Blue carbon stocks in the Siuslaw River Estuary

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Image attributions

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Contents

Acronyms

ANOVA	analysis of variance
CAR	carbon accumulation rate
cm yr^{-1}	centimeters per year
g cm^{-3}	grams per cubic centimeter
GHG	greenhouse gas
HSD	Honestly Significant Difference
Mg C ha^{-1}	megagrams of carbon per hectare
MHHW	mean higher high water
MTL	mean tide level
NAVD88	North American Vertical Datum of 1988
NFB	North Fork Bend
PNW	Pacific Northwest
PVC	polyvinyl chloride
RTK-GPSS	real-time kinematic global positioning satellite system
SOC	soil organic carbon
Total C:N	total carbon-to-nitrogen

Summary

Protecting and restoring coastal tidal wetland ecosystems are essential natural climate solutions—contributing to reductions in atmospheric greenhouse gas emissions by increasing carbon sequestration and decreasing emissions. While studies show local watershed dynamics are important drivers of blue carbon stocks, blue carbon assessments are lacking in many estuaries. We sampled sediment carbon in three tidal marsh habitats—least-disturbed (i.e., "reference"), restored, and degraded—in the Siuslaw River Estuary, a temperate estuary in Oregon. We also examined sediment accretion rates at the least-disturbed tidal marsh to estimate carbon accumulation rates (CAR) for comparison with recent blue carbon estimation tools.

Tidal marsh habitats showed no significant differences in soil organic carbon (SOC), soil carbon, nitrogen, or organic matter despite differences in site characteristics and histories. Soil bulk density was higher at the degraded and restored tidal marsh sites compared to the reference site, and the total carbon-to-nitrogen (Total C:N) ratio was highest at the reference tidal marsh site. The lack of difference between SOC in the top meter between the reference and degraded sites may reflect the long-term dynamics of SOC, where soils gained over the last 1 to 2 centuries remain even in diked and drained tidal marshes. However, significant differences in bulk density and C:N ratios indicate that soil processes are impacted in the degraded tidal marsh as compared to the reference marsh.

Our case study suggests that the Siuslaw River Estuary has relatively high sediment carbon stocks—averaging 283 Mg C ha^{-1} in the top meter compared to 244.5 Mg C ha^{-1} within the top meter in other least-disturbed tidal marsh habitats along the West Coast. We did not detect any significant difference in sediment carbon stocks between the reference site (300 Mg C ha^{-1} at Cox Island), the restored site (279 Mg C ha^{-1} at S59), and the former tidal marsh/current pasture (250 Mg C ha^{-1} at North Fork Bend). Sediment accretion at Cox Island averaged 0.45 cm yr^{-1}, with higher accretion rates at lower elevation plots. Based on the average SOC density for the upper 10 cm at Cox Island, we estimated the site's CAR to be 1.728 Mg C ha^{-1} yr^{-1}, based on the accretion rate and average SOC density in the upper 10 cm (0.0384 g cm^{-3}). In other words, each year, the sediments at Cox Island store enough carbon in 1 ha to equal the annual emissions of one passenger car. In the top meter of sediments, Cox Island stores enough carbon to equal the emissions from approximately 220 passenger cars per year, the electricity used in approximately 150 U.S. homes for a year, or 1,100 round-trip flights from New York to London. These carbon stocks likely took centuries to accumulate, illustrating the importance of conserving these irreplaceable natural assets.

Introduction

Estuarine and nearshore ecosystems are significant carbon sinks that sequester substantial atmospheric carbon dioxide and store it over long periods as sediment carbon. Protecting and restoring these blue carbon ecosystems can help reduce atmospheric greenhouse gases (GHGs), serving as a natural climate solution while contributing to important ecological outcomes. However, tidal marsh carbon stocks and sequestration rates vary, even at regional scales, which complicates carbon and GHG accounting associated with protection and restoration projects (Janousek et al., 2025a; Peck et al., 2020).

In the Pacific Northwest (PNW), recent blue carbon studies have measured carbon stocks, assessed GHG flux rates, and identified key environmental drivers influencing these blue carbon values (Holmquist et al., 2024; Janousek et al., 2025a; Schultz et al., 2023; Williams et al., 2025). These studies have found high levels of carbon storage in PNW tidal wetlands, even relative to terrestrial ecosystems (Janousek et al., 2025a; Kauffman et al., 2020). In PNW tidal marshes, median sediment carbon stocks are 245 Mg ha^{-1}, but the measurements have a wide range, with increased carbon stocks at sites with higher tidal elevations and finer sediments (Janousek et al., 2025a; Kauffman et al., 2020; Peck et al., 2020). Notably, Janousek et al. (2025a) concluded that spatial variability in carbon stocks at the least-disturbed sites along the Pacific coast of North America is more likely driven by local factors (e.g., elevation, salinity, plant composition, local watershed) than by large-scale climatic gradients. While Oregon is among the coastal states with high-quality blue carbon data, expanded sampling across additional estuaries can help fill gaps in current blue carbon stock datasets and may provide further insight into the role of local watershed dynamics in determining carbon stocks.

Land use history affects carbon stocks. Historical degradation of tidal marshes most likely decreased carbon sequestration capacity and contributed to the loss of historical soil organic carbon (SOC; Kauffman & Bhomia, 2017; Tan et al., 2020). Approximately 85% of historical tidal wetlands have been lost from the Pacific coast of the United States (Brophy, 2019), with increased restoration efforts in recent decades. A recent study in the Stillaguamish Estuary in Washington found that sediment carbon stock in the top 30 cm was lower in the restored marsh than in the natural marsh, but carbon accumulation rate (CAR) was higher in the restored marsh than in the natural marsh, likely due to high rates of accretion post-restoration (Poppe & Rybczyk, 2021). The relatively high rates of accretion in the Stillaguamish Estuary immediately following restoration were higher than rates reported for Oregon estuaries (Brophy et al., 2016, 2018) and southern Puget Sound (Drexler et al., 2019), highlighting the need to understand accretion and associated carbon accumulation across a wider range of PNW estuaries.

Tidal wetland restoration techniques in the PNW can vary substantially, ranging from partially breaching or completely removing dikes to modifying large channel networks and restoring native vegetation. These variations further complicate our understanding of blue carbon in restored systems and illustrate the need for studies that compare restored marshes to reference and unrestored marshes within an estuary (Brophy et al., 2016, 2018; Crooks et al., 2014; Drexler et al., 2019; Poppe & Rybczyk, 2021). Indeed, local stratification across land use histories (e.g., least-disturbed and converted sites) was recently recommended as a best practice for blue carbon studies (Dahl et al., 2025).

The Siuslaw River Estuary historically comprised 1,090 ha of tidal vegetated wetlands and 1,300 ha of unvegetated wetlands. Of this area, 67% has experienced major alterations, such as dikes, tide gates, and restrictive culverts. Nearly all the tidal forested wetlands (96%) and 28.5% of tidal marshes have been converted to other land uses (Brophy, 2019). Despite these historical losses, recent restoration efforts within the Siuslaw River Estuary have been substantial. In 2005, 192 ha of tidal wetlands were in active restoration status, and by 2024, an estimated 280 ha more had some sort of restoration action, with an additional 138 ha slated for restoration action in the next few years (Brophy, 2019; Graves & Nuckols, 2025). To date, no carbon stock data have been collected for the Siuslaw River Estuary, though previous studies have evaluated sediment accretion and organic matter and have estimated the percent carbon at selected sites in the estuary (Brophy, 2009; Brophy et al., 2016).

