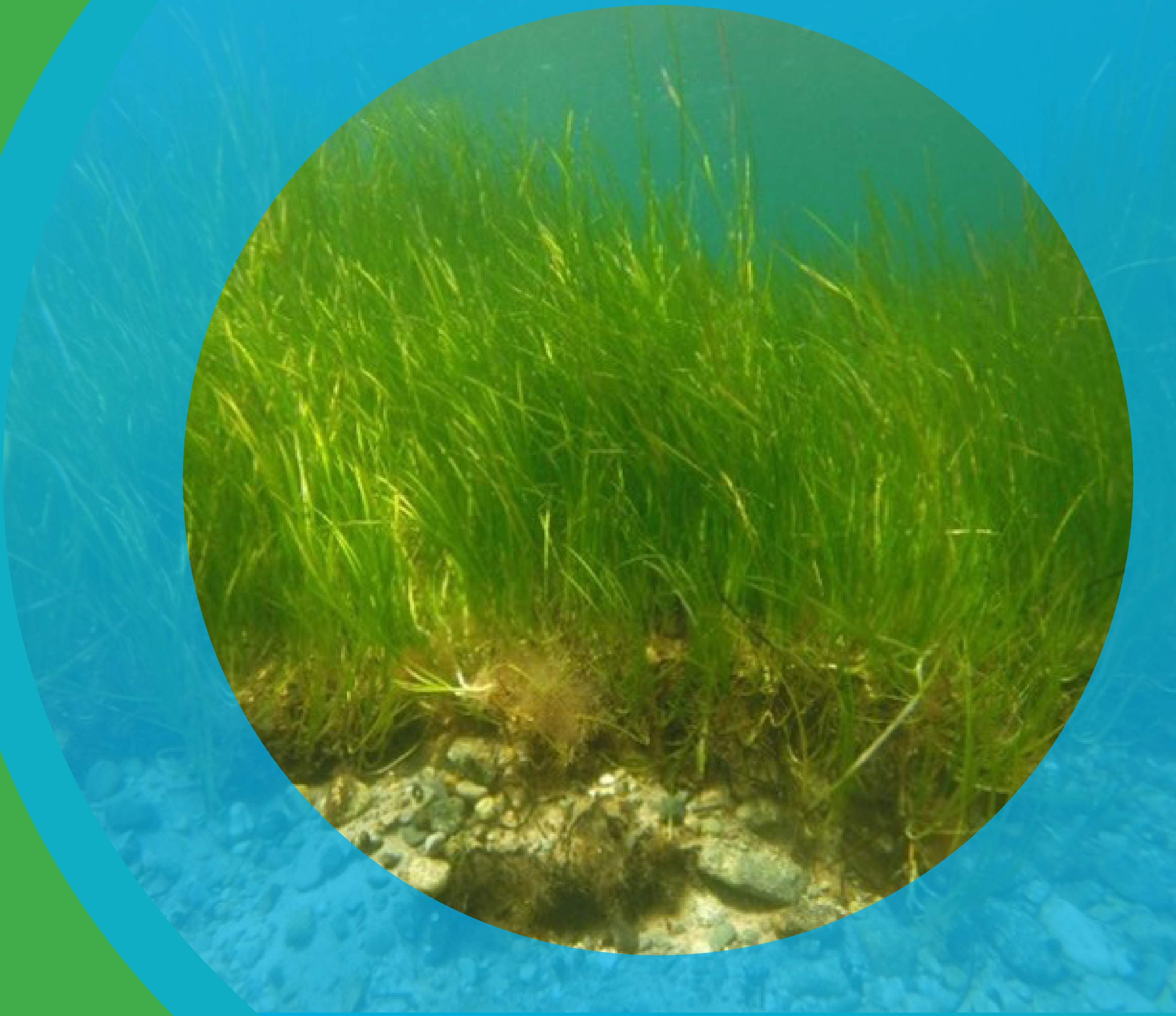

Region 1

The Blue Carbon Reservoirs from Maine to Long Island, NY

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www.epa.gov/region1

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The Blue Carbon Reservoirs from Maine to Long Island, NY

(cover photos: eelgrass bed, Phil Colarusso)

This document reflects the efforts and results of the Blue Carbon Reservoirs from Maine to Long Island, New York Project and New England Blue Carbon Inventory Workgroup, including identification and collection of updated habitat maps for eelgrass beds and salt marshes across New England and calculations for blue carbon stock inventories.

Executive Summary

In response to the New England Governor and Eastern Canadian Premier 2017 Climate Change Action Plan recommendation to "manage blue carbon resources to preserve and enhance their existing carbon reservoirs," the U.S. Environmental Protection Agency (EPA) convened a New England Blue Carbon Inventory Workgroup, comprised of a variety of federal, state, academic, and non-profit organizations to develop an inventory of blue carbon stocks from Maine to Long Island, New York. The Workgroup focused its inventory efforts on salt marshes and eelgrass meadows, leveraging existing habitat maps for geographic data. Existing data for soil organic carbon stocks were then used to calculate blue carbon stock estimates. For visual display purposes, sediment carbon heat maps were developed to highlight areas of greatest carbon accumulation. The habitat distribution and sediment carbon heat maps can be accessed on the Northeast Ocean Data Portal (**www.northeastoceandata.org/eelgrass**) which is a public source of expert-reviewed, interactive maps and data on the ocean ecosystem, economy, and culture of the northeastern United States and can be used to facilitate decision making by government agencies, tribal nations, businesses, non-governmental organizations (NGOs), academic institutions, and individuals. Based on available data and Workgroup calculations, the target geographic area has an estimated 218,222 acres of eelgrass meadows, salt marsh and saline *Phragmites*, which are estimated to provide a reservoir of 7,523,568 megagrams of blue carbon, or the equivalent to the annual carbon emissions from over 5,944,024 passenger vehicles. Due to data limitations, the carbon stock estimate represents a mere fraction of the actual quantity of accumulated carbon in these habitats. The findings from the Workgroup's efforts and the resulting map products can help inform land and coastal management policies, fisheries management, and climate change mitigation practices. Further refinements and expansion of data are needed, including more detailed habitat maps, deeper soil core data for soil organic carbon content, and inclusion of more marine flora into calculations.

Introduction

Recognizing the urgent need to address climate change, the New England governors (Maine, Vermont, New Hampshire, Massachusetts, Rhode Island, Connecticut) and the premiers of the five eastern Canadian provinces (New Brunswick, Newfoundland and Labrador, Quebec, Nova Scotia and Prince Edward Island) adopted a regional Climate Change Action Plan (CCAP) in 2001. The plan set ambitious greenhouse gas emission reductions goals (10% below 1990 levels by 2020) and looked to reduce climate change impacts by adaptation (Committee on the Environment and the Northeast International Committee on Energy of the Conference of New England Governors and Eastern Canadian Premiers, 2001). In 2015, the governors and premiers signed a resolution to further reduce greenhouse gas emissions to 35-45% below 1990 levels by 2030 (39^{th} Annual Conference of New England Governors and Eastern Canadian Premiers, 2015).

To achieve these ambitious goals, the governors and premiers recognized that better management of natural resources and habitats that function as carbon sinks would be required. In 2017, they published an update to the CCAP, which identified the need to "manage blue carbon resources to preserve and enhance their existing carbon reservoirs" (Conference of the New England Governors and Eastern Canadian Premiers, 2017).

