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A pedogeomorphic strategy for blue carbon accounting of tidal marsh soils

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Core Ideas

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Core Idea 1: Tidal marshes are rich in soil carbon, yet uncertainty remains on how to best quantify these blue C stocks.

Core Idea 2: Blue C inventories typically sample to 1 m, but on average 40% of the C within 2 m occurs in the lower meter.

Core Idea 3: A pedogeomorphic framework is an effective C accounting approach for quantify tidal marsh C stocks.

Core Idea 4: CUST_CORE_IDEA_4 :No data available.

Core Idea 5: CUST_CORE_IDEA_5 :No data available.

Plain Language Summary

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There is great interest across the globe in the amount of carbon stored in tidal marsh soils because of the potential of these ecosystems to capture the greenhouse gases that contribute to global warming. Multiple studies, however, have found little agreement in the best approach to ascertain the quantity of carbon stored in these extensive ecosystems. We studied tidal marshes among two regions of the Atlantic coast and found that partitioning sampling among tidal marshes based on their geomorphic setting was a very effective approach to quantifying soil carbon on a regional basis. Most studies only sample to 100 cm, but our studies found that almost as much carbon is held at depths between 100 and 200 cm, emphasizing the need to sample to at least 2 meters for accurate carbon accounting.

A pedogeomorphic strategy for blue carbon accounting of tidal marsh soils

Abstract:

Tidal marsh soils have some of the largest carbon stocks of any ecosystem, yet uncertainty remains about the best approach to quantify these C stocks. We tested whether separating tidal marshes into pedogeomorphic units (PGUs) could improve regional-scale blue C accounting. We studied two separate regions on the Atlantic coast: southern New England (NE) and northern Southeast (SE). We identified four dominant PGUs in each region and measured soil C stocks in 105 pedons to 2 m. Average carbon stocks among PGUs ranged from 84-430 and 140-790 Mg C ha^{-1} for the 1 and 2 m sampling depths, respectively. We found significant differences in C stocks among PGUs ($p<0.0001$) in each region with NE marshes having significantly higher per area C stocks compared to SE at both sampling depths. A common a benchmark in blue C inventories is to sample to 1 m, but on average 40% of the C within 2 m occurred in the lower meter, underscoring the need to sample to 2 m. Recent studies suggest that until a better approach is identified, a single value of 27 kg C m^{-3} be used for C accounting in tidal marshes. On average, this overestimated C stocks in the SE by 37% and underestimated in the NE by 35%. Our findings emphasize that C stocks in tidal marshes can vary greatly by geomorphic setting and suggest a pedogeomorphic framework with sampling to at least 2 m offers an effective approach for future tidal marsh C accounting.

Introduction:

Tidal marsh ecosystems exist along salinity gradients between marine and freshwater systems and provide many critical ecosystem services including carbon sequestration (Barbier et al., 2011). Quantification of blue carbon stocks in tidal marshes across the globe has been a topic of great interest owing to the high carbon sequestration potential of these ecosystems and the danger they face due to anthropogenic climate change (Macreadie et al., 2021; Maxwell et al., 2024; Needleman et al., 2018; VanZomerenet al., 2019; Watson et al., 2017). These studies, and attempts to model tidal marsh carbon stocks, have found little agreement in the best approach to ascertain the quantity of carbon stored in these extensive ecosystems since stocks can vary by an order of magnitude depending on the marsh and methods and spatial scale of the modeling (Maxwell et al. 2024). Tidal marshes are currently being subjected to accelerated sea level rise resulting in a rate of loss of as much as 2% per year (Mcleod et al., 2011, Watson et. al., 2017) adding to the uncertainty of the quantity of carbon held in these ecosystems. Thus, there is a need for an approach for accurate carbon stock accounting that can effectively prioritize marshes and regions for conservation and restoration efforts aimed at maximizing carbon sequestration.

Carbon sequestration in tidal marshes occurs as marshes accrete with sea level rise by accumulating biomass and sediment from in-situ organisms as well as tidal waters (Harrison & Bloom, 1977; Kelley et al., 1988; Reed et al., 1999; Vernberg, 1993; Wood et al., 1989). Tidal marshes are uniquely adept at sequestering large amounts of carbon due to their high net plant productivity and a number of factors which limit organic matter decomposition including near-permanent reducing conditions, high sulfide concentrations, and high salinity levels (Baustian et al., 2017; Cruz et al., 1989; Howes et al., 1981; Malik et al., 2018; Rabenhorst & James, 1993). Accurately quantifying carbon sequestration and stocks in these systems at regional and global scales, however, is quite difficult (Byrd et al., 2018; Chmura et al, 2003; Holmquist et al., 2018; Maxwell et al., 2024). Regional carbon accounting has also been hindered by limited sampling depth. Although many tidal marsh soils have high carbon density values below 100 cm (Artigas et al., 2015; Hansen et al., 2017; Scott and Greenberg, 1983), many studies only sampled the upper 30 cm, or at most the upper 100 cm (Gorham et al., 2020; Hinson et al., 2017; Holmquist et al., 2018; Maxwell et al., 2024) leading to underestimates of the amount of Holocene aged carbon held in these marshes.

Holmquist et al. (2018) noted that current maps of tidal marsh carbon stocks are inaccurate and until a better approach to determine tidal marsh stocks is identified a fixed value of 27 kg C m^{-3} be used for modeling purposes within the upper meter of soil. Recent research indicates that geomorphic influences play a major role in tidal marsh formation, driving variation in morphology and thus carbon stocks in tidal marsh soils (Ardenne et al., 2018; Gorham et al., 2020; Stolt, 2016; Tan et al., 2020). For example, Stolt (2016) found significant differences in organic horizon thicknesses among different tidal marshes based on their geomorphic position on the coastal landscape. Considering that organic soil materials are a major contributor to carbon stocks, utilization of geomorphic characteristics at a regional level may allow for high-accuracy regional carbon accounting in tidal marsh soils.

Accurate identification and mapping of coastal wetlands is essential for establishing baseline data on the distribution and future prospects of carbon reserves along coastal areas (Brown et al., 2021). Recognizing pedogeomorphic factors and soil properties as primary drivers of carbon accretion may be crucial for developing a reliable blue carbon inventory for a given region. The objective of this study was to investigate the use of geomorphic setting and corresponding soil characteristics of tidal marshes to ascertain tidal marsh soil carbon stocks across two regions along the Atlantic coast of the United States. We hypothesized that marshes with similar geomorphic characteristics within a region will have similar soil characteristics and thus similar carbon stocks, and that differences in geomorphic characteristics and environmental conditions within and among regions will lead to different carbon stocks on an area basis.

Methods:

Site selection and PGU classification

Tidal marshes were identified in Atlantic coastal areas of the northern Southeast (SE) and southern New England (NE) using digital SSURGO and NRCS Soil Survey data. Areas considered for study included all soils mapped as a tidal marsh along the coastlines, embayments, and lagoons. For the SE, digital data for an area of coastal North Carolina were reviewed including Pamlico and Albemarle Sounds. For NE, digital data of marshes in coastal Connecticut, Rhode Island, and southeastern Massachusetts, including Narragansett Bay, were reviewed. We partitioned each identified tidal marsh into a pedogeomorphic units (PGU) based on geomorphic characteristics including estuarine influence, position in relation to the open ocean or embayment, protection from wave action, and potential sediment load.

Four PGUs were found to dominate the coastal landscape in each region (Figures 1 and 2) The total aerial extent of each PGU was calculated for both regions (Table 1). Both NE and SE included PGUs described as back barriers. These marshes are characterized as being situated between the open ocean and spit/dune-system on one side and a lagoon or embayment on the landward side. Back barrier systems are protected from all but the strongest storm surges and thus generally shielded from wave-action (Oertel & Woo, 1994). Tidal fluctuations and daily sediment loads are low as there tends to be limited input into the coastal lagoon or tidal embayment. Rather than daily inputs of sediment from the rising tide, the primary source of sediment in these systems occurs during overwash events during strong storms (Boothroyd et al., 1985; Walters, 2013).

The other three PGUs in NE included tidal creeks, coves, and tidal rivers. Tidal creek systems occur in low-lying areas adjacent to the coast (Bost et al., 2023; Fitzgerald et al., 2002). Tidal creek PGUs are defined by their network of relatively long yet narrow, shallow tidal creeks that exhibit bidirectional tidal water level fluctuations but weak tidal currents (Brinson, 1993; Stolt, 2016). The creeks have low hydrodynamic energy without significant wave action. The banks of tidal creek are typically well vegetated limiting erosion and promoting sediment deposition (Healy, 2005).