In this study, we evaluated sediment carbon storage, bulk density, soil organic matter, SOC, and nitrogen at a least-disturbed (i.e., "reference"), a restored, and a converted tidal wetland site in the Siuslaw River Estuary. We compared carbon stock and soil parameters measured in this study with those reported for tidal marshes across the PNW (Janousek et al., 2025a, 2025b). Our study provides additional information for decision-makers considering blue carbon in tidal wetlands as a natural climate solution and fills gaps in blue carbon data availability by sampling a previously unsampled estuary along the Oregon coast.

Methods

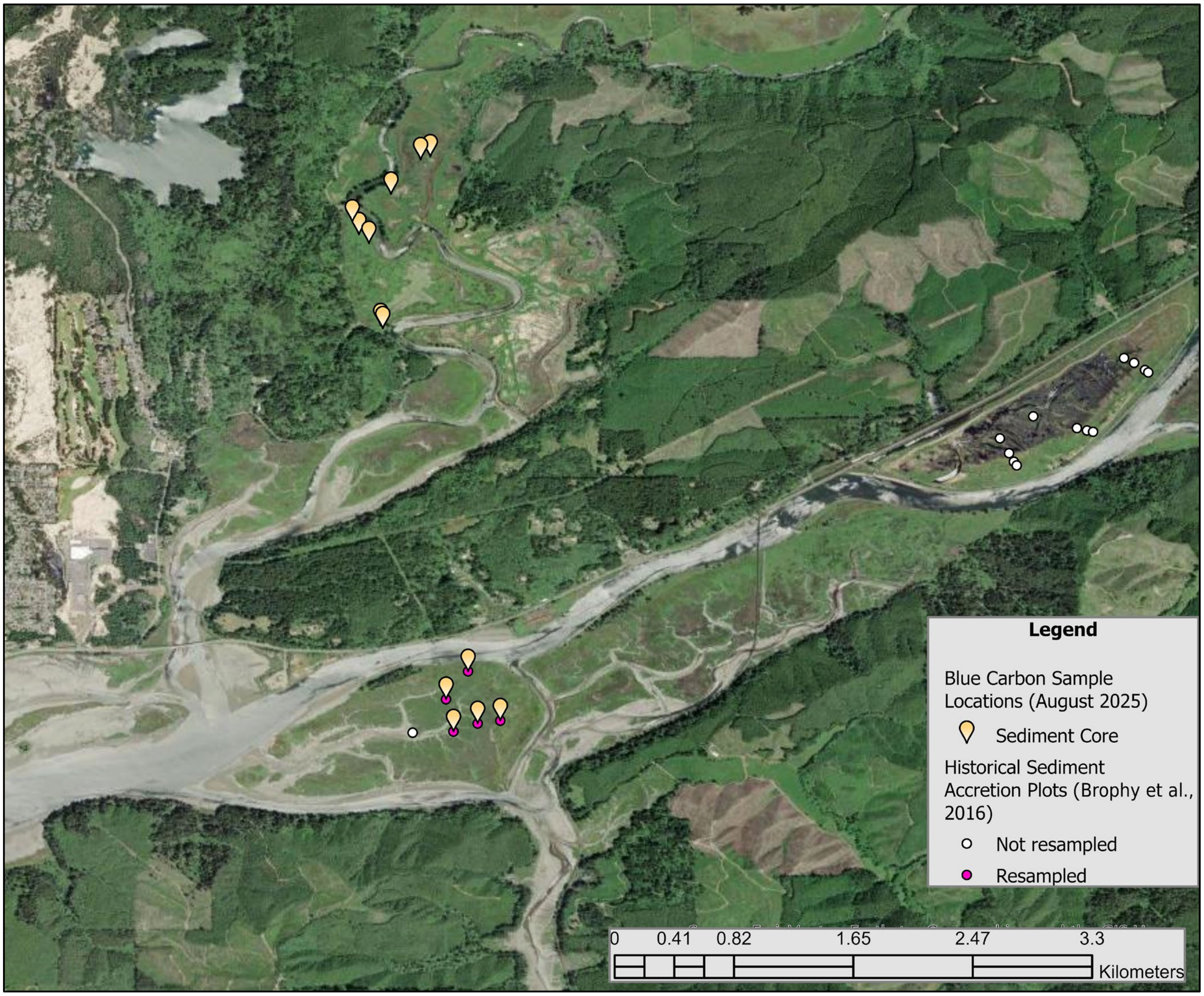
We collected data from three sites: the least-disturbed reference marsh (Cox Island), the restored marsh (S59), and the diked, former tidal wetland (nontidal pasture; North Fork Bend [NFB]; Table 1 and Figure 1). All sites were either current or former tidal wetlands and represented a range of salinity levels. Current tidal marsh vegetation was typical of Pacific coast estuarine marshes except at NFB, which was dominated by a mix of grasses, sedges, and forbs typical of tidal wetlands converted to pasture.

Table 1. Summary of sites and their type, area, elevation of sampled plots (mean [SD]), measured soil salinity (mean [SD]), and site history.

Site	Type	Area (ha)	Elevation (m)*	Soil salinity (ppt)	Site history
Cox Island	Reference tidal marsh, predominantly emergent marsh with some remnant forested areas at the highest elevations.	79.81	2.03 (0.18)	11.7 (3.91)	Limited disturbance: tree removal, likely some historical grazing. No history of diking or draining.
S59	Restored tidal marsh, predominantly emergent marsh with some mudflats. Historic vegetation was most likely emergent marsh and scrub/shrub.	34.32	1.74 (0.26)	6.60 (4.76)	Site was diked and used for cattle grazing, minor ditching. Tidal flow was restored due to the removal of two tide gates, the first through a natural breach (ca. 1996) and the second through intentional removal in 2001.
NFB	Pasture; degraded tidal wetland, historically forested tidal wetland and scrub/shrub.	99.96	1.21 (0.05)	1.92 (1.31)	Site was diked and used for cattle grazing. Site alterations also include a constructed levee and two tide gates.

* Each elevation is based on the North American Vertical Datum of 1988 (NAVD88).

Figure 1. Map of blue carbon sample locations and sediment accretion plots at three sites within the Siuslaw River Estuary.



Note. Historical sediment accretion plots that were not resampled were either logistically challenging to reach or had been removed as part of large-scale restoration at haich ikt'at'uu.

We evaluated sediment properties at each site by collecting sediment cores with a gouge auger (6.35-cm diameter, up to 1 m deep) or a soil core sampler (4.8-cm diameter, collected in 10-cm increments). We aimed to collect five cores at each site. The soil core sampler was only used in the drier, more compacted soils of NFB. The soil core length was recorded and photographed, and cores were cut into 10-cm subsamples and bagged to await transfer to the Oregon State University Soil Health Lab for analysis.

Soil compaction during coring was minimal (< 2 cm). At Cox Island, we located soil cores at plot locations established by Brophy et al. (2016), which also allowed us to resample for accretion rate (Figure 1). At the other two sites, soil core sample locations were allocated using a haphazard sampling technique, where we predetermined general areas based on an elevational gradient in each site and located sample locations haphazardly within those zones. GPS locations were taken at each sampling location. See Appendix A for our core collection and soil subsampling methods.

Wetland elevation was determined for Cox Island using the real-time kinematic global positioning satellite system (RTK-GPSS, NAVD88). For sample locations at S59 and NFB, elevation was extracted for each field-recorded GPS location from digital elevation models based on 2009 lidar (OCM Partners, 2026). Dominant vegetation within a 0.5-m radius of the coring location was recorded.