Seagrasses, salt marshes, and mangroves are the aquatic habitats most commonly associated with the term blue carbon, which is the carbon sequestered in vegetated coastal habitats. All plants accumulate carbon through their normal growth processes, but these three habitats can sequester carbon in the sediments for decades to centuries (McLeod et al., 2011). Salt marsh sediments accumulate carbon largely from decaying plant tissue generated within the marsh, with a lesser contribution from detritus transported and deposited during tidal flow (Vincent et al. 2014; Burdick et al. 1996). In contrast, sediment carbon accumulation in eelgrass meadows is largely driven by allochthonous sources (Novak et al., 2020). Mangroves do not occur in the northeastern US, so this study considered only seagrass and salt marshes.

This study is an initial effort to provide a quantitative baseline of the existing blue carbon reservoirs for the geographic region spanning the northernmost point in Maine to the southern shores of Long Island, New York.

A diverse group of scientists from various federal and state agencies and academia graciously volunteered their time, expertise, and data to help construct the databases necessary to generate the baseline estimates of blue carbon reservoirs. A small grant from the United States Environmental Protection Agency (US EPA) provided the resources to access staff from the Northeast Regional Ocean Council with expertise in management of large datasets and generation of high-resolution mapping products.

Seagrass

In In the cold temperate waters of New England, only two species of seagrass are currently found, eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*). Quantitative data on widgeon grass distribution and acreage is very limited. Its diminutive size makes it easily overlooked by standard seagrass mapping techniques, such as aerial photointerpretation or acoustic surveys. Anecdotal observations suggest that widgeon grass distribution is likely increasing in New England. While recognizing this potential increase, widgeon grass likely comprises less than 2-3% of the total seagrass area in New England. Thus, this study considers only eelgrass in the calculation of the seagrass contribution to the carbon reservoirs.

In New England waters, eelgrass can be found from the shallow subtidal to generally around 5-6 meters (m) at mean low water (MLW). At more northern latitudes (New Hampshire north), it can be found intertidally and in exceptionally clear water it might be found as deep 7-8 m MLW. It generally occurs in protected, quiescent waters, but can grow in areas of high currents and moderate exposure. Eelgrass occurs as small, isolated patches consisting of a few plants to large expansive meadows (Figure 1) hundreds of hectares in size.

Eelgrass meadows serve numerous critical ecological functions. Several studies have demonstrated the important habitat function of eelgrass in New England. Heck et al. (1989) trawled eelgrass meadows on Cape Cod, Massachusetts (MA) and collected 22 fish species and eight decapod crustacean species. Fish collected represented all life stages, supporting the nursery role of eelgrass. Chandler et al. (1996) sampled eelgrass meadows from Boston, MA to Gloucester, MA using minnow traps, gill nets and visual diver surveys. They recorded 33 different fish species. Lazzari (2002) sampled eelgrass meadows in Casco Bay, Maine (ME) with a beam trawl, collecting 17 species of fish and species of decapod crustaceans. Much of his catch was dominated by young-of-the-year and juvenile life stages, highlighting the important nursery function eelgrass meadows play.

Seagrasses are prolific primary producers that support the coastal food web by providing food for herbivores or through the detrital pathway (Duarte and Krause-Jensen, 2017). In New England, Roman et al. (1990) measured annual aboveground production rates of 444-987 g/m^2 in an eelgrass meadow on Cape Cod. They found eelgrass production rates to be roughly equivalent to, or greater than, the production rates in an adjacent salt marsh dominated by cordgrass (*Spartina alterniflora*). Beal et al. (2004) measured primary production rates of 69-365 g/m^2 for eelgrass meadows in Cobscook Bay, ME. Colarusso (2006) measured primary production rates of 252-789 g/m^2 in a meadow in Nahant, MA.

Eelgrass meadows reduce coastal erosion by dampening wave energy and stabilizing sediments (Nepf, 1999, Fonseca et al., 2019). The aboveground vegetative canopy absorbs wave energy, while the root and rhizome structures provide stability for the sediments. Nepf (1999) measured and modeled reductions in turbulence and bed sheer within the canopy of a vegetated meadow. Fonseca et al. (2019) examined how shoot densities, meadow formation and pliability of the shoots could impact turbulence reduction. Ricart et al. (2021) also suggests that seagrass meadows can locally alleviate low pH conditions for extended periods of time with important implications for the conservation and management of coastal ecosystems and possible localized amelioration of ocean acidification.

Until recently, the ability of seagrasses to accumulate and sequester carbon was overlooked. Duarte et al. (2005) described the role seagrasses play in the oceanic carbon cycle. Fourqurean et al. (2012) used a global review of published studies to calculate the global importance of seagrass carbon sequestration. This global review also documented the lack of data in many geographic areas. In the northwest Atlantic, no data existed north of Chesapeake Bay. Thus, Novak et al. (2020) filled part of that data gap by collecting samples in eelgrass meadows from Rhode Island to Maine. Currently, very little published research exists on the measured fluxes of greenhouse gases (GHG) (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) into or from seagrass meadows. This lack of available research on GHG exchange in seagrass meadows an important data gap that could be filled to more completely understand the climate mitigation role seagrasses play.

Figure 1: Eelgrass can occur in thick extensive meadows (photo: Phil Colarusso)

Figure 2: Eelgrass build organically rich peat layers below the meadow (photo: Phil Colarusso)

Eelgrass meadows accumulate carbon via two main pathways. The first pathway involves the absorption of carbon from the water column into new plant tissue via photosynthesis and the second is the ultimate deposition of decaying plant tissue (such as old roots, rhizomes and some cast leaves) into the soil below the meadows. The majority of carbon accumulated in sediments is a result of the second pathway. The meadow canopy acts as a baffle, slowing current speeds and enhancing particle deposition (Nepf, 1999; Fonseca et al., 2019). As the tide goes in and out, the meadows promote sedimentation of organic particles from the water column. Stable isotope data of sediments within eelgrass meadows shows the majority of the carbon originates from outside of the meadow (Novak et al. 2020). Once incorporated in the sediments, the carbon can stay isolated for decades or even centuries, as long as the meadow stays intact (Novak et al. 2020).

Particle deposition rates in eelgrass meadows can vary significantly based on proximity to sources of organic particles and hydrology. Meadows existing in quiescent parts of coastal inlets, embayments or lagoons will often have higher carbon accumulation rates, as these water bodies are natural depositional areas (Novak et al. 2020). Meadows existing on open coastline or in areas of strong current tend to have lower carbon accumulation rates, as these locations tend to be erosional by nature (Novak et al. 2020). Over time sediment deposition results in organically rich layers accreting (Figure 2), similar to the peat visible in salt marsh sediments at low tide.

Salt Marsh

Salt marshes are self-sustaining coastal systems consisting of a mosaic of microhabitats and localized hydrologic regimes that develop over thousands of years through a dynamic process involving hydrology, vegetation, soil accretion, and marsh surface elevation gain (Figure 3; Redfield 1972). Common reeds (*Phragmites*) are the common dominant species in the upland edge of salt marshes and in tidally restricted or brackish marshes. Marine sediments and organic debris are delivered to marsh surfaces during daily tidal flow and trapped by salt marsh vegetation. The bulk of organic matter (carbon) is deposited in soils through growth of plant below ground biomass (roots and rhizomes), with additional carbon inputs from above-ground growth from previous growing seasons (Figure 4). This self-maintenance process enables the marsh surface elevation to increase with sea level rise and, in turn, provides favorable conditions for plants to grow, resulting in more carbon deposition and sediment trapping (Morris et al. 2002; Burdick and Roman 2012).