Coves were identified as marshes which face seaward and are sheltered on 3 sides by adjacent uplands or spits. Thus, cove marshes are protected from the majority of wave action but are still subjected to open water tides (Anderson, 1973). Unlike back barrier PGUs, coves are situated on the seaside of the upland and consequently have a greater amount of tidal range and are not typically subject to overwash events (Anderson, 1973). Tidal river PGUs occur along the banks of tidally influenced rivers. These rivers mostly originate from glacial-drainage systems with larger channels and greater water flow than tidal creeks (Fitzgerald et al., 2002; Orson et al., 1987). Tidal rivers tend to have a single main channel and fewer interwoven streams and drain a larger watershed compared to tidal creeks (Stolt, 2016). Variation in tides and wave action in tidal rivers varies depending on the proximity to the open ocean.

The three PGUs unique to SE were anthropogenic tidal creeks, lagoon islands, and submerged wetlands. Lagoon island PGUs are situated in estuaries on relict flood tidal deltas or washover fans. These relict features have been submerged with rising sea levels and now act as a mineral base for modern day salt marshes. Submerged wetland marshes occur on the mainland side of the lagoons and were previously freshwater wetlands at the lower reaches of relic rivers which are now inundated with salt or brackish water. Anthropogenic tidal creeks PGUs have the highest semi-diurnal tidal range (>1 m) of the estuarine tidal marshes in the southeast. These PGUs are hydrologically connected to some degree to the anthropogenic intracoastal waterway that runs from Virginia to Florida. Tidal water runs in and out of these marshes from the intercoastal waterway, through the tidal creeks, and in and out of the inlet that connects the systems to the Atlantic Ocean.

Google Earth satellite imagery was used to verify site characteristics and accessibility. Reconnaissance surveys were completed to choose representative marshes of each PGU for detailed sampling and analysis. Study site selection was dependent upon accessibility and ease (or difficulty) in traversing and sampling. The NE marshes were relatively small in size and fairly easily accessed, traversed, and sampled on foot with sampled marshes ranging in size from approximately 3 to 100 ha. We selected 32 marshes for sampling in NE including 7 back barriers, 8 coves, 6 tidal creeks, and 11 tidal rivers (Figure 1). At each PGU a single transect was sampled. In contrast, the spatial extent of SE marshes was more than an order of magnitude larger than marshes in NE (Table 1). These marshes were relatively difficult to access and traverse because of the size of the marshes with sampled marshes ranging in size from approximately 800 to 11,000 ha and many marshes had thick stands of black needle rush (*Juncus roemerianus* S.). Many of the SE marshes required a boat or airboat to access and sample with the longest transects being over 1,600 m in length. Thus, we selected 4 marshes for study in the SE, one of each PGU (Figure 2) with four sampling transects spread across each marsh with the assumption that the variability among the transects was comparable to variability among marshes of the same PGU.

Field Sampling

Soils were described and sampled along transects perpendicular to the open water in representative areas of each marsh. A total of 59 pedons were sampled in SE and 46 pedons from NE. Field descriptions and sampling of soils were performed with a tiling spade which was used to remove a plug of soil with approximately 30 cm sides. This plug was used to collect samples from the upper 30 cm using the brownie method where a block of known volume is cut from the plug for bulk density calculations (Stolt & Hardy, 2022). Soils below 30 cm were sampled with a Macaulay peat sampler to collect undisturbed samples until refusal (typically non-fluid mineral soil materials) or 200 cm, whatever was shallower. In cases where the soil could not be fully sampled by the Macaulay peat sampler to 200 cm, soils were sampled and described with a bucket auger. For samples collected with the bucket auger, bulk density was estimated using an exponential regression model based on soil organic matter content and bulk density of samples which were collected with a known volume (Supplemental data F1 and F2). Due to the minimal thickness of organic horizons and non-fluid sands in SE back barrier, these soils below 30 cm were sampled using a vibracore (Stolt et al. 2017). Field-based soil descriptions following standard procedures (Schoeneberger et al. 2014) were made to facilitate classification to the family level in Soil Taxonomy (Soil Survey Staff, 2022).

Laboratory Analysis

Standard methods were followed to determine presence of sulfidic materials and electrical conductivity to classify pedons to the family level (Soil Survey Staff, 2022). After these timesensitive analyses were performed, soils were dried at 105°C until no change in weight was detected. Samples were weighed to the nearest hundredth of a gram to determine dry weight and bulk density. The weight and volume of coarse mineral fragments which did not pass through a #10 sieve were subtracted from original sample measures to calculate bulk density.

All NE samples were subsampled and placed in pre-weighed crucibles and dried and cooled again. The sample and crucibles were weighed to the nearest hundredth of a gram before placing into a muffle furnace at 550°C for 5 hours. Once cooled, samples were weighed, and loss on ignition (LOI) was calculated to determine soil organic matter (SOM). In order to determine soil organic carbon (SOC) 188 samples representing a range of mineral and organic soil materials with a range of SOM contents and soil textures were selected for organic carbon analysis via high temperature combustion (Nelson & Sommers, 1996). These samples were subsampled in triplicate and carbon contents were determined using a Costech Analytical ECS 4010 (Costech Analytical, Valencia, CA, USA) high temperature combustion elemental analyzer. Samples of a known carbon content were run periodically samples to ensure calibration. A SOM to SOC regression model was applied to the mineral (<24% SOM; n= 115; r^2 =0.98) and organic (>24% SOM; n= 73; r^2 =0.95) samples to determine SOC for all the samples (Supplemental data F3). All SE samples were subsampled and analyzed for SOC content on a LECO 928 (LECO Corporation, St. Joseph, MI, USA) high temperature combustion elemental analyzer with check samples run periodically to ensure calibration.

Total C stock of each pedon was calculated by summing stocks for each horizon (Equation 1) to 100 and 200 cm. In some cases, it was not possible to collect a sample from each horizon to 200 cm. In such cases, it was assumed that the last sampled horizon extended until 200 cm and the bulk density and carbon content of that last horizon also extended until 200 cm. Because of the relatively low carbon content of the last horizon sampled (often <1%), we assumed that bulk density and carbon content of those horizons not sampled were not significantly different than the actual soil materials below the last horizon and to 200 cm.

Total carbon stored in each PGU in each region was determined by multiplying the total spatial extent of a given PGU by its average carbon stock.

Equation 1: Equation to calculate total kg C m^{-2} of each horizon in a soil profile. BD = bulk density, SOC = soil organic carbon, HT = horizon thickness, CF = coarse fragments.

$$Horizon\ C\ Stock\ \left(kg\ C\ m^{-2}\right) = BD\ \left(g\ cm^{-3}\right) \times SOC\ (\%) \times HT\ (cm) \times (100 - \%\ CF) \times .001$$

Statistical Analysis

R version 4.4.2 (R Core Team 2024) was utilized to compare carbon stocks of regions and PGUs. We used a single factor ANOVA to test for significant differences ($p<0.05$) among mean carbon stocks of the four PGUs within each region. A Tukey-Kramer Honest Significant Difference test was applied to the regional ANOVA results to find significant differences between all possible pairs of means after applying the ANOVA. Due to the differing sampling strategies, we utilized student t-tests to examine differences in means between regional PGUs one by one.

Results and Discussion

Carbon Stocks of Pedogeomorphic Units:

Average carbon stocks among PGUs from both regions range from 84-430 and 140-790 Mg C ha^{-1} for the 100 and 200 cm sampling depths, respectively (Table 2; Figures 3 and 4). Back barrier marshes had significantly lower C stocks at both 100 and 200 cm sampling depths of the four examined PGUs within each region (Figures 3 and 4). Within NE, back barrier marshes average C stocks were 200 Mg C ha^{-1} for the 100 cm sampling depth and 270 Mg C ha^{-1} for 200 cm while SE stocks were much lower (84 and 140 Mg C ha^{-1}, respectively). Organic horizons of back barrier marshes are relatively thin compared to most other PGUs (Table 2) because of their position on the coastal landscape and dynamic nature of the PGU. Low-energy sediments are delivered to the back-barrier marshes through daily micro-tidal fluctuations from the coastal lagoon or tidal embayment; however, much of the sediment deposited on these marshes is sands delivered during high-energy overwash events during storms (Boothroyd et al., 1985; Walters, 2013). These coarse textured sandy deposits have low carbon density values (Table 2) and thus contribute little to the carbon stocks of back barrier marshes. Intense storms, such as hurricanes, can deposit decimeters of coarse sediment over back barrier marshes burying the marsh surface (Stolt & Hardy, 2022). These overwash events likely intermittently lower the primary productivity of back barrier marshes by covering the plants and thus decrease total carbon inputs from above and below-ground biomass. The combination of thin organic horizons, low carbon density sediment contributions, and periods of low bio-productivity are the primary reasons back barrier marshes have the lowest carbon stocks.

