges that their quantification of only the top 1 m of carbon globally is conservative [34]. Deeper sampling and understanding of site history are crucial to fully determine the implications of sea level rise and submergence on the C cycle because many coastal wetlands have undergone shifts in vegetation and depositional history.

The goal of this research is to estimate the full-depth carbon storage in Jamaica Bay salt marshes, critical carbon-rich ecosystems that have been and continue to be threatened by intense anthropogenic disturbance and sea level rise. We demonstrate the way conventional approaches can significantly underestimate carbon stocks by not considering their full depth. To further illustrate the role these ecosystems can play in climate change via positive feedback loops, we estimate full-depth historical carbon stocks and losses for the marshes as well. By recognizing the importance of depth in determining carbon storage and loss in salt marshes, we can better understand the urgency of protecting coastal salt marshes (especially older, deeper marshes) and better anticipate a future in which sea level rise and human activity degrade them.

Site selection

Jamaica Bay is an estuary with salt marshes, part of Gateway National Recreation Area, which is managed by the National Park Service and located in New York City. John F. Kennedy airport was built on top of eastern Jamaica Bay marshes, providing a large-scale example of anthropogenic draining and disturbance of salt marshes. However, the area remains a vibrant valuable ecological community of birds, fish, mussels, horseshoe crabs, and diamondback terrapins for the region. The remnant tidal marshes are dominated by low marsh grass (*Spartina alterniflora*) which is invading previous high marsh environments (*Spartina patens* and *Distichlis spicata*) in three of the marshes—Joco, East High Meadow, and Yellow Bar. These marshes are largely intertidal, with emergent, persistent vegetation, and regularly flooded, based on the U.S. Fish and Wildlife Service's National Wetlands Inventory (Code E2EM1N).

As the home of an airport, five Combined Sewage Outfall (CSO) sites, three landfills, and surrounded by the urbanized New York city sprawl, Jamaica Bay has been highly impacted by human impact for over four centuries, including pollution by metals, oils, greases, hazardous materials, solids, hydrocarbons, pesticides, and herbicides [44]. Sediment cores reveal the extent to which eutrophication and heavy metal pollution continue to impact the local marshes [35].

The area is projected to face greater than average sea level rise as the Atlantic Ocean's meridional overturning circulation weakens with climate change [55,39]. As sea level rise accelerates, it threatens to overtake coastal marshes [20,30,34]. This is especially a concern in Jamaica Bay, where marsh preservation has declined due to anthropogenic disturbance that depletes the marsh of inorganic sediment; [35]; see Fig. 1). Sea level rise, coastal storms, storm surges and coastal flooding make Jamaica Bay particularly vulnerable [20].

Additionally, high loads of nutrients in Jamaica Bay have contributed to marsh loss; a rise in the soil percent nitrogen and increasing nitrate with the rise in human population contributed to decreased soil strength and increased decomposition rates [53,5]. While nutrient loading may increase aboveground biomass, it can lead to declining root biomass and increased decomposition, which can compromise soil strength [48,53,5]. The ability of coastal marshes to retain their carbon stocks depends on their accretion rates outpacing sea level rise. Thus, understanding changes in the area of Jamaica Bay in recent decades due to the combined effects of sea level rise and inorganic sedimentation starvation is of particular interest [35]. Fig. 1 displays an ArcGIS-based map detailing the data collection at the site's recognized marsh island area (U.S. Fish and Wildlife Services).

Methods and approach

Data collection methods

The depth of accumulated peat in Jamaica Bay marshes was measured using hand-held 0.6 cm diameter probes at 20 sites from 2000 to 2019 (see Fig. 1). All but one of these probes was greater than 2 m, and the 11 probes taken in 2019 were used for calculations. These probes are fiberglass rods, each measuring 1.24 m in length, which are

Fig. 1. Locations of cores (red diamonds) and probes (orange circles) collected in Jamaica Bay salt marshes (teal) by Peteet and students from 2000 to 2019 [49]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

screwed together and inserted directly into the peat of the marsh until refusal to determine its depth at a given point. In Jamaica Bay, where there are many small fragmented marsh islands, probe data was mostly collected via opportunistic sampling points due to roughness of the terrain and limited access points via boat.

A side-opening Dachnowski Russian corer, which ensures no compaction of the sediment, was used to collect sediment cores from three of the marshes (Yellow Bar, JoCo, and East High Meadow) in a previous study [35]. The three most recently collected cores (2014) were used for the carbon stock calculations after comparison with the three other cores collected since 2000 to confirm that they are representative of the data collected at the site during the past two decades. These cores were taken from the surface of the marsh downward, and represent the entire peat stratigraphy. Cores were stored in a layer of polyethylene food wrap and aluminum foil and stored at 4 °C in the Lamont-Doherty Earth Observatory Core Repository. The top 50 cm of the cores were subsampled at 4 cm increments. The loss-on-ignition (LOI) analyses were conducted to obtain carbon content data using a standard mass subtraction method [14]. LOI samples were heated for two hours at 550 °C using a Fisher Scientific Isotemp Muffle Furnace. LOI is then calculated at each sub-sample to document the change in organic material with depth in the core.