Figure 3a&b. Salt marsh habitat in the Northeastern United States (photos: Rob Vincent)

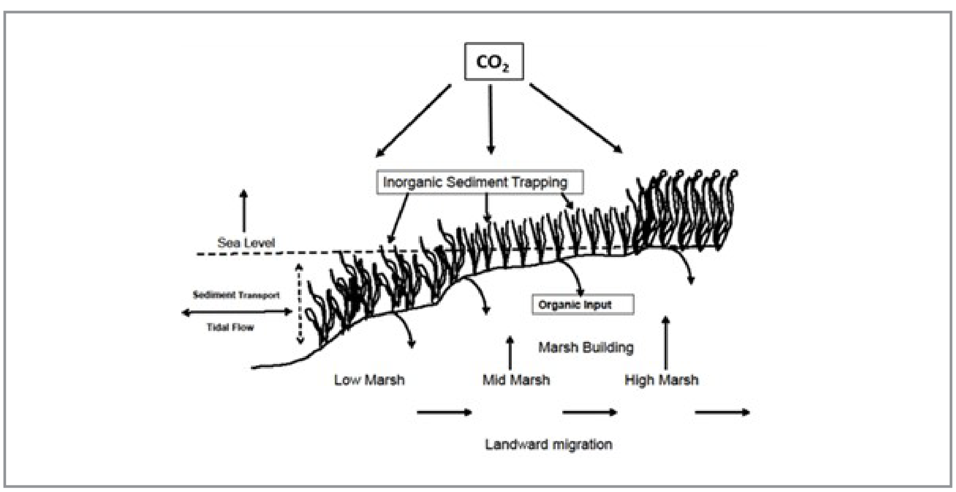

Figure 4. Conceptual model for Salt marsh self-maintenance, carbon sequestration and storage process (Vincent et al., 2013)

The salt marsh self-maintenance process breaks down when marsh accretion rates fail to keep pace with the rate of sea level rise (Morris et al., 2002), resulting in the loss of plant communities and associated carbon accumulation, and loss of long-term carbon storage due to erosion and decomposition over time (Vincent et al., 2013 & 2014).

Salt marshes are important natural carbon sinks that provide climate mitigation benefits if managed for conservation and restoration (Herr et al., 2015; Sutton-Grier and Moore, 2016; Kroeger et al., 2017; Johnson et al., 2018). Healthy marshes are one of the most effective carbon sinks on the planet, sequestering 4-10x more carbon per unit area than upland forests, and can provide approximately ten times the amount of carbon storage found in peatlands (McLeod et al., 2011; Chmura et al., 2003). Marshes that are functioning poorly, on the other hand, can be sources of powerful and harmful greenhouse gases, like methane and nitrous oxide (Moseman-Valtierra et al., 2013; Howard et al., 2014; Figure 5). The bulk of the carbon in a salt marsh is in the soils. On average, approximately 95% of the total carbon measured in salt marshes is found in the upper 1 m of soil, 1% in the above-ground biomass, and 4% in the below-ground biomass (Alongi, 2020).

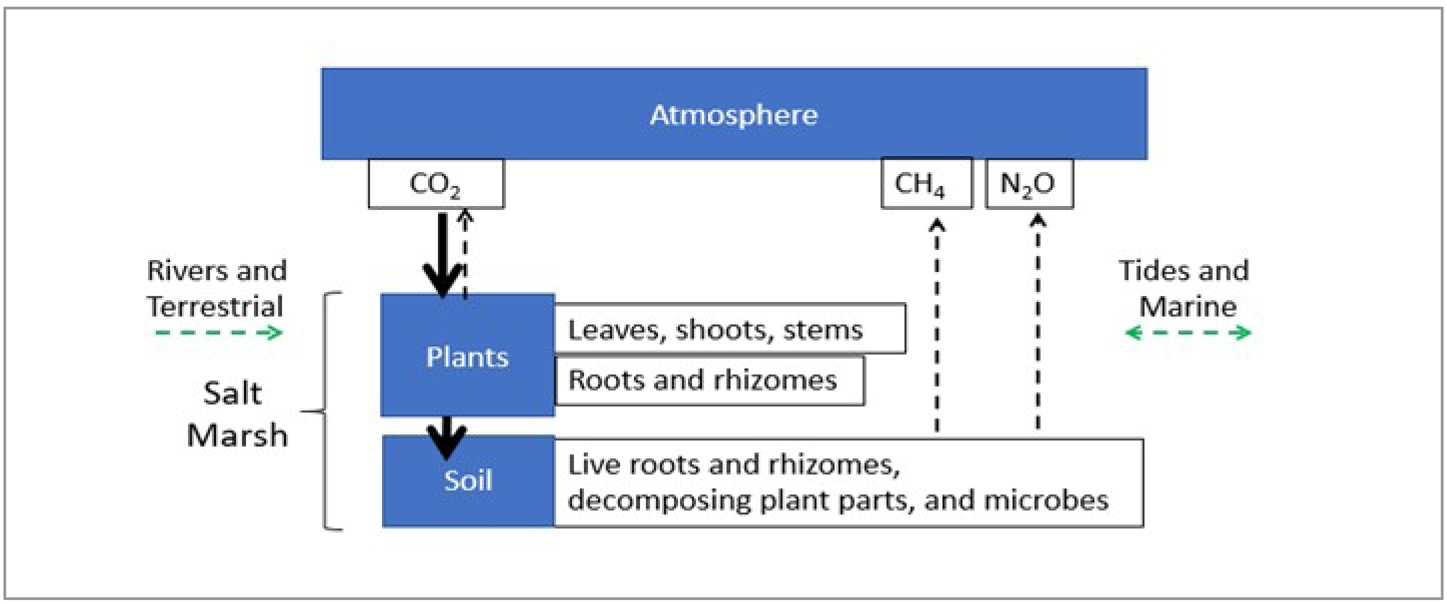

Figure 5: Concept map of carbon flow in salt marsh. The blue boxes represent the major carbon stocks, the bold dark arrows represent the dominant direction of carbon flow in a functioning marsh, and the dashed black lines represent release of carbon and other gasses from the marsh surface. Organic matter is deposited on the marsh from terrestrial inputs and from tidal/estuarine inputs (Johnson et al., 2018).

The atmospheric carbon captured by plants during photosynthesis is deposited and stored in salt marsh sediments as the above-ground (leaves and stems) and below-ground (roots and rhizomes) parts of the plants die off (Figure 6). As a result, plant community type can influence carbon storage in salt marsh sediments and can be useful for spatial analysis of carbon storage estimates (Choi et al., 2001). Wetlands in general are regulated by hydrology, with elevation defining the extent of tidal flow in coastal areas. In salt marshes, plant communities tend to occur in distinct zones determined by elevation, stress tolerance levels, and competitive ability. As a result, elevation, hydrology, and plant zonation, work in combination to influence carbon sequestration and storage in a salt marsh. Therefore, more detailed salt marsh maps characterizing the extent and nature of these three variables are important for generating estimates of coast-wide carbon storage in salt marsh habitat.

Figure 6. A 1m long salt marsh soil core showing plant below-ground biomass and the long-term carbon storage capacity of salt marsh habitat (photo: Beverly Johnson). At an average salt marsh accretion rate of 2.8 mm annually (Goodman et al., 2007), the upper 30 cm core represents approximately 107 years of carbon storage.

As noted above, the primary carbon source in salt marsh habitat is plant material, with hydrology and associated factors regulating plant growth. Climate change effects on sea level rise (such as thermal expansion, glacial melt water, and storm surge from increased storm intensity) can lead to excessive flooding, vegetation loss, and coastal erosion, resulting in loss of habitat and carbon storage over time (Figure 7a). Therefore, the climate mitigating function of salt marsh habitat through sequestration of atmospheric carbon and long-term storage in salt marsh sediments is altered as plant community composition changes in response to climate impacts, providing further support for detailed salt marsh habitat mapping over time. Furthermore, protecting salt marsh habitat, via sediment applications (i.e., thin-layer deposition of dredged or other sediments) and creating marsh mitigation zones (i.e., areas set aside for salt marsh protection), could also mitigate the impacts on current carbon stored in the salt marsh habitats from climate change-related habitat loss.