In general, the magnitude of the carbon stock is driven by the thickness of the organic horizons within the sampling depth of the pedon (Figure 5). The variability in carbon stocks for individual pedons, however, especially those pedons with thin or no organic horizons, suggests that other factors play a significant part in the magnitude of carbon stocks. Comparisons of carbon stocks of the SE back barrier and anthropogenic tidal creek marshes are a good example. Both of these marshes have minimal organic horizons, but the anthropogenic tidal creek marsh carbon stock is more than double that of the back barrier 84 vs. 170 Mg C ha^{-1} for the 100 and 140 vs. 310 Mg C ha^{-1} for the 200 cm sampling depths, respectively (Table 2). The pedogeomorphic setting for these marshes are quite different. The back barrier system is microtidal with minimal sediment being deposited on the marsh from the daily tides originating in the lagoon behind the barrier. The major source of sediment is from episodic overwash events during severe storms bringing in thick deposits of organic-poor sands that retard the formation of organic horizons. Of the SE PGUs, the back barrier has the lowest average carbon density (9.2 kg C m^{-3}) of the mineral components of the soils (Table 2). In the anthropogenic tidal creek systems daily tide ranges are a meter with spring tides as much as 2 meters. Water floods the system from the intercoastal waterway and the inlet connecting the marsh to the ocean bringing in a constant source of carbon-rich sediment that is trapped by the marsh vegetation. The average carbon density of the mineral component of anthropogenic tidal creek soils is nearly double that of the back barrier (9.2 vs. 17.3 kg C m^{-3}). The sediment input is in a balanced state such that organic horizons do not form but the vegetation is not smothered; allowing these marshes to accrete and sequester carbon despite lacking organic horizons.

In a similar manner, pedogeomorphic factors that control sediment deposition also likely explain the difference in carbon stocks between NE tidal rivers and tidal creeks. Although on average both tidal river and tidal creek marshes have similar organic horizon thicknesses (90 vs. 80 cm, respectively), carbon stocks were greater in the tidal river marshes at both the 100 (330 vs. 430 Mg C ha^{-1} and 200 (520 vs. 750 Mg C ha^{-1}) cm sampling depths. The meandering nature of tidal creeks, coupled with a larger edge area compared to the tidal river, facilitates sediment trapping along the edges by *S. alterniflora*, which dominates these low marsh zones. This trapped sediment forms a slight berm along the creek edge, restricting sediment deposition away from the creek (Denise et al., 1999). Tidal rivers likely have higher sediment loads than tidal creeks as the tidal rivers are of higher energy and the source of sediment is from both eroding sediment from the upland during high flows and the typical sediment in the inundating tidal waters. Average carbon density values for both the mineral (24.5 vs. 31.0 kg C m^{-3}) and organic (38.0 vs. 47.5 kg C m^{-3}) soil materials are higher in the tidal rivers than tidal creeks (Table 2) which supports the conclusion that the carbon rich sediment load is greater in tidal rivers resulting in higher carbon stocks.

In NE, cove and tidal river marshes held similar relatively high carbon stocks at both the 100 and 200 sampling depths (Table 2). Cove marshes had the highest mean organic horizon thickness (151 cm). Cove marshes are likely the oldest and most stable of the tidal marsh systems we investigated. These marshes, although located adjacent to open water, are anchored and sheltered by upland on 3 sides. We hypothesize this protection decreases wave energy and allows organic materials to accrete uninterrupted by erosion or being buried by sediment. Although cove marshes had on average a 28% lower mineral horizon carbon density than tidal rivers (22.4 vs. 31 kg C m^{-3}), the organic horizon carbon density values were essentially the same (49.5 and 47.5 kg C m^{-3}) suggesting that carbon rich sediment was not driving the high organic horizon carbon density but collapse and compaction of the organic soil materials over time in the cove marshes.

In the SE, the lagoon island marsh had significantly higher carbon stocks at both 100 cm (mean = 400 Mg C ha^{-1}) and 200 cm (mean = 690 Mg C ha^{-1}) than the other PGUs (Figure 4, Table 2). Both the submerged wetland and lagoon island marshes are well-protected environments, similar to the NE cove and tidal river marshes, which has facilitated organic material accumulation with minimal erosion during the sea level rise experienced during the Holocene. The thicker organic horizons in the lagoon island marsh (mean = 124 cm) compared to the submerged wetland marsh (mean = 82 cm) likely explain the higher carbon stocks. Currently, the lagoon island marshes are more fragmented and eroded compared to the submerged wetland marshes, which remain closely connected to submerged stream channels. This fragmentation, combined with the higher carbon stocks suggests that lagoon island marshes have been on the landscape longer and have had more time to accumulate carbon in the shallower portions of their profiles. However, they appear not to have reached sufficient age to significantly increase carbon stocks deeper in their profiles. Over time, as sea levels rise and erosion continues, it is possible that lagoon island marshes may erode away, while submerged wetland marshes could transition into lagoon island marshes. This potential transformation underscores the dynamic nature of tidal marsh systems and the importance of understanding pedogeomorphic relationships to prioritize marsh conservation and restoration.

Interregional comparisons of carbon stocks

The two regions we focused on are about 650 km apart. Southern NE is within the mesic soil temperature regime while the SE is thermic. The SE has an extensive flat coastal plain while NE was most recently glaciated with no classic coastal plain and marshes butting up against glacial uplands. The area of the SE that we studied occurred around the extensive Pamlico-Albemarle Sound while southern NE has Narragansett Bay as its large estuary. On average a hurricane makes landfall in North Carolina every 2 years (NCSCO, 2019), while in NE only 9 hurricanes have made landfall since 1900 (NESEC, 2024). These major regional differences drive the coastal environment and the formation of tidal marshes on the broad scale while on the regional scale the position on the coastal landscape or PGU control tidal marsh formation. Because of the difficulty in accessing and transversing the large SE marshes, sampling multiple examples of each PGU, like we sampled in the NE, was beyond the scope of our studies. Thus, our sampling strategies differed enough to inhibit a robust statistical comparisons of carbon stocks between regions. Instead, we examined differences in means with one by one comparison using student t-tests (Table 4).

Of the various PGUs that we identified as the most common in the two regions, only the back barrier marshes are found on similar coastal landscape settings. Carbon stocks of the SE back barrier marsh was significantly lower than any of the PGUs in the NE at both the 100 and 200 cm sampling depth. Of the 16 pairwise comparisons of the 100 cm sampling depth, 9 of the SE PGUs had significantly lower carbon stocks than the NE with only 2 of the SE PGUs having higher stocks (lagoon island and submerged SE marshes had higher carbon stocks than the NE back barrier marshes). Similarly, for the 200 cm sampling depth, of the 16 pairwise comparisons, 9 of the SE PGUs had significantly lower carbon stocks than the NE with only 3 of the SE PGUs higher. The lagoon island PGU had higher carbon stocks than the NE back barrier and tidal creek PGUs while the SE submerged wetland PGU had higher stocks than the NE back barrier PGU. These trends and data suggest that in general SE marshes have lower carbon stocks than those of the NE on a per area basis. These differences are likely a function of the differences in temperature, coastal settings, and the higher impact of storms and hurricanes in the SE which can alter and inhibit the formation of organic horizons, deposition of carbon rich sediment, and carbon sequestration (Maxwell et al., 2024; Smith et al., 2022).