At Cox Island, we estimated annual accretion rates by taking two shallow cores at plots with feldspar marker horizons installed in fall 2013 (Brophy et al., 2016). For each shallow core, we measured the depth at which we observed the feldspar marker and used the average of the two measurements to estimate annual accretion rates (cm yr^{-1}). We also installed and flagged new feldspar marker horizons adjacent to the historical plots to continue monitoring accretion rates at Cox Island, with resampling planned for 2030. (Appendix A provides an explanation of feldspar marker horizons.)

Soil analysis was conducted by the Oregon State University Soil Health Lab. For each core subsample, bulk density was determined as the dry soil mass divided by the sample volume, using dry weight measured after samples were dried at 105 °C for 24 hours. Total carbon and nitrogen content was determined using an Elementar Vario MACRO cube carbon–nitrogen analyzer. Organic matter content was estimated using loss-on-ignition methods. Each subsample's electric conductivity was quantified and converted to salinity (ppt) using a conversion factor of 0.64.

We calculated carbon stocks (Mg ha^{-1}) for each core based on equivalent soil mass using cubic spline methods (von Haden et al., 2020). All cores were at least 10 cm long, and we calculated carbon stocks to 10 cm for each one. For longer cores, we calculated to greater depths as appropriate: to avoid excessive extrapolation, we only calculated stocks to 30 cm for cores at least 20 cm long, to 50 cm for cores at least 40 cm long, and to 1 m for cores at least 70 cm long. The equivalent soil mass method accounts for the soil profile's differences in carbon density and is especially important to consider when comparing sites with different land use histories and management practices, where differences in soil bulk density are expected (Bansal et al., 2023; Wendt & Hauser, 2013). Using feldspar measurements to estimate sediment accretion rate and the average carbon density in the top 10 cm at Cox Island, we estimated the CAR as the product of the sediment accretion rate and the soil's average carbon density (Ouyang & Lee, 2014).

Exploratory statistical analyses were conducted in R. We tested differences in bulk density, organic matter, percent carbon and nitrogen, and carbon stocks using Welch's analysis of variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post hoc analysis to identify significant pairwise comparisons. For depths deeper than 30 cm, low sample sizes at the pasture site (n = 2) necessitate caution in interpreting between-site differences. We examined relationships between carbon stocks, elevation, and soil salinity with linear regression. See Appendix A for the methodology of using feldspar markers for soil accretion monitoring.

Results

We collected 14 sediment cores across three sites: Cox Island, the least-disturbed tidal wetland (n = 5); S59, the restored tidal wetland (n = 5); and NFB, the former tidal wetland converted to pasture (n = 4). Core length varied from 70 cm to 1 m at Cox Island and S59. At NFB, the soil was drier and more compacted, limiting sample depths. Two core lengths at NFB were 10 cm and 30 cm. The other two were 80 cm each. The total number of subsamples varied by core and by site, depending on sampling depth.

Soil bulk density varied among sites and by depth, with significant differences among sites at 30 cm and 50 cm (Table B1 in Appendix B, Figure 2). At shallower depths, bulk density was higher at NFB, the former tidal wetlands. At 1 m, bulk density was similar across all three sites, though sample size was limited at NFB, and results should be considered preliminary for comparisons to NFB below 30 cm. Organic matter, percent carbon, and percent nitrogen were not significantly different among sites at 30 or 50 cm, or at 1 m (Table B1). The total carbon-to-nitrogen (Total C:N) ratios differed among sites, with the highest values at Cox Island and lower values at NFB (Table 2, Figure B2).

Figure 2. Soil bulk density by site and soil depth at three study sites within the Siuslaw River Estuary.