LOI analysis for JoCo, Yellow Bar, and East High Meadow marshes that were used for this study's calculations can be seen in Fig. 2 [35]. The resulting organic content is then converted to carbon content (g/ cm^3) for each depth increment (see below) (see Fig. 3).

Computational methods

Google Earth Pro and ArcGIS were used to map data and apply measured carbon and depth data onto the areal extent of Jamaica Bay marshes obtained from Landsat and Copernicus satellite imaging and USGS GIS maps. Present-day carbon estimates were based on the area obtained from November 2019 satellite images of the Jamaica Bay marshes, the most recent available images unobscured by cloud cover, and U.S. Geological Survey data [52].

We calculated the full-depth estimate of carbon stock, the top meter estimate of carbon stock, and the top 50 cm estimate of carbon stock using the average values for carbon content and depth in JoCo, East High, and Yellow Bar (see Eq. (1)).

$$CS = CC*A*D \quad (1)$$

CS is the total carbon stock (kgC) and CC is the carbon content ($kgCm^{-3}$) calculated from LOI and soil bulk density data from the sediment cores and a regression Eq. [11] (see Eq. (2)). A is the area of the marsh (m^2) and D is the depth (m).

$$CC = CF*LOI*BD \quad (2)$$

CC is the carbon content (kg m^{-3}), CF is the average of the conversion factor range found in Craft et al. [11] for determining carbon content from LOI in North American estuarine salt marsh soils, LOI is the loss on ignition value obtained from core data (organic mass loss/total dry mass), and BD is the bulk density of sediment (kg m^{-3}) at each subsample from the core data [11]. The full conversation factor range in Craft et al. [11] is used to create the uncertainty range for the carbon stock estimates. The full-depth and partial-depth measurements were compared using a two-sample z-test to determine statistical differences between the depth methodologies. Additionally, the interspatial variability of the data was compared to the variability between depth methodologies to determine the relative scale of impact that estimations using full depths can have compared to partial depth estimates.

Older satellite images from Google Earth Pro in 1984 were used to estimate the net area loss of Jamaica Bay, which can be used to calculate the associated amount of carbon lost during this timeframe. A further historical estimate was created for Jamaica Bay by using a USGS map for 1885 and an areal estimate (see 1897 map in [35,6]**.** For the sake of this study, we assume that between 58 and 75% of the carbon stored in the lost marsh area becomes labile upon marsh destruction [42,41]. It is likely that some portion of the carbon stock remains sequestered in the basal bay sediments, and further investigation is needed to constrain uncertainty in the amount of carbon that becomes labile. This range of uncertainty is included in our data. Previous estimates of carbon export due to sea level rise have also assumed that carbon loss is a function of the volume of carbon lost and the carbon content of that volume [46].

Results

Partial-depth estimates of carbon stock severely underestimate full-depth estimates at this site, which was on average 2.87 m deep (see Fig. 4). The top meter estimate was 55% of the full-depth estimate, and