Comparison to recent global carbon stock models

Given the recent interest in blue carbon stocks across the world (Friess et al., 2022; Thomas, 2014), multiple studies have attempted to sum the total carbon stored in these critical ecosystems across regions and the world (Deb & Mandal, 2021; Gorham et al., 2020; Hinson et al., 2017; Holmquist et al., 2018; Maxwell et al., 2024; Ouyang & Lee, 2020). Holmquist et al. (2018) analyzed over 1,900 tidal wetland soil cores (mean core length = 55 cm) from across the conterminous U.S. to test different strategies for mapping soil carbon stocks: (1) applying a single nationwide mean carbon density; (2) empirical model-based estimates incorporating soil type, salinity, vegetation, and climate; and (3) existing soil maps (SSURGO). Holmquist et al. (2018) reported that while soil type emerged as the strongest factor in determining carbon stocks, inaccuracies in SSURGO (for example, overestimates of coastal-wetland carbon stocks by approximately 50% in the upper 100 cm) were sufficient to nullify its use. As an alternative to using soil type, Holmquist et al. (2018) recommended that until a better approach be identified to map soil carbon stocks to a 100 cm depth, a single carbon stock of 270 Mg C ha^{-1} be used for coastal wetlands across the entire US. We tested this singular value against our modeled carbon stocks across the two regional study areas by assigning the average carbon stock for the upper meter to every PGU in our study areas and multiplying that by the total number of hectares for each PGU to estimate the gigagrams of carbon held within the regions. The single carbon stock value of 270 Mg C ha^{-1} overestimated individual PGU carbon stock values by as much as 221% and underestimated by as much as 37% (Table 3). On average the single carbon stock value overestimated carbon stocks by 38% in the SE and underestimated by 35% in NE.

More recently, Maxwell et al. (2024) combined data from over 3,700 tidal marsh soil cores worldwide with a 30 m-resolution global tidal marsh extent map and environmental variables (e.g., elevation, temperature, vegetation index) to produce a spatially explicit model of soil organic carbon to 100 cm depth. The Maxwell et al. (2024) model underestimated the carbon stocks in the upper 100 cm of SE tidal marsh soils by 47% (53,300 vs 28,000 Gg), but was much closer in the NE, underestimating carbon stocks by 14% (1,980 vs 2,310 Gg).

One advantage of using soil survey data to model carbon stocks is soils are classified to 2 m depth. Neither the Holmquist et al. (2018) or Maxwell et al. (2024) provided modeling approaches for soil carbon stored at depths greater than a meter. We found that on average 40% of the carbon held in a tidal marsh soil is held below the first meter (Table 2). This is an issue when it comes to calculating tidal marsh soil carbon stocks as many tidal marsh soils frequently contain carbon buried below 100 cm due to organic matter accretion caused by constant sea level rise since the middle of the Holocene. Considering that the single value approach (Holmquist et al.; 2018) already underestimates the carbon stocks in NE, and the Maxwell et al. (2024) model underestimates the carbon stocks in both regions, accounting for the carbon below 100 cm of tidal marsh soils is imperative. The USDA-NRCS Coastal Zone Soil Survey is a fairly recent initiative to provide improved and more detailed soils data for estuarine and subaqueous soils (USDA-NRCS, 2024). This initiative has incorporated detailed sampling and analysis of tidal marsh soils throughout the nation. Recent soil survey updates of some coastal soils now include carbon stocks to 100 and 200 cm in their official soil descriptions (see Westbrook OSD; https://soilseries.sc.egov.usda.gov/OSD_Docs/W/WESTBROOK.html). These data have the potential to improve the use of PGUs to estimate carbon stocks to 200 cm of tidal marsh soils.

Summary and Conclusions

The formation of tidal marshes and the consequent carbon sequestration is a function of autochthonous organic C production from local plant communities and allochthonous C influx from mineral and organic sediment in the tidal waters. Both of these contribute to marsh accretion that allows the marsh to maintain elevation with sea level rise. Marshes that are highly productive and trap carbon rich sediment in stable positions on the landscape are able to sequester large amounts of carbon and have significant carbon stocks. Those marshes in dynamic positions on the landscape are less likely to consistently sequester carbon and have relatively limited carbon stocks. In this study we partitioned the coastal landscape of two regions along the Atlantic coast into different tidal marsh settings (pedogeomorphic units, PGUs) to test if carbon stocks differed among these units in a discernable pattern to improve regional-scale blue carbon accounting. We found that tidal marsh carbon stocks varied significantly with distinct PGUs due to underlying geomorphic and pedologic processes. These processes were responsible for the thickness of organic horizons and the carbon density of the soil materials; the two primary drivers of the magnitude of the carbon stock. Tidal marshes in dynamic PGUs like back barriers had significantly lower carbon stocks than other PGUs within a region. Organic horizons of these marshes were relatively thin and the overwash sands that periodically cover the marsh surface due to intense storms had relatively low carbon density values. In contrast, the marshes on PGUs that were on stable portions of the landscape such as coves have the highest carbon stocks of all the PGUs. These marshes are protected from excessive depositional and erosional events, have high bioproductivity, and are likely the oldest of the tidal marshes. Over that time they have sequestered considerable carbon in thick organic horizons and have trapped carbon rich sediment.

Because of the magnitude of the carbon stocks in tidal marshes, the overall extent of these systems in coastal environments, and that these systems are often difficult to access, transverse, and sample, several studies have tested modeling approaches to estimate tidal marsh carbon stocks at broad scales. We compared our findings to two of these approaches and found that the model values did not compare well with our measured carbon stocks. In addition, it is important to point out that these modeling approaches only estimated carbon stocks in the upper meter. We found that on average 40% of the carbon in a 2 m core of tidal marsh is in the lower meter emphasizing the importance of sampling these systems to at least 200 cm.

Our studies suggest that rather than using models optimized for global tidal marsh estimation for regional tidal marsh estimation, a model optimized by region should be used. Soil Survey data can be easily accessed online to identify tidal marshes and aerial photographs such as Google Earth can be used to readily identify pedogeomorphic features for classification of PGUs within a region. Archived data can be assessed and supplemented with additional field samplings of representative PGUs, recognizing the pedogeomorphic processes that operate in each system. These PGUs take regional variability into account by integrating geomorphic position with the soil environment and properties, making an effective regional-scale carbon stock estimation. By focusing on pedogeomorphic features, we can better capture the nuances of carbon storage patterns, particularly in regions where local environmental conditions and geomorphic history play large roles in carbon sequestration. Integrating these approaches with advancements in remote sensing and geospatial modeling could further enhance the accuracy and utility of regional carbon stock estimates, ensuring they better reflect the unique characteristics of tidal marsh landscapes.

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Table 1: Typical mapped soil series, total spatial extent, spatial extent of sampled marshes, and pedons analyzed of each PGU.

PGU	Typical family classification mapped in PGU	Spatial extent of PGU in the region (ha)	Spatial extent of marshes sampled in this study (ha)	Number of pedons analyzed
		Northern Southeast (SE)		
BB[1]	Mixed, thermic Typic Psammaquents	10,730	844	16
LI[2]	Fine, mixed, superactive, nonacid, thermic Typic Sulfaquents	15,359	1,540	14
SW[3]	Loamy, mixed, euic, thermic Terric Haplosaprists	37,026	10,520	13
ATC[4]	Sandy or sandy-skeletal, mixed, euic, thermic Terric Haplosaprists	209,140	1,140	13
		Southern New England (NE)		
BB[1]	Sandy, mixed, mesic Histic Sulfaquents;	953	704	8
C[5]	Euic, mesic Typic Sulfihemists;	1,376	578	9
TC[6]	Loamy, mixed, euic, mesic Terric Sulfihemists	1,358	430	9
TR[7]	Loamy, mixed, euic, mesic Terric Sulfihemists	2,517	1,200	20

Note: [1]Back barrier, [2]Lagoon island, [3]Submerged wetland, [4]Anthropogenic tidal creek, [5]Cove, [6]Tidal creek, [7]Tidal river

Table 2: Mean organic depth, 100 cm and 200 cm C stock (Mg C ha-1), and mineral and organic carbon density of PGUs

PGU	Mean depth of organic horizons (cm)	Mean 100 cm C stock (Mg C ha^{-1})	Mean 200 cm C stock (Mg C ha^{-1}) (percentage of carbon stored between 100 cm and 200 cm)	Mean mineral horizon carbon density (kg m^{-3})	Mean organic horizon carbon density (kg m^{-3})
			Northern Southeast (SE)		
BB[1]	3	84	140 (40%)	9.2	35.9
LI[2]	124	400	690 (42%)	27.0	39.4
SW[3]	82	290	530 (45%)	21.7	33.5
ATC[4]	0	170	310 (45%)	17.3	N/A
			Southern New England (NE)		
BB[1]	15	200	270 (26%)	18.4	39.3
C[5]	151	430	790 (46%)	22.4	49.5
TC[6]	80	330	520 (37%)	24.5	38.0
TR[7]	90	430	750 (43%)	31.0	47.5

Note: [1]Back barrier, [2]Lagoon island, [3]Submerged wetland, [4]Anthropogenic tidal creek, [5]Cove, [6]Tidal creek, [7]Tidal river

Table 3: Total modeled carbon stocks (gigagrams) of tidal marshes in our study area.