Figure 7a&b. Sea level rise and storm surge effects on a salt marsh habitat in New England (photos: Rob Vincent)

Methods

Habitat mapping

The first step in deriving a baseline estimate of carbon was to develop a regional estimate of eelgrass and salt marsh distribution. Using publicly accessible maps and underlying data for existing eelgrass meadows and salt marshes, habitat mapping layers were added to the Northeast Ocean Data Portal (**www.northeastoceandata.org/eelgrass**). The Northeast Ocean Data Portal (hereafter referred to as "Portal") is an interactive data and geographic mapping visualization system created and maintained by the Northeast Regional Ocean Council to support various coastal management activities (such as those related to marine life and habitat, aquaculture, marine transportation, energy and infrastructure, water quality, and many others). The compiled data and habitat maps generated from this New England Blue Carbon Inventory effort will continue to reside on this Portal for environmental practitioners to use.

For this analysis, only the most recent coastal vegetation datasets from each state were considered (Table 1). Each dataset is available to download in Geographic Information System (GIS) format via a state GIS database or repository, except for the coastal wetlands data from the Maine Coastal Program and eelgrass data from the Peconic Estuary Partnership.

Eelgrass mapping

Eelgrass distribution maps exist for all states included in this assessment. The maps were created by various state and academic institutions and, as a result, methodologies vary slightly. All eelgrass maps were created using photointerpretation of aerial imagery with varying levels and types of ground-truthing. Over the years, multiple eelgrass distribution maps have been created for most of the New England coastline. The regional composite eelgrass layer on the Portal was updated by obtaining and compiling the most recent eelgrass spatial data from Maine to New York. This process included updating the associated metadata and a review of the maps by the workgroup.

Salt marsh mapping

Due to differences in how wetlands were surveyed (i.e., methods, year) and classified, individual state datasets depicting coastal wetlands throughout the region of interest were not compiled for inclusion on the Portal. However, the Portal was updated using a newer regional tidal marsh dataset derived from remote sensing data via the Saltmarsh Habitat & Avian Research Program (SHARP) (see Table 1). The SHARP data are very high resolution (3-m grid size) and contain multiple vegetation classes: High marsh, Low marsh, Mudflat, *Phragmites*, Pool/Panne, Open water, Terrestrial border, and Upland (Correll et al. 2019).

The SHARP dataset covers the region of interest and extends further south to the eastern shore of Chesapeake Bay. However, the data contained gaps due to missing data in the National Wetlands Inventory data that formed the basis for the SHARP analysis. The largest data gap was in the Buzzards Bay area around New Bedford, MA with smaller data gaps within this state around Boston and on Martha's Vineyard. To fill these gaps, a new interpretation of 2005 marsh habitat information from the Massachusetts Department of Environmental Protection Wetlands dataset, which was produced and released by the United States Geological Survey Coastal and Marine Hazards and Resources Program (2021; Table 1), was included. This interpretation provided a finer scale representation of vegetated versus unvegetated marsh based on high-resolution bathymetry and topography.

Carbon analysis and mapping

There are two primary purposes for conducting carbon analysis and mapping. First, to identify locations where carbon is currently being sequestered by eelgrass meadows and tidal marshes. Second, to provide a quantifiable baseline against which future management actions can measure change. The blue carbon stock datasets for eelgrass meadows and in high and low tidal marsh habitats in Table 2 were identified by the New England Blue Carbon Inventory Workgroup as the most complete and recent data available on the Atlantic Coast.

Table 1. Coastal vegetation datasets identified by the work group.

State	Year	Source	Seagrass metric	Coastal wetlands metric	Database
RI	2016	University of Rhode Island Environmental Data Center	Acres Zostera, Ruppia	N/A	RIGIS
RI	2012	NOAA Office for Coastal Management& Narragansett Bay National Estuarine Research Reserve	N/A	Acres brackish, salt marsh	RIGIS
CT	2017	Connecticut Department of Energy and Environmental Protection	Acres Zostera	N/A	CT DEEP GIS
CT	2010	US Fish & Wildlife Service National Wetlands Inventory	N/A	Acres freshwater, salt marsh	FWS NWI
ME	2018	Maine Department of Environmental Protection	Acres Zostera	N/A	ME Geolibrary
ME	2001-2010	Maine Department of Marine Resources	Acres Zostera	N/A	ME Geolibrary
ME	2013-2014	Maine Natural Areas Program	N/A	Acres freshwater, brackish, salt marsh	ME Natural Areas Program GIS
ME	2013-2014	Maine Coastal Program	N/A	Acres freshwater, salt or brackish marsh	Received from ME Coastal Program via email
NH	2019	New Hampshire Department of Environmental Services & Piscataqua Region Estuary Partnership	Acres Zostera, Ruppia	N/A	UNH Granit
NH	2013	NOAA Office for Coastal Management& Great Bay National Estuarine Research Reserve	N/A	Acres brackish, salt marsh	NH Geodata
MA	2005	Massachusetts Department of Environmental Protection	N/A	Acres freshwater, salt marsh	MassGIS
MA	2010-2019	Massachusetts Department of Environmental Protection & Massachusetts Division of Marine Fisheries	Acres Zostera	N/A	MassGIS
MA	2005	USGS Coastal and Marine Hazards and Resources Program		Acres vegetated salt marsh	Ackerman, K.V., Defne, Z., and Ganju, N.K., 2021, Geospatial Characterization of Salt Marshes for Massachusetts: U.S. Geological Survey data release, https://doi.org/10.5066/P97E086F
NY	2014	Peconic Estuary Partnership	Acres Zostera	N/A	Received from Peconic Estuary Partnership/New England Interstate Water Pollution Control Commission via email
NY	2019	New York Natural Heritage Program	Acres Zostera	Acres freshwater, brackish, salt marsh	gis.ny.gov
ME to VA	2014-2016	Saltmarsh Habitat & Avian Research Program (SHARP)	N/A	Acres high marsh, low marsh, salt pools/pannes, *Phragmites australis*, mudflat, open water, upland, terrestrial border	SHARP website: www.Sciencebase.gov

Table 2. Blue carbon stock datasets.

Source	Number of sites	Vegetation type
Barry et al. 2022	59	Salt marsh, *Phragmites*
Colarusso et al. 2016	5	Eelgrass
Gonneea et al. 2018	11	Salt marsh
Doyle 2018	9	Eelgrass
Johnson et al. 2015	3	Salt marsh
Kulesza 2018	16	Salt marsh
NCSS 2021(a)	25	Salt marsh/eelgrass
NCSS 2021(b)	94	Salt marsh/eelgrass
Novak 2018, 2020	4	Eelgrass
Novak et al 2020	11	Eelgrass
O'Keefe Suttles et al. 2021(a)	10	Salt marsh
O'Keefe Suttles et al. 2021(b)	6	Salt marsh
O'Keefe Suttles et al. 2021(c)	17	Salt marsh
Pickoff 2013	7	Salt marsh
Rohr et al. 2018	1	Eelgrass
Russ 2014	16	Salt marsh
Sonshine 2012	3	Eelgrass
Teng et al. 2022	22	Salt marsh
US EPA 2016	28	Salt marsh
US EPA 2021	26	Salt marsh
Vincent and Dionne 1997	3	Salt marsh
Yellen and Woodruff 2020	7	Salt marsh

Due to the challenges in merging data from multiple sources and variation in sample designs and methodologies between studies, the New England Blue Carbon Inventory Workgroup relied on data with proven QA/QC reviews (USDA, USGS data releases) and published data from peer reviewed journal articles. In a small number of cases where geographic coverage was lacking, unpublished data were considered. In those cases, methodology, variability, and data range of each study were reviewed before inclusion in the dataset. Data outliers and obviously erroneous values were excluded.