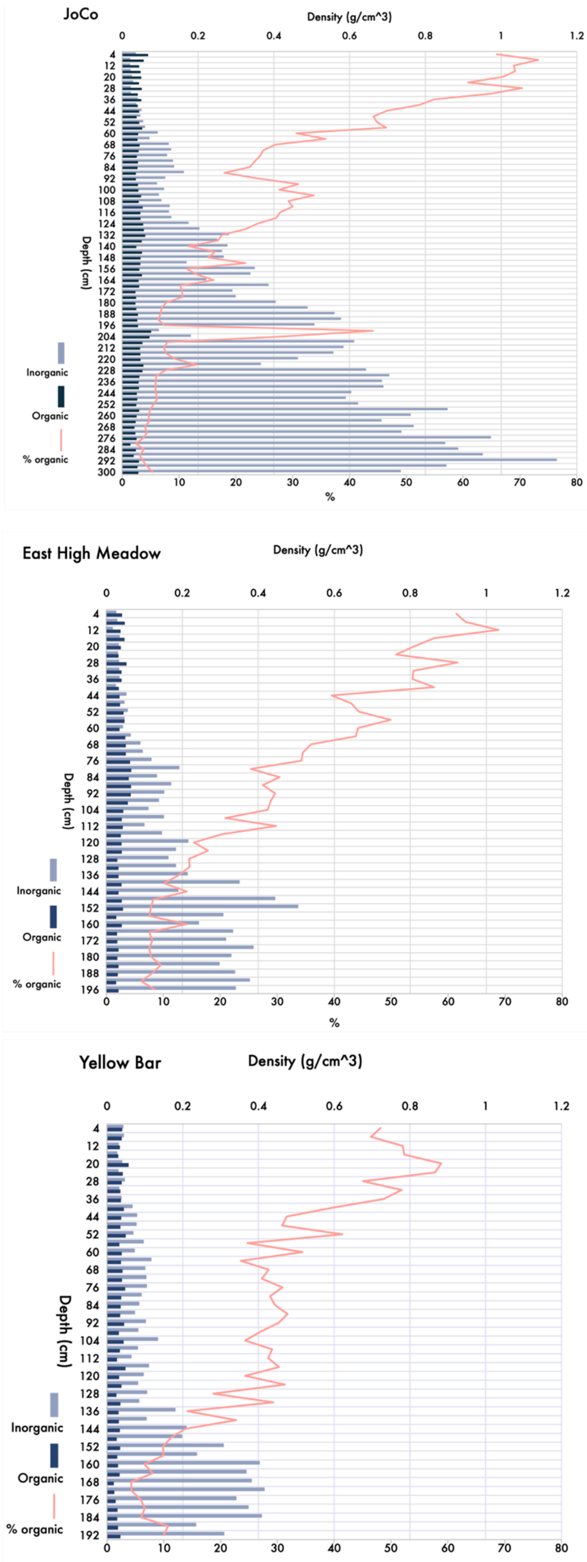

Fig. 2. Loss-on-ignition (LOI) analyses (pink curve) show the percentage of organic material based on the density of inorganic (light blue) and organic content (dark blue) by depth. a) Upper three meters of JoCo Marsh, b) upper two meters of Yellow Bar Marsh, and c) upper two meters of East High Meadow Marsh. Adapted from data published in [35]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Satellite images of Jamaica Bay marshes in 1984 (a) and 2019 (b) used for area calculations, demonstrating marsh loss. Source: Google Earth Pro, Landsat and Copernicus.

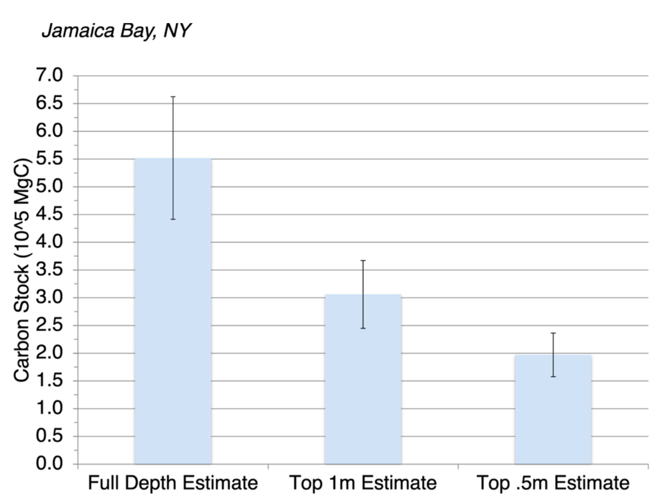

Fig. 4. Carbon stock estimates (E5 MgC) for Jamaica Bay marshes based on depth.

the top 0.5 m estimate was 36% of the full-depth estimate. Via a two-sample z-test, the full-depth value was found to be significantly greater than both partial depth estimates ($p < 0.05$). The differences between the full depth value and the partial depth values (2.5×10^2

MgC greater than the 1 m estimate, $3.6x10^2$ MgC greater than the 0.5 m estimate) are an order of magnitude greater than the interspatial variability in the data from calculating carbon stocks using the different sediment cores (which have a maximum variability of $8.6x10^1$ MgC between cores). This demonstrates the extent to which full-depth estimates provide substantial variability compared to partial-depth estimates.

A decline in carbon stock estimate was found for both 1984 and 2019 (see Fig. 5). Between 1885 and 1984, the carbon stock estimates declined 91% from $9.4x10^6$ MgC to $8.6x10^5$ MgC, with $5.7x10^6$ MgC estimated to have become labile in the process. From 1984 to 2019, carbon stock estimates declined another 35% to $5.5x10^5$ MgC, with $2.0x10^5$ MgC estimated to have become labile. During the full timeframe from 1885 to 2019, carbon stocks declined 94% with $5.9x10^6$ MgC estimated to have become labile during marsh loss. Error bars in Figs. 4 and 5 include the uncertainty from the LOI conversion factor range in [11] and the rate of disturbed carbon that becomes labile upon marsh loss based on values in the literature [42,41]. Even with margins of error, carbon stock estimates between each historical estimate were distinct.