		Holmquist et al. 2018 (gigagrams C)	**Our study (gigagrams C)**		***Relative difference (%)**
PGU	Hectares	100 cm C Stock	100 cm C Stock	200 cm C Stock	100 cm C Stock
Northern Southeast (SE)					
BB[1]	10,730	2,900	901	1,500	**221**
LI[2]	15,359	4,150	6,140	10,600	**33**
SW[3]	37,026	10,000	10,700	19,600	**7**
ATC[4]	209,140	56,500	35,600	64,800	**59**
Total	272,255	73,500	53,300	96,600	**38**
Southern New England (NE)					
BB[1]	954	258	191	258	**35**
C[5]	1,377	372	592	1,090	**37**
TC[6]	1,358	367	448	706	**18**
TR[7]	2,518	680	1,080	1,890	**37**
Total	6,207	1,680	2,310	3,940	**28**

*Note: *Red colored indicates underestimates and black colored indicates overestimates*

[1]Back barrier, [2]Lagoon island, [3]Submerged wetland, [4]Anthropogenic tidal creek, [5]Cove, [6]Tidal creek, [7]Tidal river

Table 4: Interregional pairwise comparison of 100 and 200 cm carbon stocks of PGUs. ns = not significant, * p<0.05, ** p<0.01, *** p<0.001.

		Southeast			
		BB[1]	LI[2]	SW[3]	ATC[4]
		100 cm			
New England	BB[1]	***lower	***higher	*higher	ns
	C[5]	***lower	ns	**lower	***lower
	TC[6]	***lower	ns	ns	***lower
	TR[7]	***lower	ns	***lower	***lower
		200 cm			
	BB[1]	**lower	***higher	**higher	ns
	C[5]	***lower	ns	**lower	***lower
	TC[6]	***lower	*higher	ns	**lower
	TR[7]	***lower	ns	**lower	***lower

Note: "Lower" indicates the SE mean C stock was lower in the pairwise comparison. "Higher" indicates the SE mean C stock was higher in the pairwise comparison.

[1]Back barrier, [2]Lagoon island, [3]Submerged wetland, [4]Anthropogenic tidal creek, [5]Cove

[6]Tidal creek, [7]Tidal river

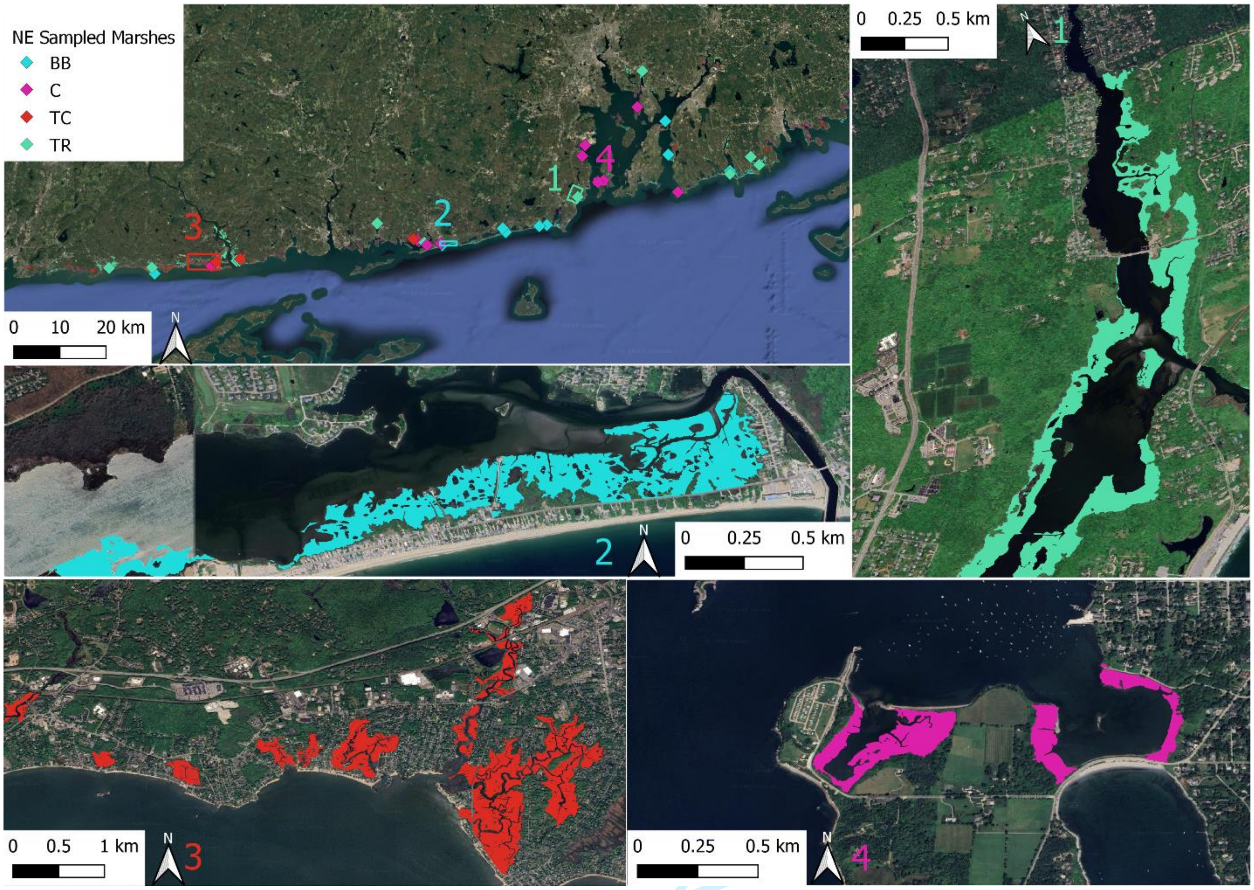


Figure 1: Example PGUs in NE and sampled pedons (colored diamonds) and their geomorphic positions on the landscape.

1: Tidal River (TR) PGU. These marshes are situated along modern day river channel banks. This example marsh is along the Narrow River in Narragansett, RI. Latitude: 41.45, longitude: -71.45.

2: Back barrier (BB) PGU: These marshes are situated between open ocean and lagoons or small embayments. Barrier spits between the ocean and marsh protect the marshes from open ocean currents and waves. Latitude: 41.32, longitude: -71.77.

3: Tidal creek (TC) PGU: These marshes form in low-lying seaside areas indirectly connected to open water via small creeks and inlets with considerable protection from ocean waves and currents. Latitude: 41.27, longitude: -72.39

4: Cove marsh (C) PGU: These marshes form in areas adjacent to open water but are well protected by spits or uplands on 3 sides. Latitude: 41.48, longitude: -71.39.