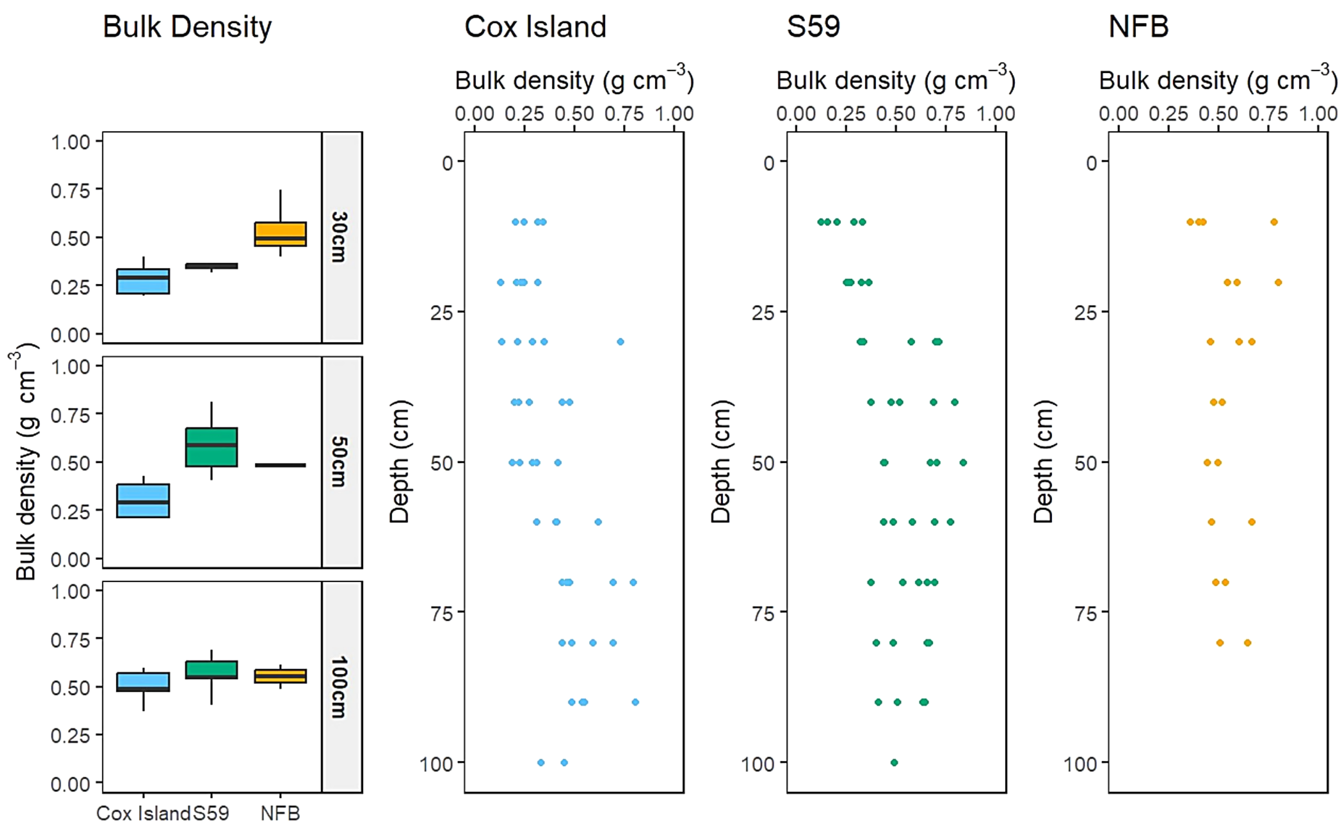


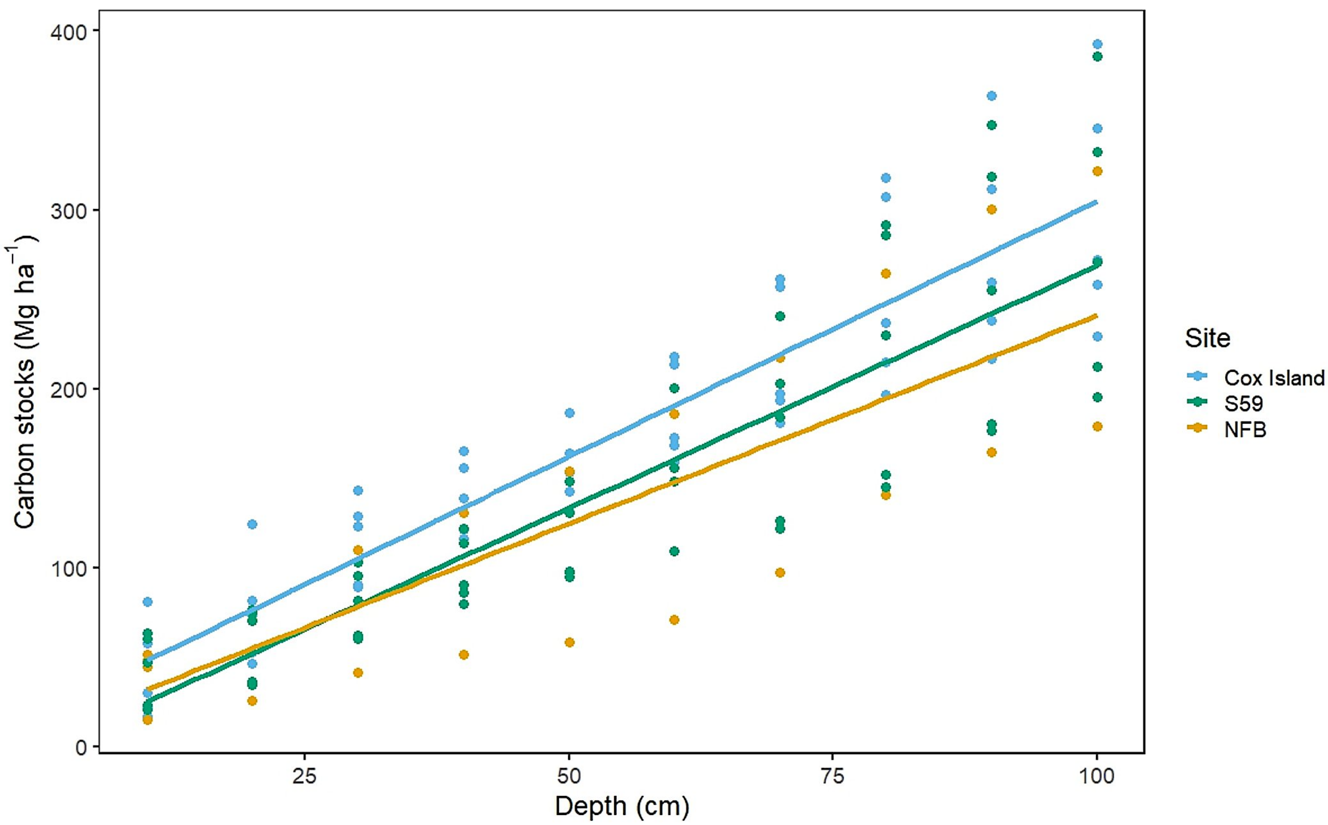
Table 2. Bulk density, percent organic matter (% OM), percent carbon (% C), percent nitrogen (% N), and Total C:N ratio for three tidal wetland sites in the Siuslaw River Estuary.

Site	n	Bulk density (g cm^{-3})	% OM	% C	% N	Total C:N ratio
Cox Island	45	0.392 (0.173) ^{a}	16 (9.15)	9.27 (5.38)	0.5 (0.247)	17.8 (2.22) ^{a}
S59	44	0.495 (0.183) ^{b}	13.8 (7.8)	8.02 (4.93)	0.521 (0.266)	14.9 (2.14) ^{b}
NFB	20	0.542 (0.12) ^{b}	14 (6.19)	7.55 (4.09)	0.584 (0.286)	12.6 (0.996) ^{c}

Note. Values reported are the mean (SD) for all processed subsamples at each site (all depths). Superscript letters indicate significant differences between site means based on Welch's ANOVA.

Soil carbon stocks were higher at Cox Island than at the other two sites across all depths (Figure 3), though not significantly different at 10, 30, or 50 cm, or at 1 m (Table 3). Average sediment carbon stocks at 1 m were 300 Mg C ha^{-1} at Cox Island, 279 Mg C ha^{-1} at S59, and 250 Mg C ha^{-1} at NFB. Soil carbon stocks at a 30-cm depth had weak to moderate positive relationships with both elevation (R^2 = 0.303) and soil salinity (R2 = 0.237; Figure B3 in Appendix B).

Figure 3. Cumulative soil carbon stocks (Mg C ha^{-1}) by depth (cm) at three sites in the Siuslaw River Estuary.



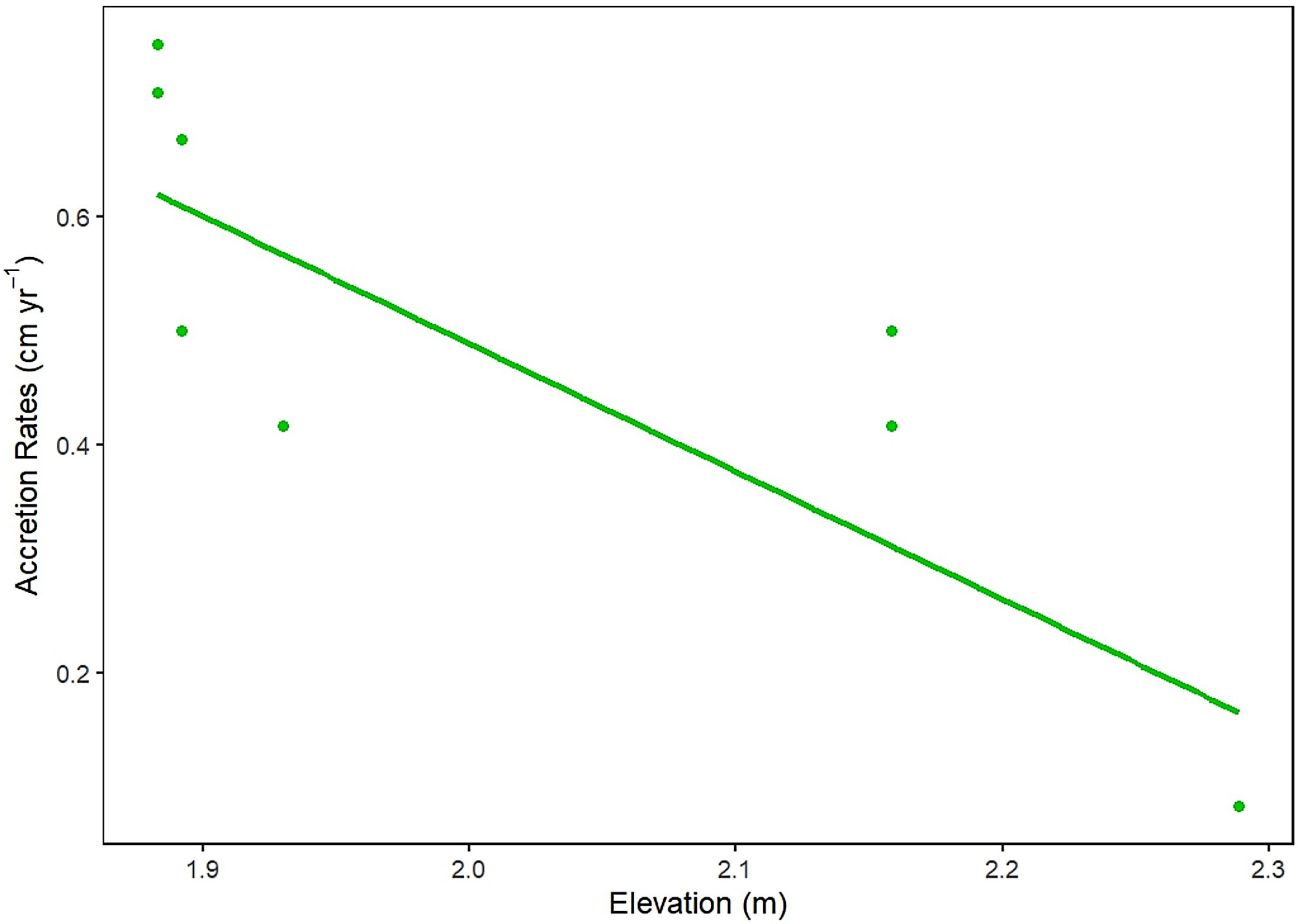
Note. Trendlines are based on linear models between stock and depth.