For inclusion in the dataset, ideally samples needed geographic positional system (GPS) coordinates from where they were taken, and percent organic carbon and dry bulk density measurements. Some studies had large numbers of cores with the same GPS coordinates for their location, in which case those cores were treated as replicates and averaged to calculate a single mean for inclusion into the dataset. For a limited number of samples that did not have GPS coordinates available, the data was included in the analysis if it did have a specific marsh identified. Finally, for a small number of samples that did not measure dry bulk density, the modeled relationship between dry bulk density and percent carbon from the rest of the dataset was calculated and the strong correlation ($R^2 = 0.82$) was used to fill the gaps (Appendix A). This approach and result are consistent with other peer reviewed literature (Morris et al. 2016). In total, 189 site points were included in the analysis: 114 points within salt marsh; 40 within *Phragmites* and 35 within eelgrass providing good coverage of the geographic region (Appendix B).

Methods (continued)

The distributions of measured bulk density (Bd) and organic carbon (OC) were not normal. As a result, the distribution of OC stock density (g OC cm^{-3}) and concentration (kg m^{-2}) were also not normally distributed and were log transformed before analysis. Mean comparisons were performed based on Tukey's Honest Significant Difference (HSD) test, which is more robust for multiple comparisons using the variance (pooled variance) from the entire dataset.

For this analysis, the available data allowed for the calculation of carbon stocks to a depth of 30 cm. Carbon stocks in these systems extend much deeper, however the project scope was restricted by the available data. Certainly, in many of these habitats, the accumulated peat layer extends several meters. Each sediment core was subsampled at varying depth intervals over the full 30 cm horizon. For carbon stock values, a comparison between the summation of each of the individual depth intervals versus a mean value over the full 30 cm was completed. Each approach produced nearly identical results (Appendix C) suggesting that sediment core depth was not a significant source of variation. Latitudinal variation was analyzed and did not produce any significant sources of variation. Vegetation type did produce significant differences in sediment carbon density. Three sources of vegetation type showed significant differences in sediment carbon density; these were marsh, eelgrass and *Phragmites*. The marsh category included a variety of salt marsh vegetation types, such as low and high salt marsh. Data variability did not warrant any further refinement of the marsh category.

To calculate carbon stock totals, the mean sediment carbon density (g/cm^3) for eelgrass, salt marsh and *Phragmites* were used and extrapolated up to the total acreage for each habitat per state. Working from this small scale to the regionwide scale can result in different estimates due to the rounding off of numbers in the calculations.

To create a "heat map" effect, the relevant mean carbon stock values were applied to every grid cell where eelgrass, salt marsh, or *Phragmites* were present, and then a moving window procedure was used to calculate the sum of carbon stocks within a 3 x 3 grid cell window. The process highlights areas where the distribution of coastal habitats may result in locally large and/or dense carbon stocks.

Four blue carbon data products were produced and added to the Portal. Each layer represented mean blue carbon stocks as mega-grams (equivalent to metric tons) of carbon per 30 m x 30 m grid cell:

- Eelgrass Meadows alone
- Salt Marsh alone
- *Phragmites* alone
- Eelgrass Meadows, Salt Marsh and *Phragmites* together (Figure 3)
- Width of 90% confidence interval, Eelgrass Meadows, Salt Marsh and *Phragmites* together

Results

Mapped vegetation area

The target area of Maine to New York contains just over 200,000 acres of blue carbon mapped vegetation habitat (Table 3). Just over 50% of that total is salt marsh, with eelgrass comprising about 30% and *Phragmites* comprising 15%. Approximately 52% of the total blue carbon habitat is found in Massachusetts, while Maine's comprised nearly 25% of the total.

Massachusetts had substantially more salt marsh than any other state, and Massachusetts salt marsh alone comprised nearly 30% of the total blue carbon mapped habitat in the region. Maine also contains a large quantity of mapped salt marsh with over 31,000 acres, while the remaining states each contain substantially less mapped vegetation area. Perhaps due to its extensive marsh systems, Massachusetts also possesses dramatically more *Phragmites* than the other states.

Maine contains the largest amount of mapped eelgrass comprising approximately 34% of the regional total. New York and Massachusetts each comprised about 30% of the regional total, with Rhode Island, Connecticut and New Hampshire making up much smaller amounts of the total mapped vegetation area.

Table 3: Mapped habitat acreage by category and state[1]

State	Eelgrass	Salt Marsh	*Phragmites*	Total
Maine	21,666	31,779	547	53,992
New Hampshire	1,436	6,762	219	8,418
Massachusetts	19,115	64,975	28,363	112,453
Rhode Island	1,038	4,043	259	5,340
Connecticut	1,101	7,546	583	9,230
New York	19,642	8,072	1,075	28,789
Total	63,998	123,177	31,047	218,222

[1] *Acreage data generated from maps created on the Northeast Ocean Data Portal*

Examples of the regional habitat maps are presented in Figures 9 and 10. These maps are available on the **Northeast Ocean Data Portal**, where the user can zoom into any area of interest and access the metadata associated with each location.