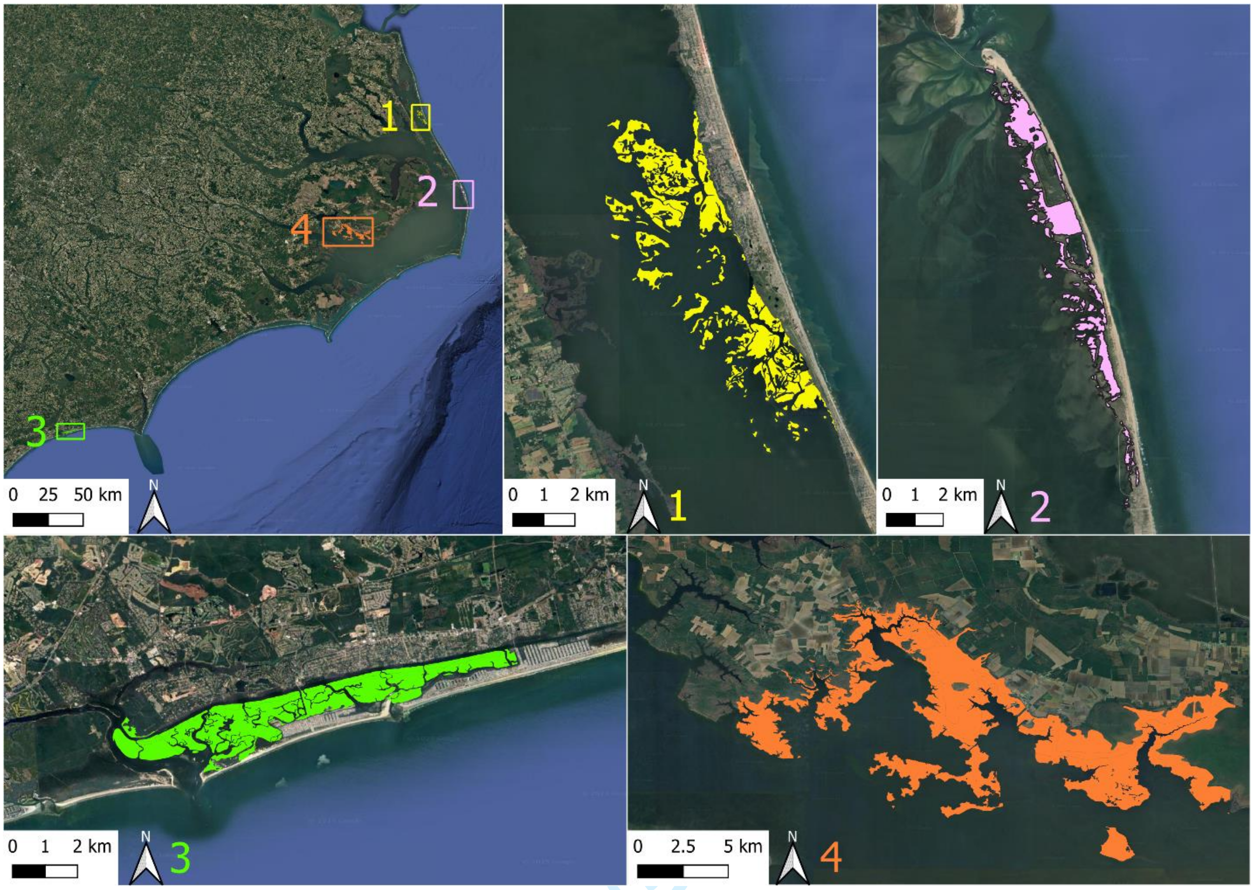


Figure 2: Sampled PGUs in SE and their geomorphic positions on the landscape.

1: Lagoon island PGU. These marshes form on remnant soils of alluvial fans or flood-tidal deltas with salt marsh peat accumulated with sea level rise in a lagoon protected from the open ocean by a barrier spit. The barrier spit is substantial and is broader and has a higher elevation than barrier islands associated with back barrier marshes. Latitude: 36.28, longitude: -75.81

2: Back barrier PGU: These marshes are situated attached to and a part of the barrier island. Marsh extends into the lagoon but is mostly attached to the barrier island. The barrier island is fairly thin and nearly flat with few dunes affording protection to the marsh. Latitude: 35.67, longitude: -75.49

3: Anthropogenic tidal creek PGU. These marshes are situated in a long narrow area between the Intercoastal Waterway and an inlet from the ocean. Latitude: 33.86, longitude: -78.52

4: Submerged wetland PGU: These marshes are situated adjacent to the upland and at the lower reaches of relic river channels. These marshes were historically freshwater wetlands and still have freshwater influence at low tide. Latitude: 35.39, longitude: -76.34

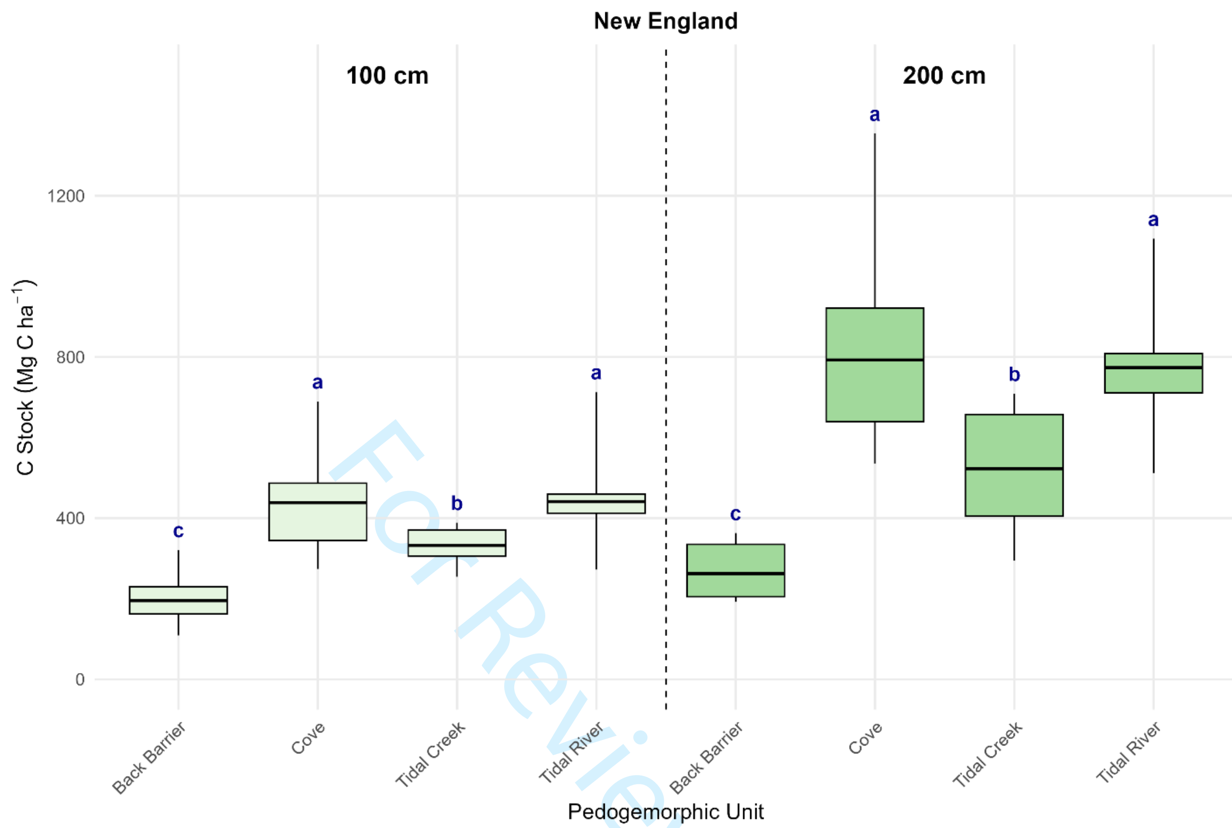


Figure 3: Box plot of NE carbon stocks among PGUs to 100 cm and 200 cm. Boxplots indicate interquartile range (box), mean (horizontal line), and whiskers (min/max data). Letters above boxes denote significant group differences at the given depth (Tukey's HSD test).