Table 3. Carbon stocks (Mg C ha^{-1}) to four depths at three sites in the Siuslaw River Estuary.

Depth	Carbon stocks (Mg C ha-1) *			F (df)	*p*
	Cox Island	S59	NFB		
10 cm	41.2 (27.3, 5)	42.6 (20.1, 5)	39.8 (16.8, 4)	0.017 (2, 11)	0.983
30 cm	115 (23.9, 5)	80.4 (19.3, 5)	84.8 (37.9, 3)	2.524 (2, 10)	0.13
50 cm	156 (21.2, 5)	114 (24.2, 5)	106 (67.4, 2)	2.984 (2, 9)	0.101
1 m	300 (67.5, 5)	279 (80.3, 5)	250 (101, 2)	0.296 (2, 9)	0.751

* Stocks are reported at mean (SD, n).

Figure 4. Measured accretion rates plotted against plot elevation at the Cox Island reference site in the Siuslaw River Estuary.



Sediment accretion at Cox Island averaged 0.45 cm yr^{-1}, with higher accretion rates at lower elevation plots (Figure 4). Using the average SOC density for the upper 10 cm at Cox Island (0.0384 g cm^{-3}), the CAR was estimated to be 0.01728 g cm^{-2} yr^{-1}, or 1.728 Mg C ha^{-1} yr^{-1}.

Discussion

We estimated soil carbon stocks and evaluated sediment properties at three sites in the Siuslaw River Estuary. Our results are highly consistent with recent studies of SOC stocks and sediment properties in tidal marsh sites across the PNW (Janousek et al., 2025a, 2025b). On average, tidal marsh sediments stored 283 Mg C ha^{-1} in the top meter, with little difference in SOC among the reference, restored, and degraded sites. These estimates are higher than recent estimates of the mean SOC to a 1-m depth for tidal emergent marshes in the PNW (244.5 Mg C ha^{-1}; Janousek et al., 2025a), suggesting that the Siuslaw River Estuary has higher stocks than similar estuaries along the West Coast. Our study was not designed to identify which estuary features contribute to higher stocks, but it does reinforce recent findings that local watershed conditions are important to understanding blue carbon.

The lack of difference between SOC in the top meter between the least-disturbed and degraded sites may reflect the long-term dynamics of SOC, where soils gained over the last 1 to 2 centuries remain even in diked and drained tidal wetlands. However, significant differences in bulk density and C:N ratios indicate that soil processes may be impacted by these different site histories. Other possible explanations include that the degraded/unrestored site (NFB), while pasture now, was historically tidal swamp (forest and scrub/shrub), and deeper stocks may reflect carbon accumulated under different ecosystem conditions than in the least-disturbed (Cox Island) and restored sites (S59; tidal marsh).

Monitoring wetland elevation changes and soil accretion, along with changes in soil carbon content, is important for tracking changes in soil carbon stocks over time, attributing carbon gains over time, and projecting the future tidal ecosystem trajectory. Accretion rates at Cox Island tracked the elevation gradient present at that site, with lower-elevation sites having higher accretion rates. In addition to allowing us to estimate CAR, accretion rates give us insight into potential site trajectories as sea levels rise in response to climate change. Where accretion rates do not keep pace with sea level rise, tidal marshes are at risk of submergence and loss.

Based on intermediate magnitude sea level rise projections for two nearby locations (South Beach/Newport ~ 50 mi [~ 80 km] to the north and Charleston ~ 50 mi [~ 80 km] to the south; Sweet et al., 2022), the Siuslaw River Estuary could experience up to 20 cm of sea level rise by 2050, equating to approximately 0.39 cm yr^{-1}. Cox Island, with an average accretion rate of 0.45 cm yr^{-1}, will likely keep pace with sea level rise, although vertical land motion (e.g., subsidence) and major earthquakes could greatly amplify the effects of sea level rise (Dura et al., 2025). Furthermore, the higher elevations on Cox Island, which have lower accretion rates (0.08 cm yr^{-1}), may experience shifts in tidal influx and salinity, which could lead to changes in marsh vegetation. Resampling accretion rates can help monitor sedimentation and help managers plan for vegetation trajectories at this and other sites in the Siuslaw River Estuary.

Using the carbon density and accretion rates, we estimated a CAR at Cox Island to be 1.728 Mg C ha^{-1} yr^{-1}. Our estimate of soil CAR was outside the range referenced for conserving tidal emergent wetlands (0.8755 to 1.0773 Mg C ha^{-1} yr^{-1}) in the PNW Blue Carbon Calculator (Schile-Beers et al., 2025). The calculator used published estimates to parameterize lookup tables for calculating the GHG outcomes from different tidal wetland scenarios. Our results provide an example where PNW Blue Carbon Calculator estimates are conservative, at least in the case of soil carbon accumulation, conforming to core carbon principles set forth by the Integrity Council for the Voluntary Carbon Market (e.g., that GHG emission reductions or removals shall be robustly quantified, based on conservative approaches).

Our case study provides an initial assessment of carbon stocks at three sites in a previously unsampled estuary. Because of sampling challenges in the dry, compacted former tidal wetland site, sample sizes were small for estimating deeper carbon stocks in the diked pasture site (NFB). Anyone conducting future monitoring efforts should work closely with restoration planners to identify opportunities to gather pre- and post-restoration data on soil carbon stocks and sediment accumulation rates, which will help develop more precise estimates for CAR in tidal wetland sites and help identify differences in carbon trajectories based on site histories.

Our case study suggests that the Siuslaw River Estuary has relatively high sediment carbon stocks—averaging 283 Mg C ha^{-1} in the top meter compared to 244.5 Mg C ha^{-1} within the top meter in other least-disturbed tidal marsh habitats along the West Coast. Each year, the sediments at Cox Island store enough carbon in 1 ha to equal the annual emissions of one passenger car. In the top meter of sediments, Cox Island stores enough carbon to equal the emissions from approximately 220 passenger cars per year, the electricity used in approximately 150 U.S. homes for a year, or 1,100 round-trip flights from New York to London. These carbon stocks likely took centuries to accumulate, illustrating the importance of conserving these irreplaceable natural assets and ensuring that these ecosystems continue to accumulate and store carbon into the future.