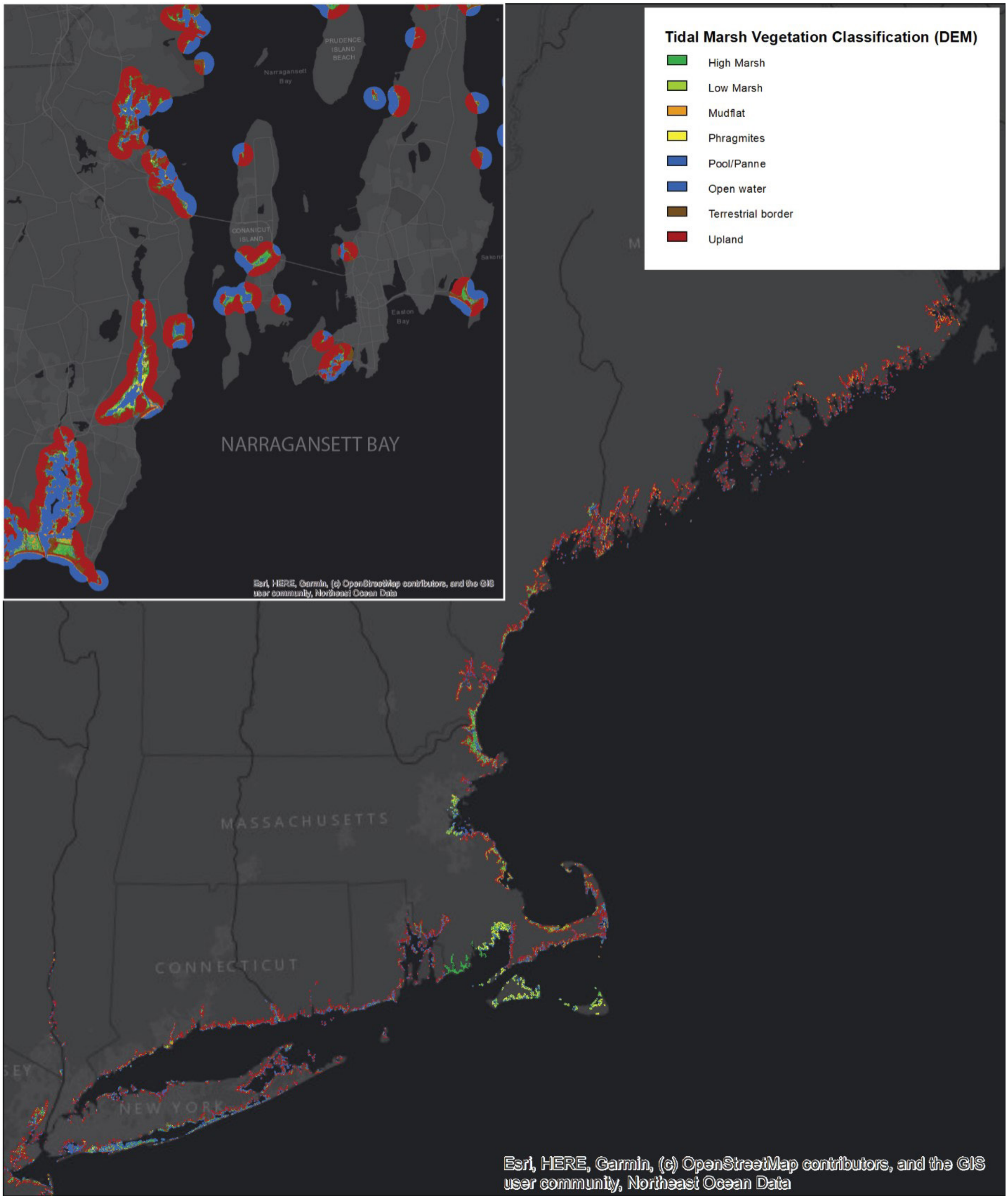

Figure 9: Salt Marsh and Phragmites habitat distribution map

Figure 10: Eelgrass habitat distribution map

Sediment data analysis

Analysis of the sediment carbon density data resulted in three distinct categories: eelgrass, salt marsh and *Phragmites australis* (Table 4). *Phragmites* had the highest mean sediment carbon density, while eelgrass had the lowest. These values were used in conjunction with the area estimates from the habitat maps to calculate carbon stock values (Table 5).

Table 4: Mean sediment carbon density by habitat

Habitat	Number of samples	Sediment carbon (mg/cm^3) Mean and standard error
Eelgrass	35	12+1.3
Salt Marsh	114	35+0.91
Phragmites australis	40	36+1.5

Table 5: Carbon stock data by state and habitat (Mg C)

State	Eelgrass	Salt Marsh	*Phragmites*	Total
Maine	315,656	1,350,401	23,908	1,689,965
New Hampshire	20,921	287,341	9,571	317,834
Massachusetts	278,490	2,761,015	1,239,679	4,279,184
Rhode Island	15,122	171,801	11,320	198,244
Connecticut	16,040	320,656	25,481	362,178
New York	286,168	343,008	46,986	676,161
Total	**932,400**	**5,234,222**	**1,356,946**	**7,523,568**

For the geographic region, 7,523,568 Mg of carbon is stored in the top 30 cm of these blue carbon habitats. Nearly 70% of the sequestered carbon in the region is found in salt marshes, while 18% is found in *Phragmites* and 12% in eelgrass.

Of the regional blue carbon stock, 57% is found in Massachusetts, 22% in Maine and substantially lesser amounts in the other states. The single largest category (Massachusetts mapped salt marsh) comprised 37% of the blue carbon stored in the region. In order to visually display the carbon stock data, a carbon heat map was created showing varying quantities of sequestered carbon (Figure 11).

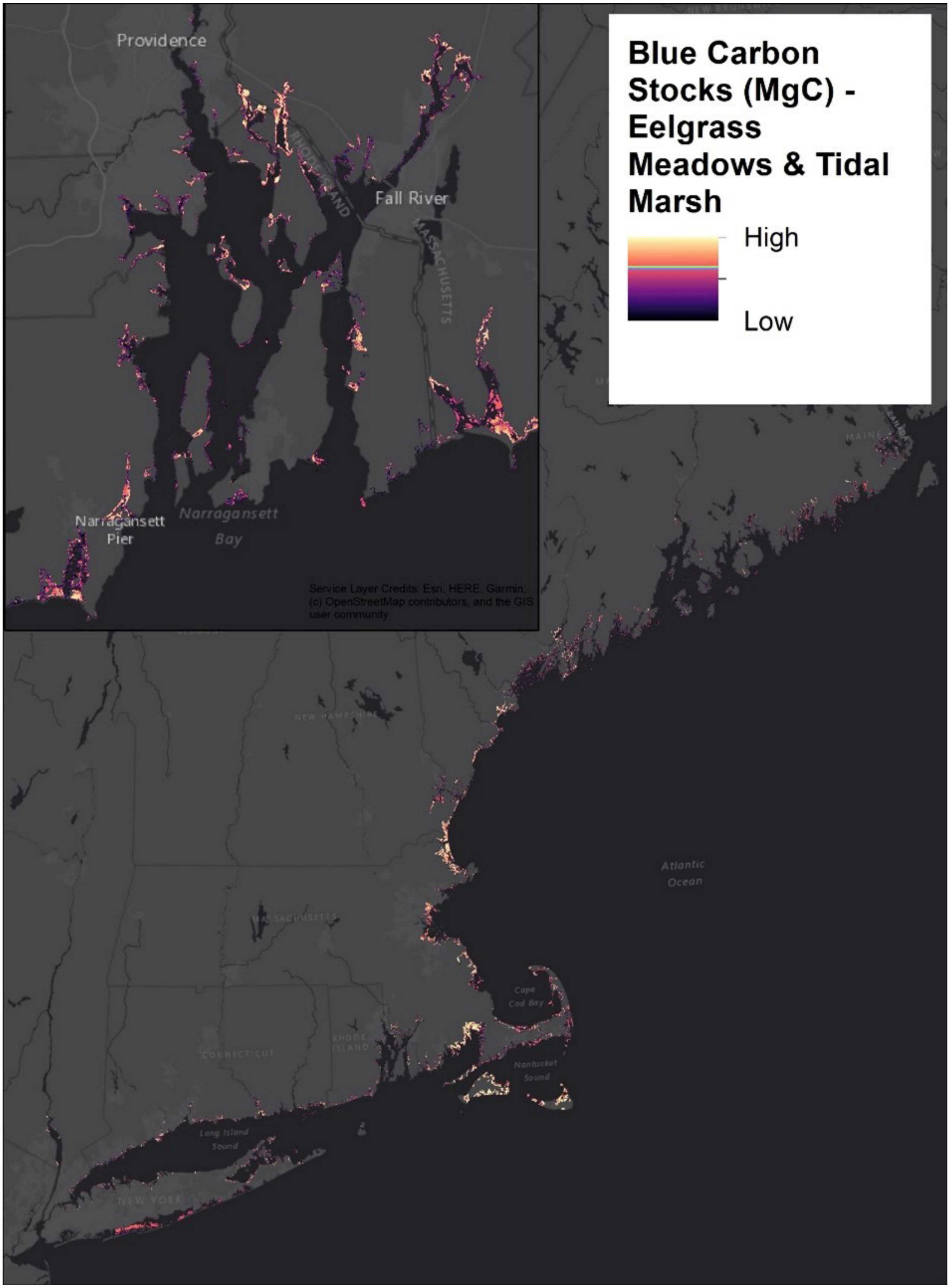

Figure 11: Sediment carbon heat map

Discussion

The goal of this effort was to produce a baseline database and map of both vegetated blue carbon habitat acreage and sequestered carbon. These data and baseline maps could be used to inform land management practices and coastal policies and regulations, including those for climate change adaptation, mitigation, and resiliency. The maps could further environmental conservation efforts, both for the habitat themselves and for the animal and plant species that live in those habitats. The maps could further support coastal protection and food security, including those for aquaculture siting and fishery management. Finally, the maps could inform decision making by government agencies, businesses, non-government organizations (NGOs), academic entities, and individuals.