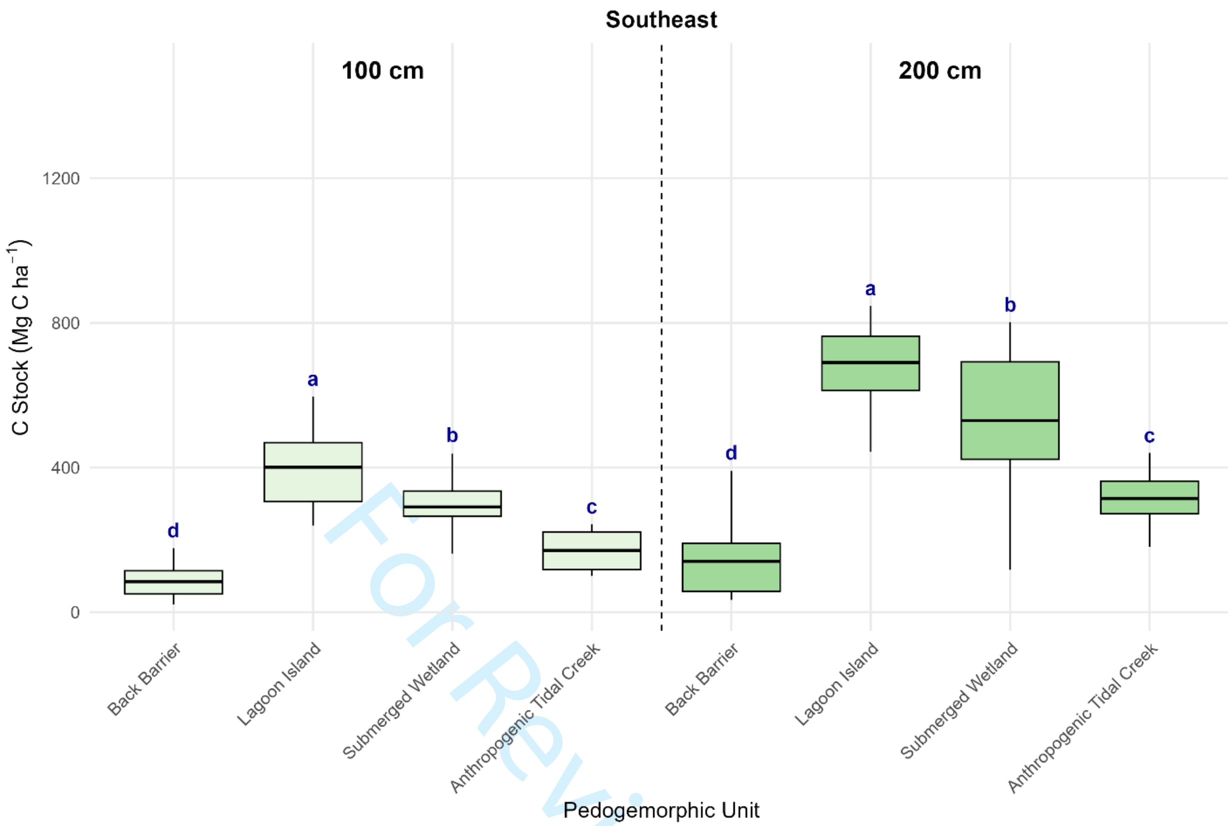


Figure 4: Box plot of SE carbon stocks among PGUs to 100 cm and 200 cm. Boxplots indicate interquartile range (box), mean (horizontal line), and whiskers (min/max data). Letters above boxes denote significant group differences at the given depth (Tukey's HSD test).

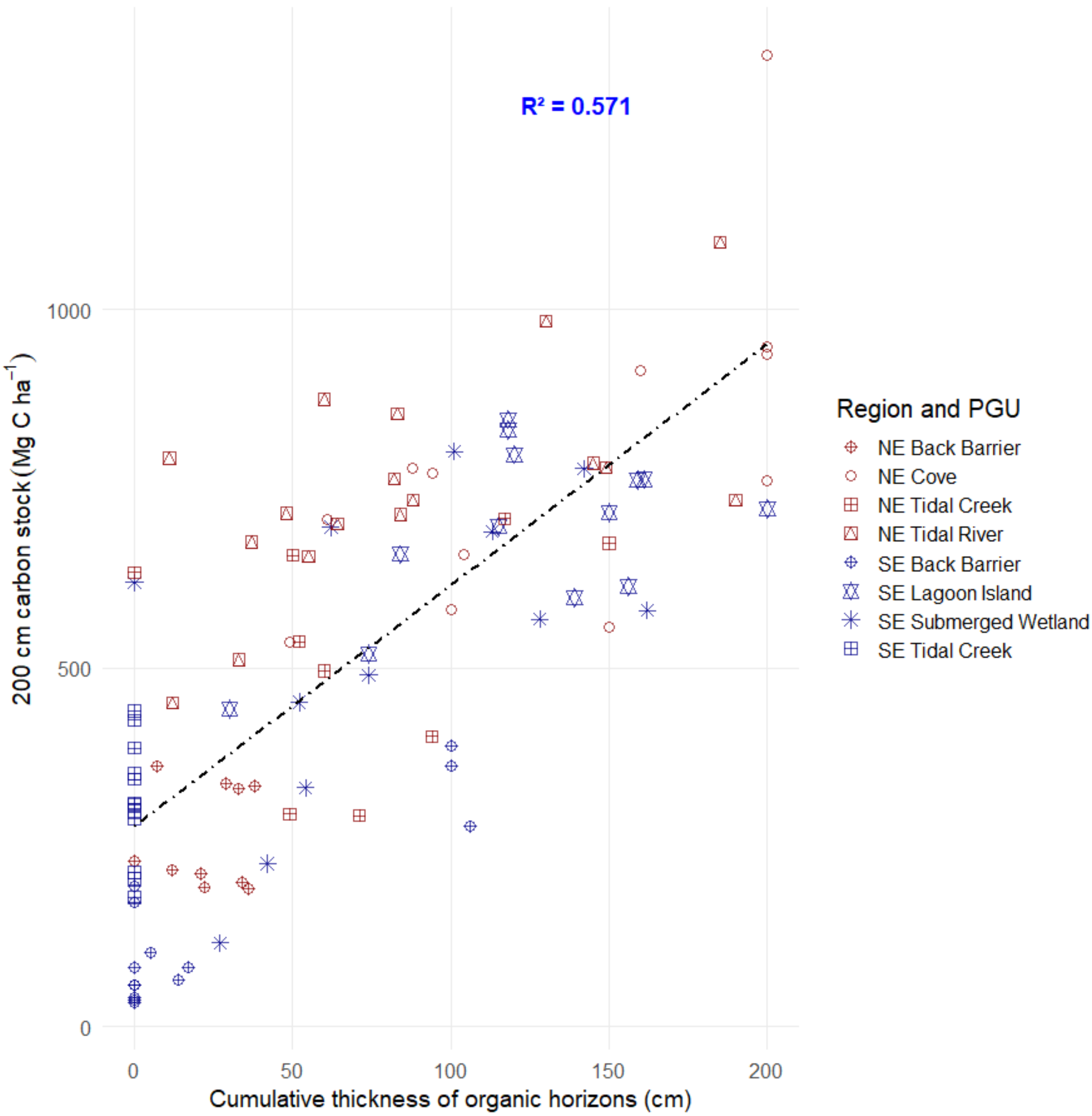
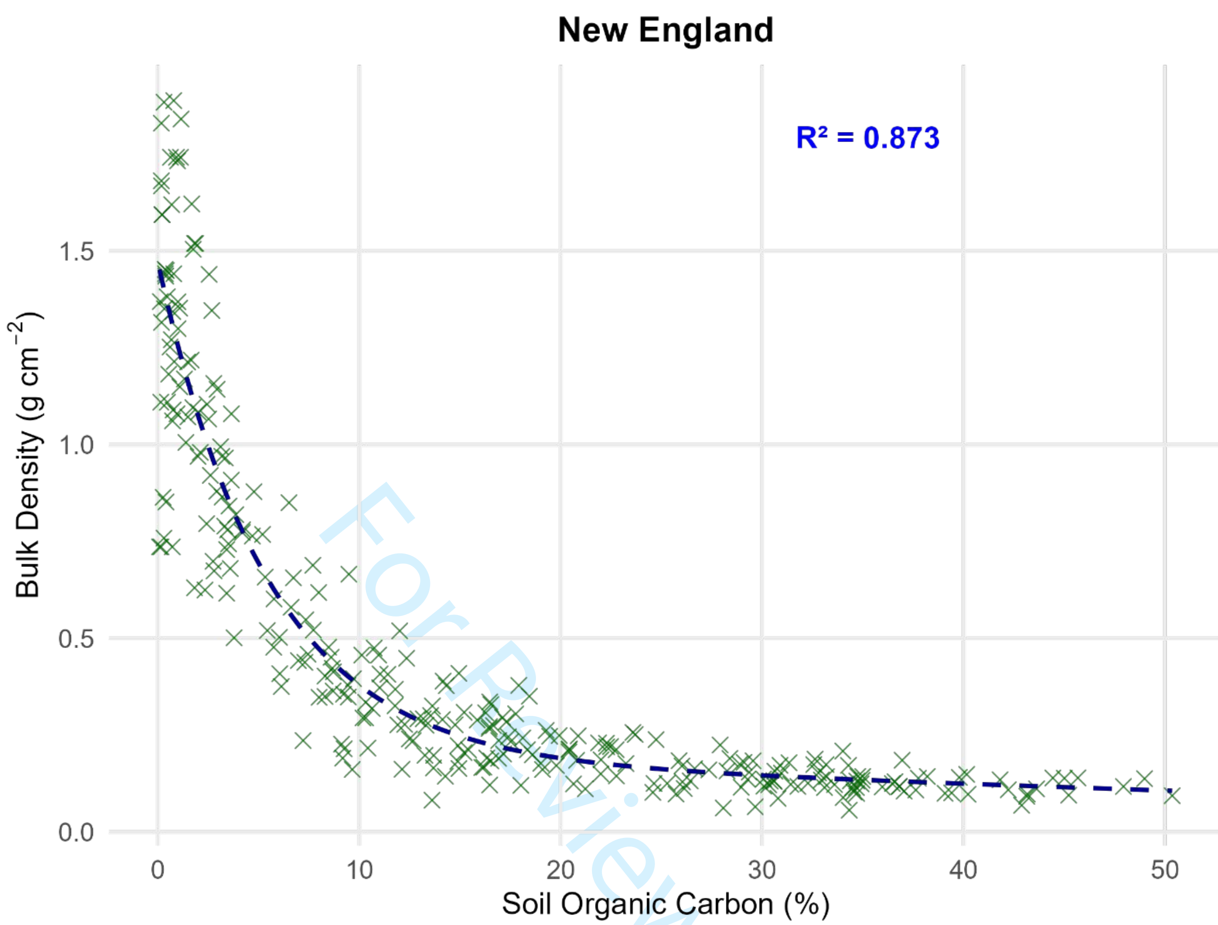
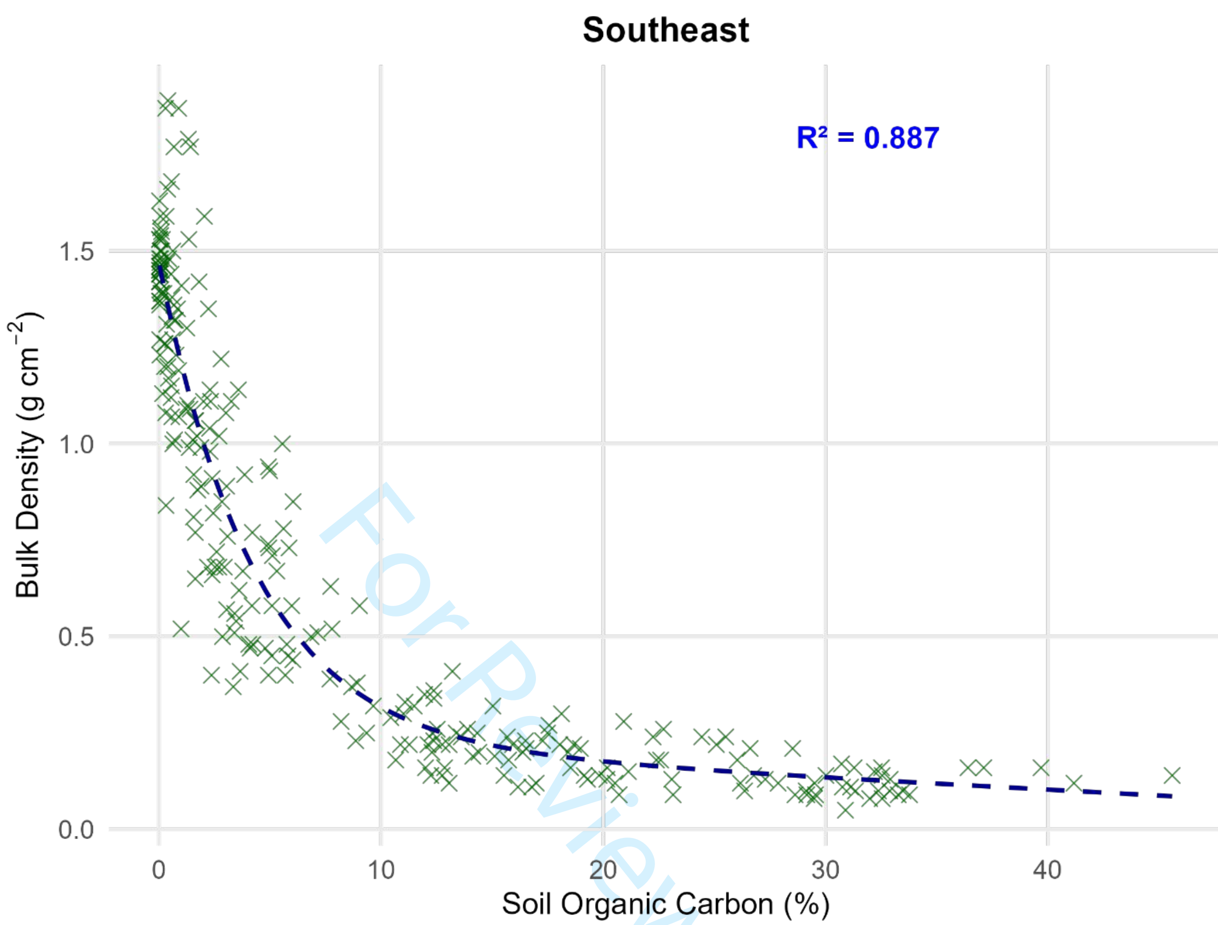