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Appendix A:

Blue carbon stock and soil accretion monitoring—field protocol

Prepared by Rose A. Graves and Jason Nuckols, The Nature Conservancy

Figure A1. Collecting sediment cores with a gouge auger in the Siuslaw River Estuary.

Monitoring objectives

1. Evaluate current soil carbon stocks in tidal marsh sites.
2. Collect relevant environmental covariate data, including salinity, dominant vegetation type, and depth to water table.
3. Establish baselines for current carbon stocks and surface elevations.
4. Establish feldspar marker horizons for future sampling.

Method overview

At selected monitoring sites, soil cores up to 1 m deep are collected from current and/or former tidal wetlands to evaluate current soil carbon stocks. Feldspar markers and surface elevation are established to allow for resampling and to estimate soil accretion and carbon accumulation rate (CAR). When determining soil organic carbon (SOC), soil cores are collected and analyzed by soil depth for (1) dry bulk density and (2) SOC content (% C). Dry bulk density multiplied by SOC content gives the carbon stock in units of mass per volume. Samples are sent to a lab for analysis of bulk density, carbon, and any other soil properties you choose to have assessed. When possible, soil cores are located adjacent to feldspar marker horizon plots. Salinity, depth to water, and surface elevation data are collected at each plot.

Methods, Part A: Sample design

The sampling design, including site selection and the number and locations of sampling plots, depends on the project's overall goals. Once sites are selected, the best practice is to use a stratified random sampling design. This practice involves subdividing the site through stratification to ensure sampling represents the variety of conditions across the site. You might consider stratification based on vegetation cover, salinity, elevation, or expected changes due to conservation or restoration projects. The number of samples per stratum should be proportional to the size of the stratum, the expected variability within the stratum, and the targeted accuracy. If high precision is needed, a power analysis using existing data (from similar studies or local/regional site data) can inform the number of samples needed. Sample sizes will likely represent your need to balance accuracy with logistical costs.

A minimum of three plots per stratum is commonly recommended. However, if there is high variability (e.g., elevation gradients), higher sample sizes are needed to characterize the average carbon stocks. Proportional allocation of samples to site strata can also be determined using a simple formula based on the area of each strata, total area of the site, and the total number of planned plots (e.g., based on logistical constraints):

$$Plots\ per\ strata = \left(\frac{Strata\ Area}{Total\ Area\ of\ Site}\right) \times Total\ \#\ of\ Plots$$

Other sampling designs that align with project goals and logistics (e.g., co-locating with vegetation monitoring transects) can also be considered. The remainder of this protocol focuses on field data collection at predetermined plot locations, based on your determined sampling design.

Methods, Part B: Core collection in the field and soil subsampling

Part B was adapted from *Tidal Wetland Deep Soil Core Standard Operating Procedure v.1* (Williams et al., 2025).

Materials for the field

- Gouge auger (recommended), Russian peat borer, or 10-cm diameter polyvinyl chloride (PVC) tube for current tidal wetlands
- Bulk density sampler and/or soil corer for former tidal wetlands (auger-style sampler or slide-hammer-driven sampler recommended)
- Meter stick
- Sharp serrated paring knife, 3 to 4 in. (~8 to 10 cm)
- Labeled plastic bags
- Thick garden gloves
- Copies of field data sheets on waterproof paper
- Pencils
- Camera to photograph cores
- Small towel or cleaning rag
- Handheld GPS
- Conductivity meter

- Permanent marker
- Bin(s) for storing samples
- Small tarp or plastic sheeting (helpful for laying field gear down)

Before going into the field

1. Gather all materials. For smaller field gear, it can be helpful to tie bright flagging to it or paint it with bright colors in case you need to find it in the field.
2. Determine your sampling design and plot locations, or the method for locating plots in the field.
3. Pre-weigh and label sample tins or bags.
4. It is helpful to make measurement marks on the outside of your auger/corer using some kind of permanent/semipermanent method (e.g., nail polish/paint marks every 10 cm from the bottom of the corer).

In the field

At the selected coring location, record the GPS location (and type of GPS, e.g., smartphone, handheld Garmin) and the dominant vegetation species within approximately a 0.5-m radius of the coring location.

To take the soil core, gently place the gouge auger at the soil surface and, with a slight motion back and forth, cut through roots in the first few centimeters of soil. You should have little to no compaction of the soil surface. With one or two people applying even, firm pressure to the auger handles, sink the auger directly into the soil until reaching the 90-cm to 1-m mark (Figure A2). If you reach the point of refusal before the full depth, take note of the depth reached and measure compaction as described below.

Using the meter stick or smaller ruler, on the top of the core, measure the degree of soil compaction to the nearest 0.5 cm as the difference between the soil level outside of the metal auger and the soil level of the core within the auger. If compaction measures more than about 2 cm, you should try to core again. If the compaction is 2 cm or less, twist the auger once in a clockwise direction to cut through any roots; you should see the surface of the core rotate with the auger.

To remove the core, simultaneously pull the corer up vertically while slowly rotating it in a clockwise direction. When removed, lay the corer on its side with the intact soil core within. Lay a meter stick next to the core (with the 0 cm mark at the very top of the core), and take a photograph of the core (Figure A3). Before you cut slices from the core, record notes about the depth intervals of obvious soil horizons, obvious roots, or other notable information about the appearance and quality of the core.

Use a ruler laid along one side of the extracted core to gently mark the sediment with a knife in predetermined increments all the way down the core. Increments can depend on the study design or needs. For example, Williams et al. (2025) recommended 2 cm but noted that 1, 3, or 5 cm can be used. Due to budget and logistical constraints, The Nature Conservancy chose to use 10 cm increments in the Siuslaw River Estuary. Smaller slices (e.g., 2 cm) are needed if you plan to use the core for radiometric dating (Pb210 and/or 137-Cs), which enables the determination of long-term sediment deposition rates and carbon sequestration rates. Larger increments can be used to determine soil carbon stocks by those depth increments.

Figure A2. A gouge auger is inserted into a tidal marsh to collect a blue carbon core.

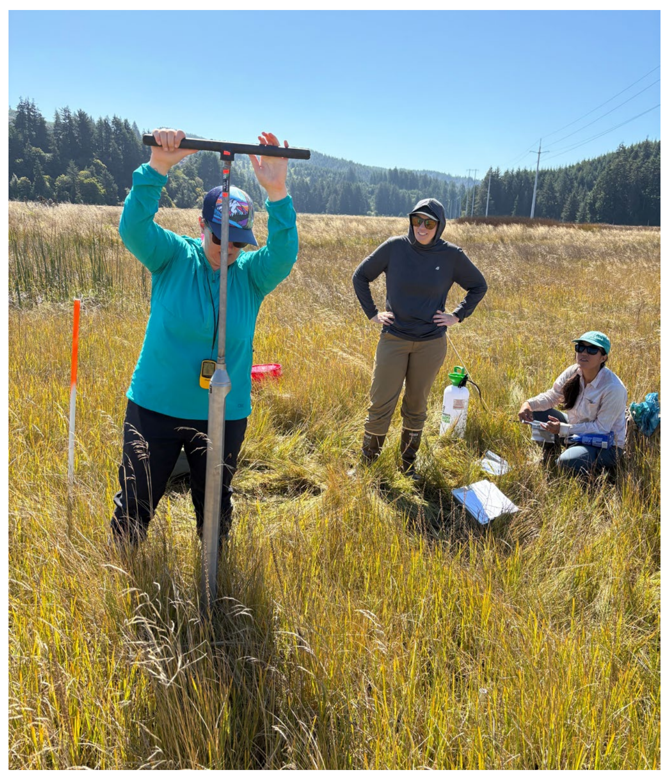


Figure A3. A blue carbon core collected from a tidal marsh in the Siuslaw River Estuary, with gaps that make the core less than fully cylindrical.