It is critical to understand that, due to data limitations, the sequestered carbon estimates represent a fraction of the actual total. Measurements deeper than 30 cm would need to be taken to get an accurate estimate of the actual total of sequestered carbon. Actual peat layers extend several meters in these habitats. That being said, this analysis still holds considerable value as the top 30 cm of the sediments are at the most risk of resuspension and reintroduction to the global carbon cycle if the vegetation layer is lost.

To put the regional blue carbon stock value of 7,523,568 Mg of carbon in context, we used the EPA greenhouse gas equivalency calculator (**https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator**). This quantity of stored carbon is equivalent to the emissions from 5,994,024 passenger vehicles driven in one year, burning 30,500,000,000+ pounds of coal, or the emissions associated with the energy use of 3,474,000 homes for a year. It is also roughly equivalent to the emissions offset by the operation of 7,498 wind turbines for a year. It is approximately equivalent to the quantity of carbon accumulated in one year in 32,646,000 acres of upland forest.

The sequestered carbon in the New England region is predominantly associated with salt marshes. In light of projected sea level rise in the Northeast, the long-term fate of salt marshes and their accumulated carbon is at great risk. Additional studies that measure carbon in deep cores and track the fate of carbon in marshes as they drown and decay need to be able to more accurately predict the magnitude of the shift from carbon sink to carbon source. The ability of marshes to migrate landward in response to sea level rise and the potential change in sequestered carbon is also an important area of needed research and management.

The relatively modest contribution of eelgrass to the total regional blue carbon stock is due to lower sediment carbon den-sity and dramatically lower habitat acreage. Stable isotope analysis has shown the majority of the sequestered carbon in the sediments in an eelgrass meadow originates from outside the meadow (Novak et al., 2020). This origin of carbon reflects the filtering capacity of the habitat and the high dispersion rate of the aboveground leaves. During the growing season and especially in the fall as the plants begin to senesce, large quantities of eelgrass leaves are cast up onto the wrack line. Thus, much of the aboveground production over the growing season does end up within the sediments in the meadow.

In addition to their carbon sequestration abilities, eelgrass meadows reduce wave energy to adjacent shorelines and possibly reverse localized ocean acidification, while salt marshes mitigate coastal flooding and erosion (Nepf, 1999; Fonseca et al., 2019). Thus, the eelgrass and salt marsh habitat maps could support future coastal climate resiliency strategies for communities at risk of coastal flooding and erosion due to climate-related extreme events. In addition, the habitat maps contain valuable information for fisheries and wildlife management. To the authors' knowledge, this dataset represents the only current com-prehensive mapping effort that displays the current distribution of both habitats for the New England region.

Through this New England blue carbon mapping effort, a quantifiable baseline of blue carbon resources was created, from which states could track the effectiveness of policies on conserving and restoring coastal habitats and the carbon stored therein. The sediment carbon heat maps provide a visual representation of geographic areas currently holding large amounts of accumulated carbon. These maps provide additional information that states and local communities can use to factor into zoning, land management, and conservation decisions.

There are other, similar regional and state efforts (West Coast, Mid Atlantic, North Carolina) to quantify blue carbon through-out the United States, many of which are using similar methodologies. This New England blue carbon mapping effort could fill an important geographic piece in a national blue carbon estimate.

Future Directions

To continue blue carbon analysis and protection in New England coastal waters, the New England Blue Carbon Inventory Workgroup identified a number of future directions and research needs:

a. **Need for more detailed and frequent mapping of habitats:** With regards to salt marsh mapping, many of the states involved with this study rely on the National Wetlands Inventory, which is a national program supported by the United States Fish and Wildlife Service, that allows for a standardized mapping approach across the entire country. Currently, there is no comprehensive national effort to map seagrass habitats. Due to the large geographic scope of the effort, maps can become outdated. Some of the states in this region also conduct their own wetland mapping programs. While this does allow for more frequent data collection, there is a risk of states using different definitions of wetlands and habitat mapping methods. Each state generates its own maps, largely based on some type of aerial survey with photographic interpretation. Again, these disparate efforts do not promote the use of consistent methods or definitions of what constitutes seagrass habitat. What is needed is a consistent, timely national effort to map both habitat types or a reasonable agreed upon set of common protocols that all states use.

b. **Need for deep cores:** This analysis was limited by the available marine sediment core data, which in the majority of cases was limited to the top 30 cm of sediments. Based on field observations, and some limited data, carbon stocks in sediments extend well below the 30 cm depth. To truly measure the full extent of stored carbon, sediment cores that go several meters deep, or to the point of refusal (bedrock), are needed for a complete accounting of stored carbon. Knowledge of carbon density variability as compared to sediment composition variability (such as peat depth) is also needed.

c. **Need for precise GPS coordinates for soil cores:** Differential GPS has an accuracy of plus or minus a meter. Proper collection of these coordinates in conjunction with collection of sediment cores would allow for a much more complete analysis. Vegetation types within salt marshes can vary on the order of meters and if one is interested in examining the differential accumulation of carbon by vegetation, precise GPS coordinates need to be taken.

d. **Expand the types of marine environments and vegetation:** Future blue carbon stock inventories and analyses need to be more comprehensive and should include additional habitats, such as unvegetated salt marsh pannes and macroalgae. Kelp has become of particular interest, due to its rapid growth and ability to thrive in the winter months. There is no question that kelp is highly productive, but challenges remain in determining how to best quantify its ability to capture and sequester carbon.

e. **Better understanding of greenhouse gas emissions and carbon storage impacts to these environments:** Greenhouse gas emissions could impact sea level rise scenarios and possibly impact sediment carbon storage. Therefore, more information is needed on how greenhouse gases might impact or offset sediment carbon storage. More detailed regional models for how carbon storage will change in seagrass meadows under various sea level rise scenarios are also needed, as salt marsh migration modeling seems more advanced than for seagrass.

f. **Need for additional data on carbon sequestration rates:** This report deals with accumulated carbon stocks, but does not address carbon sequestration rates. Understanding the mechanisms that may control the rates at which carbon accumulate in these systems is critical to their proper future management.