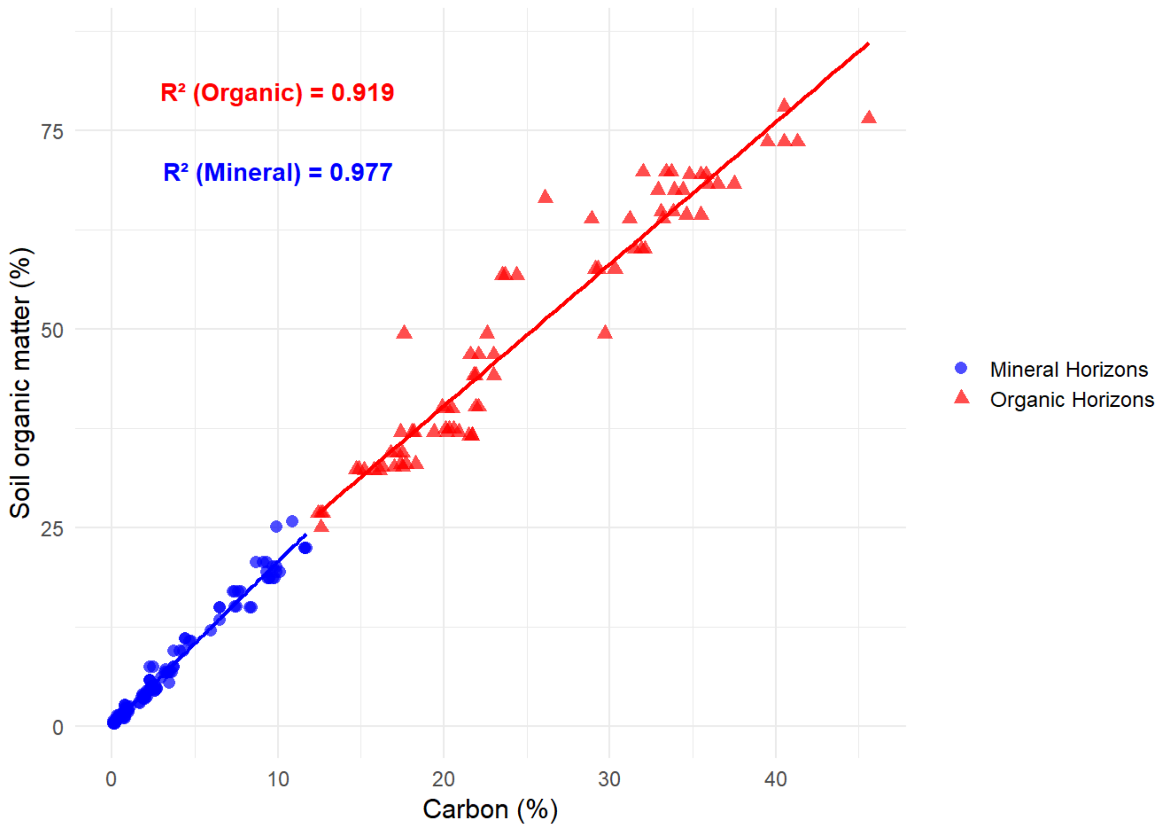
Figure 5: Linear regression of 200 cm carbon stock of all sampled pedons (Mg C ha^{-1}) vs cumulative thickness of all organic horizons within 200 cm of soil surface for both NE and SE PGUs; $p<0.0001$.



SD-F1: Relationship between bulk density (g cm^{-2}) and soil organic carbon content (%) utilized for modeling bulk density when a sample of known volume was unable to be taken in NE.



SD-F2: Relationship between bulk density (g cm^{-2}) and soil organic carbon content (%) utilized for modeling bulk density when a sample of known volume was unable to be taken in SE.



SD-F3: Relationship between soil organic matter (%) and soil organic carbon (%) of the subset of samples from NE used to model soil organic carbon from soil organic matter. The samples were split into 2 groups: mineral and organic horizons.