Note. Gaps/missing pieces prevent the core from being fully cylindrical. These imperfections should be noted in the field. These gaps/missing pieces add to uncertainty in carbon estimates but are hard to control completely in the field.

You are now ready to slice the core into subsamples. Use the knife to gently and cleanly slice each section, and place it in a marked sample tin or labeled bag. Make sure the knife is sharp so that you can cleanly cut larger roots. You may need some small scissors to cut roots.

Measure the diameter of the soil auger at the spot where you extracted the slice. Your auger may have a uniform diameter or vary slightly along its length, depending on the quality of manufacture. Measure the height of each slice (which should be as close to your chosen increment as possible) to obtain the volume of each subsample. Fill out the pertinent data on the field sheet, including the corresponding sample number and sample depth for each numbered tin or bag. If conducting Pb210 analyses, transport samples in a cooler and store in a cold fridge or freeze until analysis. Pb210 analyses can help determine long-term sediment accretion rates by assessing the downcore distribution of Pb210. Otherwise, seal sample bags and store in airtight containers.

Clean the gouge auger of all soil before you take your next core. You can use water in a tidal channel and an old rag to help clean the auger. Be sure to follow the safety considerations described in the next section.

Figure A4. View over a tidal marsh in the Siuslaw River Estuary.

Safety considerations

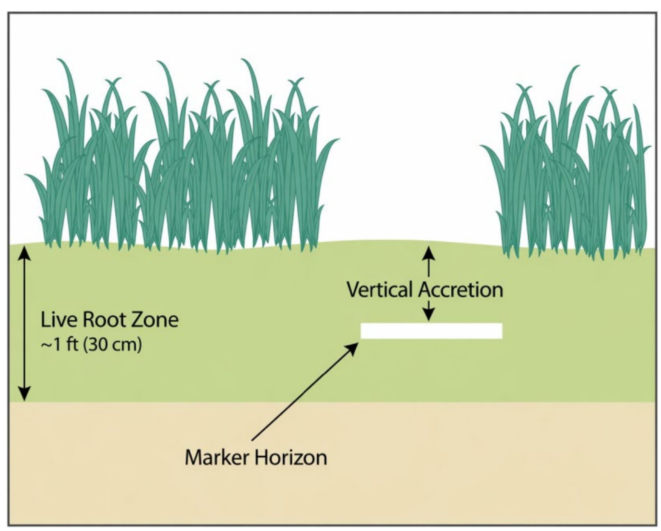
Special care should be given to transporting the gouge auger, using it in the field, and cleaning it. The edge is very sharp; therefore, garden gloves should be used to protect hands when cutting and removing core sections and when cleaning. The clean auger should be transported in a PVC sheath or by other means so it can be carried in the field without risk of injury. In the lab, while grinding the sample, wear a dust mask or an N95 respirator to avoid inhaling any dust generated during the process.

Methods, Part C: Feldspar markers for soil accretion monitoring

Part C was adapted from *Measuring Accretion With a Feldspar Marker Horizon—Version 1.00* (Whelan & Prats, 2016).

This section describes the establishment and re-measurement of feldspar horizons. A feldspar horizon is a white, inert marker layer used to measure soil accretion (e.g., Figure A5). It acts as a permanent or semipermanent stable reference point for tracking accumulation rates of new sediment over time, as it is easily distinguished from natural soil.

Figure A5. Representation of a feldspar marker horizon. Figure from the U.S. Geological Survey (n.d.), public domain.



The depth to the feldspar marker horizon is then measured at determined intervals in the future by the coring plug method.

Establishing feldspar marker horizons

Materials for the field

- Feldspar—a brilliant white material that forms a cohesive layer once it gets wet and is easily distinguishable from the surrounding sediment
    - *Note*: Feldspar can be sourced from pottery/ceramics suppliers. Feldspar typically comes in 50-lb (~ 23 kg) bags, each of which is sufficient for 8 to 10 feldspar plots, each measuring 0.5 m by 0.5 m.
- 0.5 m by 0.5 m square made from PVC or other material for marking the plot
- Meter stick
- Measuring cup
- N95 respirator, or a similar mask
- Eye protection
- Watering can or 1 gal. (~ 3.8 L) sprayer
- Camera
- GPS unit
- PVC plot marker stakes (2 m tall; with one end painted bright colors to easily find it)
- Mallet
- Copies of field data sheets on waterproof paper
- Pencils
- Trash can with the bottom cut out (if plot is expected to be inundated during establishment)

Before going into the field

1. Gather all materials. For smaller field gear, it can be helpful to tie bright flagging on it or paint it with bright colors in case you need to find it in the field.
2. Place the feldspar bags in something waterproof to carry (e.g., 5-gal. [~ 19 L] bucket).
3. Determine your sampling design and plot locations, or the method for locating plots in the field.
4. *Note*: We recommend co-locating feldspar plots with soil cores if possible.

In the field

At the selected plot location, record the GPS location (and the type of GPS—e.g., smartphone, handheld Garmin) and the dominant vegetation species within approximately a 0.5-m radius of the coring location. If possible, we recommend recording the elevation of each feldspar plot (ideally when established) using the high-precision real-time kinematic global positioning satellite system (RTK-GNSS). Alternatively, you can use a GPS receiver with tilt correction activated and GPS corrections received by a cellular hotspot. Before surveying, consider performing an equipment setup verification at a nearby National Geodetic Survey mark. This approach should result in less than 0.1 ft (~ 3 cm) of elevation error.

Place the plot square on the surface of the tidal marsh to outline where the feldspar plot will be (Figure A6). Mark at least one corner of the plot with a length of PVC pipe pushed down into the ground or gently pounded with the mallet until secure (Figure A7). Record which corner is marked using cardinal directions so that feldspar will not be trampled when finding it again (e.g., NE corner of plot). Record

Figure A6. Establishing a feldspar plot in the Siuslaw River Estuary.

the water level with respect to the soil surface. If no water is present, write "dry." If water is present, measure the water depth using the meter stick and record it on the data sheet.

Using the measuring cup, evenly sprinkle the feldspar on the soil surface within the accretion plot, making sure not to leave any on the vegetation. Vegetation can be gently shaken to knock any feldspar from the plant to the soil surface, or water may be used to rinse the vegetation. Apply feldspar to the plot until the plot is evenly coated at a minimum thickness of 5 mm. A reasonable estimate is that each plot will require about 5 to 6 cups (~ 1,183 to 1,420 mL) of feldspar. Avoid breathing in the feldspar dust by wearing a protective mask or respirator (e.g., N95).

If the soil is dry on the day of the plot establishment, the feldspar needs to be compacted with water after it is applied. Carefully spray water through a watering can or sprayer to moisten the feldspar and consolidate the material. Make sure no feldspar voids are created on the soil surface. If voids are created, reapply feldspar and water.

If the soil surface is flooded on the day of the plot establishment, a trash can with the bottom removed can be used as a barrier to allow the feldspar to settle to the soil surface without drifting out of the plot's boundary. Place the trash can on the soil so there is no space between the soil and the trash can. Sprinkle feldspar onto the water surface inside the trash can. Wait 15 min or longer for all the feldspar to settle, since the feldspar tends to float when it is applied. Remove the barrier when all the feldspar has settled.