The majority of the loss of thousands of years of sequestered carbon in Jamaica Bay between 1885 and 1974 are directly and indirectly caused by anthropogenic disturbance—namely, dredging, the construction of John F. Kennedy Airport, and construction in Queens and Brooklyn [17,4], as well as sea level rise. In the decades since, research has suggested that salt marsh accretion along the Hudson River will outpace sea level rise, preventing marsh area loss [45]. However, because most of these methodologies rely on short-term accumulation rates and do not account for the long-term decomposition and compression of peat over time, they overestimate long-term marsh accretion rates and underestimate projected marsh loss [47]. Determining previous marsh loss as well as the original and present carbon stocks of the marshes are necessary to determine how they have and will continue to impact the carbon cycle. Sea level rise and climate change have also exacerbated extreme weather events, such as Hurricane Sandy, which alone may have caused up to 3 cm of marsh loss in Jamaica Bay [25]. Due in part to accelerating climate change, Jamaica Bay is estimated to have lost almost double as much area in the 1990 s as it did in the previous four decades. By 2006, one study estimated 90% of Jamaica Bay's original area had been lost, with an average loss of 18 ha/yr [19]. However, other estimates show much lower rates, such as an average loss of 2.1 ha/yr from 2003 to 2013[7]. Marsh loss has been offset by some restoration efforts (Messaros et al., 2012), but the wide range in estimates of loss warrant further investigation to constrain a wide range of uncertainty in carbon loss.

Discussion

The carbon stocks found using these methods are relevant to local and global considerations of carbon cycling. The carbon loss seen at Jamaica Bay between 1885 and 2019 (96%) outpaces the average rate of wetland loss in the state of New York as well as the United States from 1780 to 1980[13]. A model-based approach to estimating Jamaica Bay's present and mid-1870 s marsh areas found a comparable historical value (61 km^2 compared to this study's 65 km^2), but substantially higher present value (15 km^2 compared to this study's 4 km^2)[33]. Compared to a .6m-deep carbon stock estimate of a New Jersey salt marsh with high anthropogenic disturbance, our results had a carbon density almost a full order of magnitude larger (159 MgC/ha compared to our 1560 MgC/ha), illustrating the potential for deep salt marshes to contain much more carbon than existing partial-depth estimates may predict [3]. The amount of carbon estimated to have become labile during this timeframe ($5.9x10^6$ MgC) is equivalent to the annual carbon emissions of roughly 4.5 million average US cars, demonstrating the extent to which considering Blue Carbon storage and loss is relevant to the global carbon system and accounting for emissions sources [18].

Important limitations of this study include possible horizontal inhomogeneity of the peat, which would make our cores unrepresentative of the marsh islands that may have differing carbon content at depth. To account for this, we utilized data from three recent cores that presented similar trends, and the similar elevation argues for similar growth patterns throughout. However, more extensive probing would have to be completed to further validate carbon stock estimates here. Further full-depth carbon stock assessments of salt marshes are needed in order to determine the extent to which partial-depth measurements could be skewing our understanding of global salt marsh carbon stocks. Additional studies may also assess above ground carbon stocks to see a more complete picture of full ecosystem carbon storage; however, 95% of salt marsh carbon is stored in soils [1].

We find that full-depth carbon stocks were severely *underestimated* using the top .5m and 1 m methodology. The potential for full-depth estimates to increase global carbon stock estimates as well as the role