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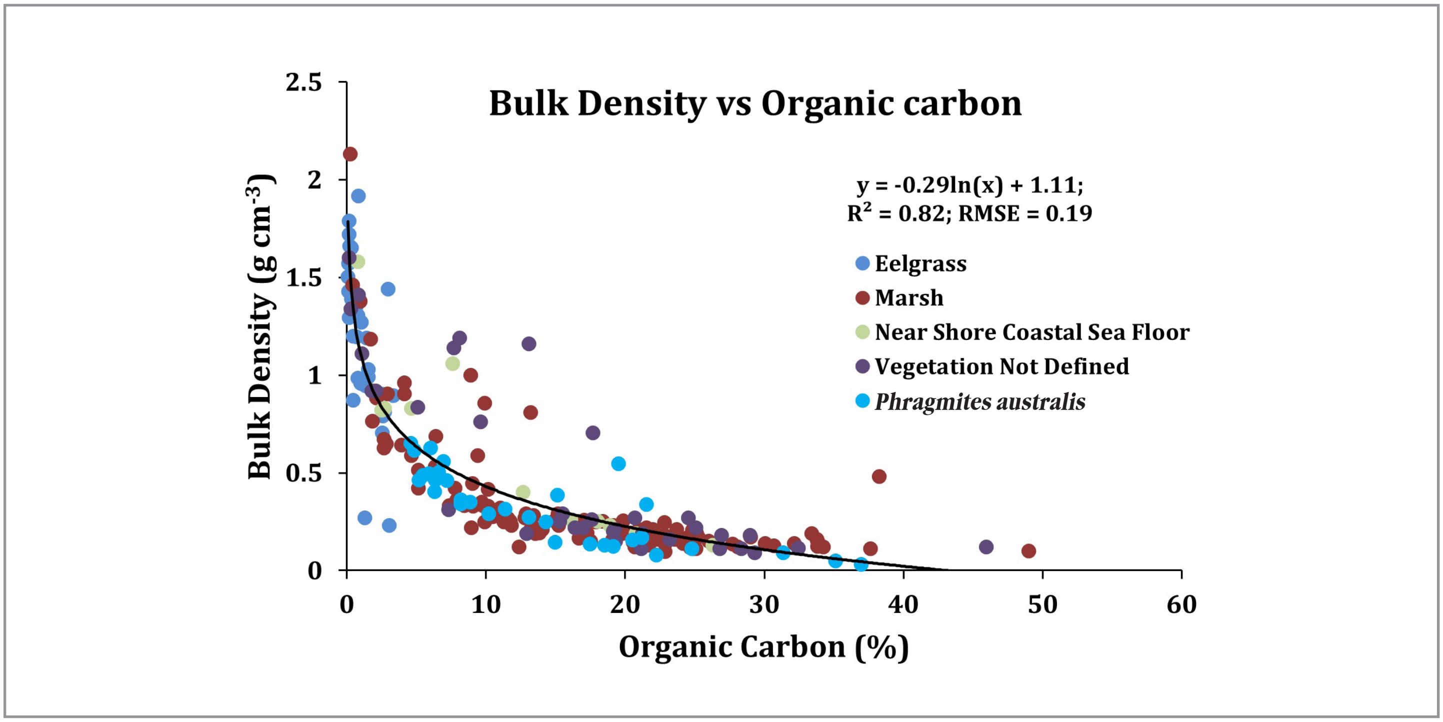
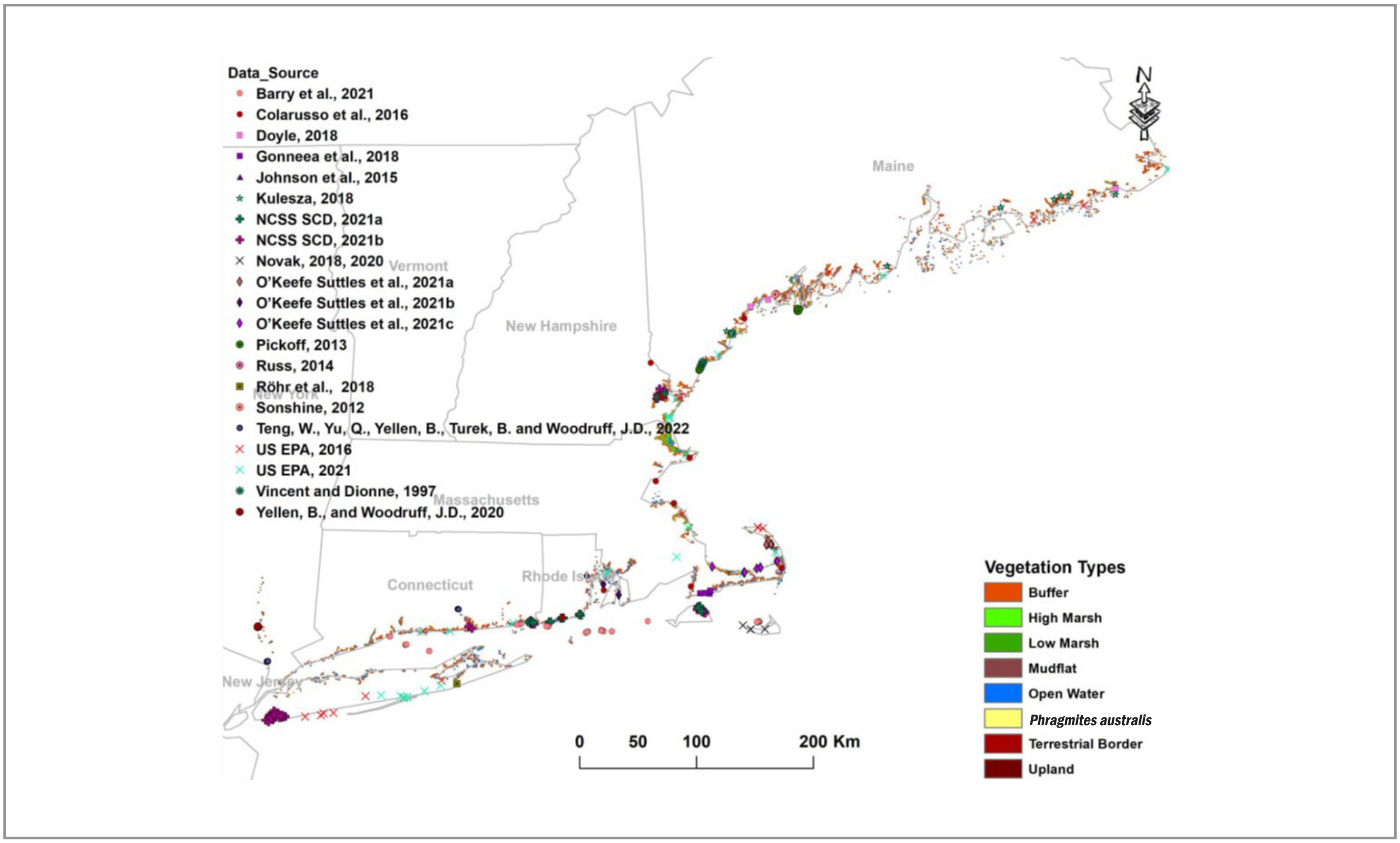
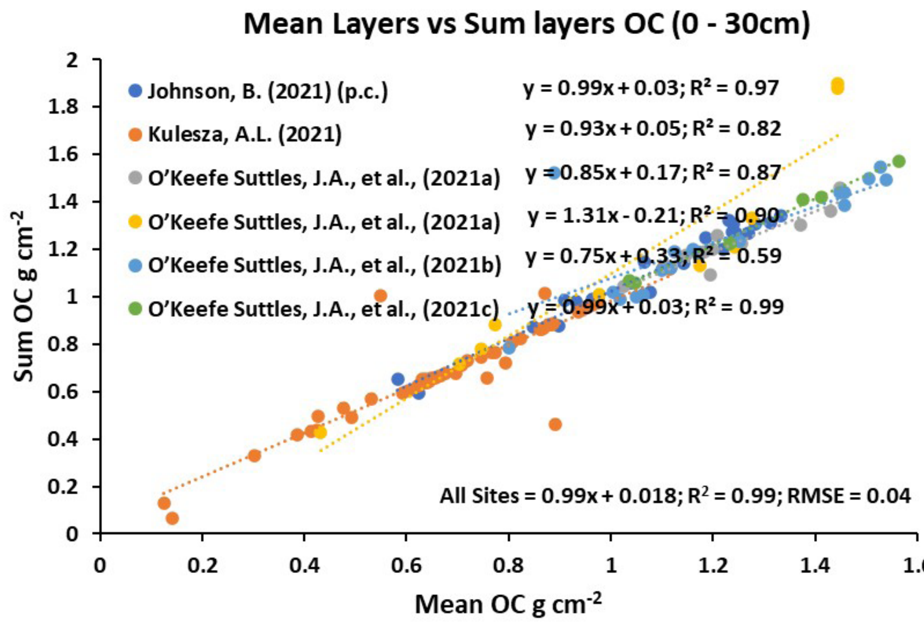


The relationship between bulk density and organic carbon based on the values from the datasets used in this study for the 0-30 cm soil thickness.

The exponential decay relationship between OC and Bd was strong (R^2 = 0.82; RMSE = 0.19) indicating a decreasing trend of Bd with increasing OC.



Distribution and locations of sediment carbon sample sites by data source.



The relationship between mean organic carbon (OC) and sum of OC based on soil layers within 30 cm soil depth.

EPA