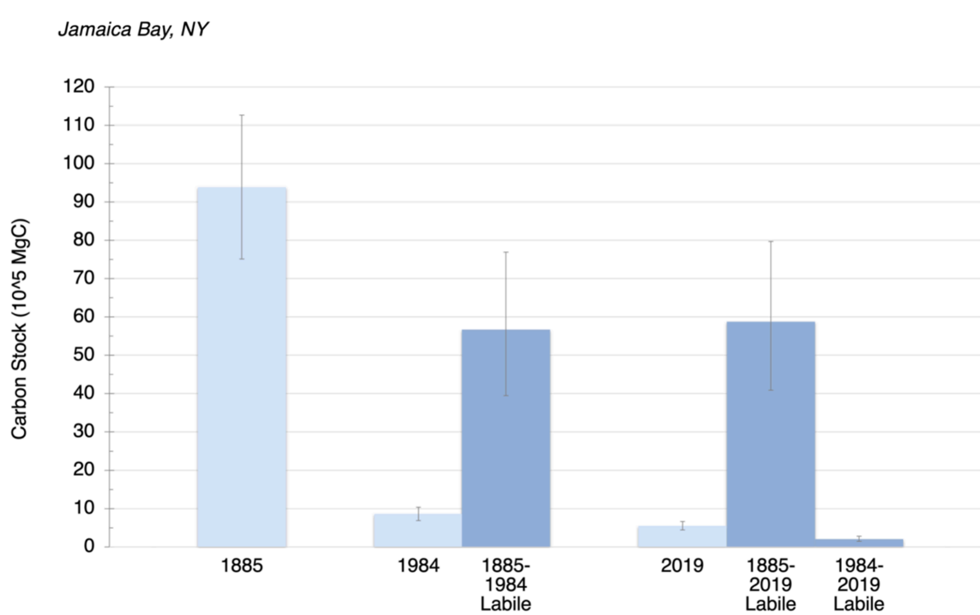

Fig. 5. Carbon stock and carbon stock loss estimates (E5 MgC) for Jamaica Bay marshes based on areal extent in 1885 (as estimated by [6], 1984, and 2019.

that we ascribe to them as potential positive feedback loops is also supported by various studies looking at the upper 1–2 m of marsh sediment. These studies found that carbon content is highest below 1 m and the CO_2 production increase upon aeration was 4x higher at 0.9–1 m than at the surface [43,40]. Both of these studies explicitly emphasize the importance of performing deeper analyses on coastal wetland carbon and its loss. The average depths of the marshes in this study are greater than 1 m, which is much deeper than previously studied salt marshes in New Brunswick and Maine by van Ardenne et al. [2]. Other studies corroborate that carbon is often stored in marshes at depths greater than 1 m [37,36,16,26]. Only a full depth study can reliably quantify an individual marsh's carbon stock because salt marshes are so variable in depth. Because global average estimates of salt marsh carbon stocks are based on partial depth estimates, we recommend future work exploring the impact full-depth methodologies have on global salt marsh carbon stock estimates. In some cases, these riverine marshes may be transitioning from freshwater or brackish to saltwater as time progresses, potentially shifting the carbon content.

In addition to resolving carbon content with depth, the rate of carbon that becomes labile upon disturbance and sea level rise is important to define. Limited and varying data leave wide ranges of uncertainty for our CO2 emissions due to marsh loss. Furthermore, a new study analyzing the top 2 m of marsh sediment has demonstrated that the rate of carbon that becomes labile with marsh loss varies with depth [40]. Thus, it is important for future studies to focus not only on full depth carbon stocks and rates of carbon loss, but also on the varying rates of carbon loss with depth through the peat profile as marshes degrade and erode. Analysis of the eroded organic matter into water suggests that disturbed carbon is largely not resettling as buried sediment [32,50,21]. It is logistically challenging to identify the source of organic matter in estuary waters, and similarly, the fate of carbon from eroded marshes [21]and, wide ranges exist in the limited literature quantifying this rate of carbon loss. New analyses will be needed to reliably constrain the uncertainty of the fate of lost marsh carbon.

Conclusions

Full-depth carbon stock studies of salt marshes are virtually nonexistent despite the fact they often sequester carbon several meters deep and are among the most efficient ecosystems at doing so per unit area. This study conducts full-depth carbon stock estimates of salt marshes in the estuary of Jamaica Bay, NY. Our results show the importance of full-depth methodologies, as the full-depth methodology estimates were between 1.8 and 2.8 times that of the partial-depth methodology estimates. We estimate full-depth carbon stock average value calculation for Jamaica Bay marshes using area cover from 1885 ($9.4x10^6$ MgC), 1984 ($8.6x10^5$ MgC), and 2019 ($5.5x10^5$ MgC), showing a 95% loss of carbon stock during this 134-year period. With this information, earth system models may incorporate salt marsh carbon reservoirs into their projections for the global carbon cycle. These carbon stocks represent a critical part of the dynamic global carbon cycle that will play a role in and be affected by climate change, and thus highlight the need for revised methodologies and policies that reflect this role.

CRediT authorship contribution statement

Grant Pace: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Dorothy Peteet:** Conceptualization, Investigation, Resources, Supervision, Writing – review & editing. **Molly Dunton:** Formal analysis, Investigation, Project administration, Visualization, Writing – review & editing. **Carol Wang-Mondaca** Investigation, Visualization, Writing – review & editing. **Syed Ismail:** Investigation, Writing – original draft. **John Supino:** Investigation, Writing – review & editing. **Jonathan Nichols:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Alongi DM. Carbon Balance in Salt Marsh and Mangrove Ecosystems: A Global Synthesis. J Marine Sci Eng 2020;8:767. https://doi.org/10.3390/jmse8100767.

[2] van Ardenne LB, Jolicoeur S, Bérubé D, Burdick D, Chmura GL. High resolution carbon stock and soil data for three salt marshes along the northeastern coast of North America. Data in Brief 2018;19:2438–41. https://doi.org/10.1016/j.dib.2018.07.037.

[3] Artigas, F., Shin, J.Y., Hobble, C., Marti-Donati, A., Schäfer, K.V.R., and Pechmann, I., 2015, Long term carbon storage potential and CO 2 sink strength of a restored salt marsh in New Jersey: Agricultural and Forest Meteorology, v. 200, p. 313–321, doi:10.1016/j.agrformet.2014.09.012.

[4] Black, F., 1981, Jamaica Bay: A history, Gateway National Recreation Area, New York-New Jersey, Historic Resources Study.: Washington, DC: US Department of Interior, National Park Service, North Atlantic Regional Office, Division of Cultural Resources,.

[5] Bulseco AN, Giblin AE, Tucker J, Murphy AE, Sanderman J, Hiller-Bittrolff K, et al. Nitrate addition stimulates microbial decomposition of organic matter in salt marsh sediments. Glob Change Biol 2019;25(10):3224–41. https://doi.org/10.1111/gcb.v25.1010.1111/gcb.14726.

[6] Cahoon DR, Lynch JC, Roman CT, Schmit JP, Skidds DE. Evaluating the Relationship Among Wetland Vertical Development, Elevation Capital, Sea-Level Rise, and Tidal Marsh Sustainability. Estuaries Coasts 2019;42(1):1–15. https://doi.org/10.1007/s12237-018-0448-x.

[7] Campbell, A., Wang, Y., Christiano, M., and Stevens, S., 2017, Salt Marsh Monitoring in Jamaica Bay, New York from 2003 to 2013: A Decade of Change from Restoration to Hurricane Sandy: Remote Sensing, v. 9, p. 131, doi:10.3390/rs9020131.

[8] Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochem Cycles 2003;17(4). https://doi.org/10.1029/2002GB001917. n/a n/a.

[9] Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, et al. Changes in the global value of ecosystem services. Global Environ Change 2014;26:152–8. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

[10] Coverdale, T.C., Brisson, C.P., Young, E.W., Yin, S.F., Donnelly, J.P., and Bertness, M.D., 2014, Indirect Human Impacts Reverse Centuries of Carbon Sequestration and Salt Marsh Accretion (J. G. Hiddink, Ed.): PLoS ONE, v. 9, p. e93296, doi:10.1371/journal.pone.0093296.

[11] Craft CB, Seneca ED, Broome SW. Loss on Ignition and Kjeldahl Digestion for Estimating Organic Carbon and Total Nitrogen in Estuarine Marsh Soils: Calibration with Dry Combustion. Estuaries 1991;14(2):175. https://doi.org/10.2307/1351691.

[12] Dahl, T.E., 2011, Status and Trends of Wetlands in the Conterminous United States 2004 to 2009: U.S. Department of the Interior, U.S. Fish and Wildlife Service, Fisheries and Habitat Conservation, 112 p.

[13] Dahl, T.E., 1990, Wetlands losses in the United States, 1780's to 1980's: U.S. FIsh and WIldlife Services.

[14] Dean Jr WE. Determination of Carbonate and Organic Matter in Calcareous Sediments and Sedimentary Rocks by Loss on Ignition: Comparison With Other Methods: SEPM. J Sediment Res 1974;v. Vol. 44. https://doi.org/10.1306/74D729D2-2B21-11D7-8648000102C1865D.

[15] Deegan LA, Johnson DS, Warren RS, Peterson BJ, Fleeger JW, Fagherazzi S, et al. Coastal eutrophication as a driver of salt marsh loss. Nature 2012;490(7420):388–92. https://doi.org/10.1038/nature11533.

[16] Engelhart, S., Horton, B., and Kemp, A., 2011, HOLOCENE SEA-LEVEL CHANGES ALONG THE UNITED STATES' ATLANTIC COAST: Oceanography, v. 24, p. 70–79, doi:10.5670/oceanog.2011.28.

[17] Englebright, S., 1975, Jamaica Bay: A case study of geo-environmental stress., in Guidebook to field excursions con-ducted at the 47th meeting of the New York State Geological Association, Syracuse, New York Geological Association, p. 279–298.

[18] EPA, 2019. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017, Chapter 3 (Energy), Tables 3-13, 3-14, and 3-15. Environmental Protection Agency, Washington, D.C. EPA #430-R-19-001.

[19] Frame, G.W., Mellander, K.M., and Adamo, D.A., 2006, Big Egg Marsh Experimental Restoration in Jamaica Bay, New York: Harmon, David, ed. 2006.

People, Places, and Parks: Proceedings of the 2005 George Wright Society Conference on Parks, Protected Areas, and Cultural Sites. Hancock, Michigan: The George Wright Society., p. 123–130.
[20] Gornitz V, Couch S, Hartig EK. Impacts of sea level rise in the New York City metropolitan area. Global Planet Change 2001;32(1):61–88. https://doi.org/10.1016/S0921-8181(01)00150-3.
[21] Haywood BJ, Hayes MP, White JR, Cook RL. Potential fate of wetland soil carbon in a deltaic coastal wetland subjected to high relative sea level rise. Sci Total Environ 2020;711:135185. https://doi.org/10.1016/j.scitotenv.2019.135185.
[22] Holmquist JR, Windham-Myers L, Bliss N, Crooks S, Morris JT, Megonigal JP, et al. Accuracy and Precision of Tidal Wetland Soil Carbon Mapping in the Conterminous United States. Sci Rep 2018;8(1). https://doi.org/10.1038/s41598-018-26948-7.
[23] Holmquist JR, Brown LN, MacDonald GM. Localized Scenarios and Latitudinal Patterns of Vertical and Lateral Resilience of Tidal Marshes to Sea-Level Rise in the Contiguous United States: Earth's. Future 2021;9. https://doi.org/10.1029/2020EF001804.
[24] Houghton RA. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus B Chem Phys Meteorol 2003;55(2):378–90. https://doi.org/10.3402/tellusb:v55i2.16764.
[25] Hu, K., Chen, Q., Wang, H., Hartig, E.K., and Orton, P.M., 2018, Numerical modeling of salt marsh morphological change induced by Hurricane Sandy: Coastal Engineering, p. 63–81.
[26] Kauffman JB, Giovanonni L, Kelly J, Dunstan N, Borde A, Diefenderfer H, et al. Total ecosystem carbon stocks at the marine-terrestrial interface: Blue carbon of the Pacific Northwest Coast, United States. Global Change Biol 2020;26(10): 5679–92. https://doi.org/10.1111/gcb.v26.1010.1111/gcb.15248.
[27] Kauffman JB, Heider C, Cole TG, Dwire KA, Donato DC. Ecosystem Carbon Stocks of Micronesian Mangrove Forests. Wetlands 2011;31(2):343–52. https://doi.org/10.1007/s13157-011-0148-9.
[28] Lamptey BL. Simulation of the relative impact of land cover and carbon dioxide to climate change from 1700 to 2100. J Geophys Res 2005;110:D20103. https://doi.org/10.1029/2005JD005916.
[29] Lovelock CE, Atwood T, Baldock J, Duarte CM, Hickey S, Lavery PS, et al. Assessing the risk of carbon dioxide emissions from blue carbon ecosystems. Front Ecol Environ 2017;15(5):257–65. https://doi.org/10.1002/fee.2017.15.issue-510.1002/fee.1491.
[30] Mcleod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, et al. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front Ecol Environ 2011;9(10):552–60. https://doi.org/10.1890/110004.
[31] Mitsch WJ, Hernandez ME. Landscape and climate change threats to wetlands of North and Central America. Aquat Sci 2013;75(1):133–49. https://doi.org/10.1007/s00027-012-0262-7.
[32] Najjar RG, Herrmann M, Alexander R, Boyer EW, Burdige DJ, Butman D, et al. Carbon Budget of Tidal Wetlands, Estuaries, and Shelf Waters of Eastern North America. Global Biogeochem Cycles 2018;32(3):389–416. https://doi.org/10.1002/gbc.v32.310.1002/2017GB005790.
[33] Orton PM, Sanderson EW, Talke SA, Giampieri M, MacManus K. Storm tide amplification and habitat changes due to urbanization of a lagoonal estuary. Nat Hazards Earth Syst Sci 2020;20:2415–32. https://doi.org/10.5194/nhess-20-2415-2020.
[34] Pendleton, L. et al., 2012, Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems (S. Thrush, Ed.): PLoS ONE, v. 7, p. e43542, doi:10.1371/journal.pone.0043542.
[35] Peteet DM, Nichols J, Kenna T, Chang C, Browne J, Reza M, et al. Sediment starvation destroys New York City marshes' resistance to sea level rise. Proc Natl Acad Sci 2018;115(41):10281–6. https://doi.org/10.1073/pnas.1715392115.
[36] Peteet D, Nichols J, Pederson D, Kenna T, Chang C, Newton B, et al. Climate and anthropogenic controls on blue carbon sequestration in Hudson River tidal marsh Piermont, New York. Environ Res Lett 2020;15(6):065001. https://doi.org/10.1088/1748-9326/ab7a56.
[37] Peteet DM, Pederson DC, Kurdyla D, Guilderson T. Hudson River paleoecology from marshes: environmental change and its implications for fisheries. Am Fish Soc Symp 2006;51:113.
[38] Reichert BK. Global ocean warming tied to anthropogenic forcing. Geophys Res Lett 2002;29:1525. https://doi.org/10.1029/2001GL013954.
[39] Sallenger AH, Doran KS, Howd PA. Hotspot of accelerated sea-level rise on the Atlantic coast of North America: Nature. Clim Change 2012;2(12):884–8. https://doi.org/10.1038/nclimate1597.
[40] Sapkota Y, White JR. Long-term fate of rapidly eroding carbon stock soil profiles in coastal wetlands. Sci Total Environ 2021;753:141913. https://doi.org/10.1016/j.scitotenv.2020.141913.
[41] Sapkota Y, White JR. Marsh edge erosion and associated carbon dynamics in coastal Louisiana: A proxy for future wetland-dominated coastlines world-wide: Estuarine. Coastal Shelf Sci 2019;226:106289. https://doi.org/10.1016/j.ecss.2019.106289.
[42] Steinmuller HE, Chambers LG. Characterization of coastal wetland soil organic matter: Implications for wetland submergence. Sci Total Environ 2019;677: 648–59. https://doi.org/10.1016/j.scitotenv.2019.04.405.
[43] Steinmuller HE, Dittmer KM, White JR, Chambers LG. Understanding the fate of soil organic matter in submerging coastal wetland soils: A microcosm approach. Geoderma 2019;337:1267–77. https://doi.org/10.1016/j.geoderma.2018.08.020.
[44] Sulej AM, Polkowska Ż, Namieśnik J. Pollutants in Airport Runoff Waters. Crit Rev Environ Sci Technol 2012;42(16):1691–734. https://doi.org/10.1080/10643389.2011.569873.
[45] Tabak, N.M., Laba, M., and Spector, S., 2016, Simulating the Effects of Sea Level Rise on the Resilience and Migration of Tidal Wetlands along the Hudson River (M. (Gee) G. Chapman, Ed.): PLOS ONE, v. 11, p. e0152437, doi:10.1371/journal.pone.0152437.
[46] Theuerkauf EJ, Stephens JD, Ridge JT, Fodrie FJ, Rodriguez AB. Carbon export from fringing saltmarsh shoreline erosion overwhelms carbon storage across a critical width threshold: Estuarine. Coastal Shelf Sci 2015;164:367–78. https://doi.org/10.1016/j.ecss.2015.08.001.
[47] Törnqvist TE, Jankowski KL, Li Y-X, González JL. Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. Sci Adv 2020;6(21):eaaz5512. https://doi.org/10.1126/sciadv.aaz5512.
[48] Turner RE. Beneath the Salt Marsh Canopy: Loss of Soil Strength with Increasing Nutrient Loads. Estuaries Coasts 2011;34(5):1084–93. https://doi.org/10.1007/s12237-010-9341-y.
[49] U.S. Fish and Wildlife Services National Wetlands Inventory: National Wetlands Inventory Wetlands Mapper, https://www.fws.gov/wetlands/Data/Mapper.html.
[50] Vaccare J, Meselhe E, White JR. The denitrification potential of eroding wetlands in Barataria Bay, LA, USA: Implications for river reconnection. Sci Total Environ 2019;686:529–37. https://doi.org/10.1016/j.scitotenv.2019.05.475.
[51] Verhoeven J, Arheimer B, Yin C, Hefting M. Regional and global concerns over wetlands and water quality. Trends Ecol Evol 2006;21(2):96–103. https://doi.org/10.1016/j.tree.2005.11.015.
[52] Welk, R.J., Defne, Z., and Ganju, N.K., 2019, Coastal wetlands from Jamaica Bay to western Great South Bay, New York: U.S. Geological Survey, https://doi.org/10.5066/P9GAGLXB.
[53] Wigand C, Roman CT, Davey E, Stolt M, Johnson R, Hanson A, et al. Below the disappearing marshes of an urban estuary: historic nitrogen trends and soil structure. Ecol Appl 2014;24(4):633–49. https://doi.org/10.1890/13-0594.1.
[54] Windham-Myers L, Anderson FE, Bergamaschi BA, Ferner MC, Schile LM, Spinelli G. Annual net ecosystem exchanges of carbon dioxide and methane from a temperate brackish marsh: should the focus of marsh restoration be on brackish environments? AGU Fall Meeting Abstracts 2015;21:B21H–569.
[55] Yin J, Schlesinger ME, Stouffer RJ. Model projections of rapid sea-level rise on the northeast coast of the United States. Nat Geosci 2009;2(4):262–6. https://doi.org/10.1038/ngeo462.
[56] Zeebe RE, Ridgwell A, Zachos JC. Anthropogenic carbon release rate unprecedented during the past 66 million years. Nat Geosci 2016;9(4):325–9. https://doi.org/10.1038/ngeo2681.