Sampling feldspar marker horizons

Marker horizons can persist for several years, depending on the energy of the tidal system. Resampling frequency recommendations vary, depending on monitoring goals. When marker horizon plots become unusable (e.g., feldspar is no longer distinguishable), new or replacement plots should be established. When new feldspar is added directly over an old plot (i.e., replacement plot), there can be increased potential for error from confusion regarding which layer(s) are measured.

Figure A7. A feldspar plot established on Cox Island Preserve in the Siuslaw River Estuary.

Materials for the field

- Coring tube (prepared 150-cc syringe w/plunger, push soil corer)
- Serrated or filet knife
- Ruler or calipers (mm), stainless steel
- Data sheets
- Pencils
- Camera
- GPS (to navigate to marked locations)
- Extra PVC pipe (to remark plots if PVC markers are damaged or missing)

In the field

Take care to limit disturbance within the feldspar plot. Avoid stepping directly on the site and use different routes to approach the plots for remeasurement. Consider keeping the timing of measurements relatively consistent regarding seasons and/or tides. Avoid sampling if the site is frozen.

Once you have navigated to the plot location, record vegetation within an approximately 0.5-m radius. Note any specific conditions (e.g., soil disturbance, water depth, marker condition). Measurement of accretion with marker horizons is accomplished by cutting a plug or taking a core, as described in this protocol. Other methods include cryogenically freezing a segment or measuring directly in the ground, but they are not described here. The technique employed for accretion measurement should be consistent over time. When establishing a monitoring program, consider your options based on logistical constraints, measurement accuracy, and site conditions.

Avoid compacting sediments during extraction (e.g., do not press down on the marsh surface). If feldspar is not found on the first try, try up to three separate locations. Record how many attempts you make. Extraction tools should be selected based on the expected accretion rates and resampling intervals (e.g., if feldspar is expected to be deep, consider a longer tool). To avoid resampling the same location, it is worth considering the use of meter sticks to establish a grid-based sampling layout with X- and Y-axes.

To resample using a *plug*, cut a small section by hand with a knife, extract it, and measure it in the field. To resample using a *core*, you will need a coring device—a large syringe with a plunger or a push corer will work. You will insert the corer into the soil, taking care not to compress the soil surface. Using a clear syringe or an open-sided corer allows you to extract the core and measure it in the field. Use a caliper or ruler to measure from the top of the marker horizon to the ground surface. The ground surface is the sediment surface, not including any vegetation, debris, roots, trash, etc., on top of the sediment surface. Record the depth in millimeters. Aim to take at least three measurements per plot. After measurement, you can gently place any disturbed material back in the plot in its original orientation and position (to the best of your ability), or you can consider sending the soil to be analyzed for total carbon and bulk density. If you choose to have a lab analysis performed, you will need to know the volume of soil to calculate bulk density.

Once you have recorded the measurements from your resampling, calculate the *soil accretion rate* by dividing the measured accretion by the time since the feldspar marker horizon was established.

Appendix B:

Supplementary figures and table

Figure B1. Boxplots of percent organic matter (% OM), percent carbon (% C), and percent nitrogen (% N) at three different soil depths by site in the Siuslaw River Estuary.

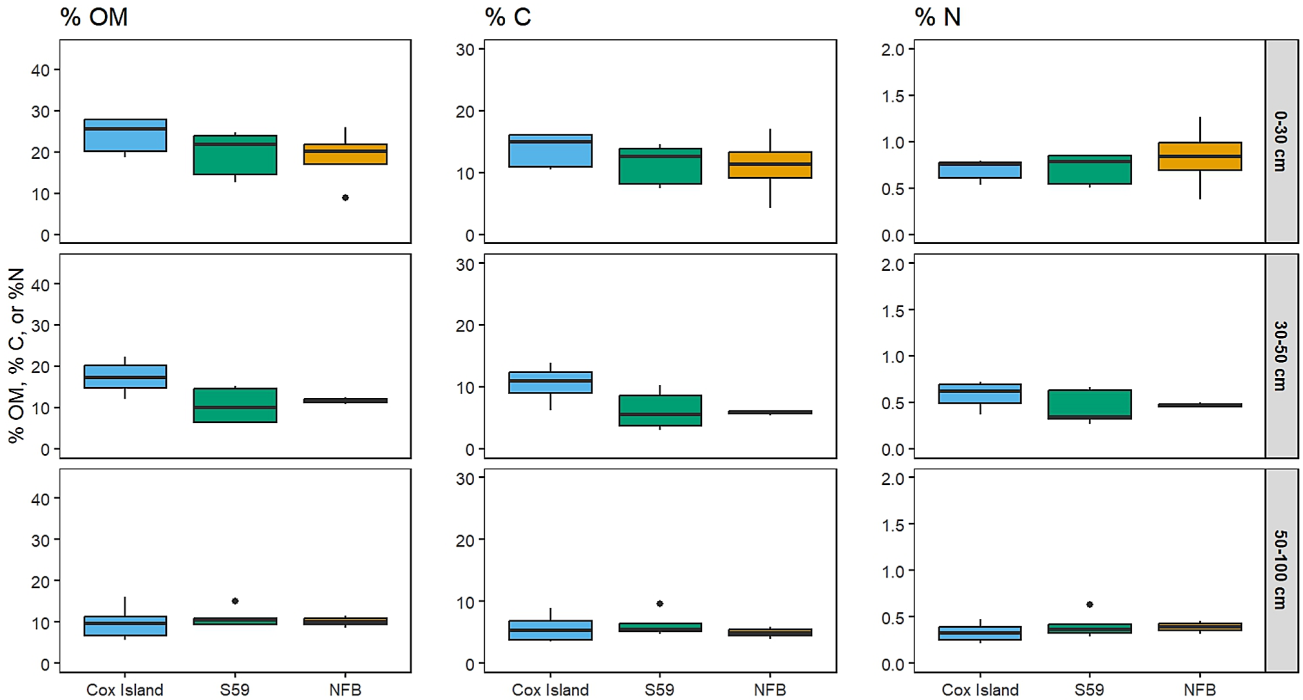


Figure B2. Boxplot of the total carbon-to-nitrogen (Total C:N) ratio at three different soil depths by site in the Siuslaw River Estuary.

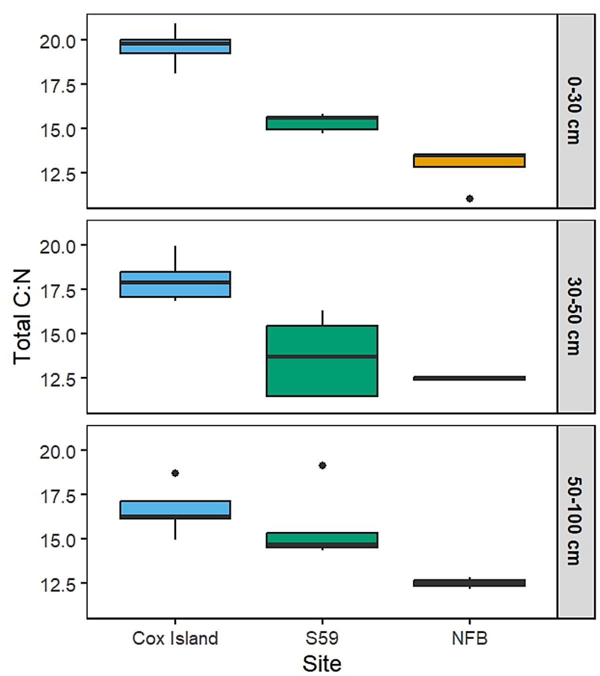
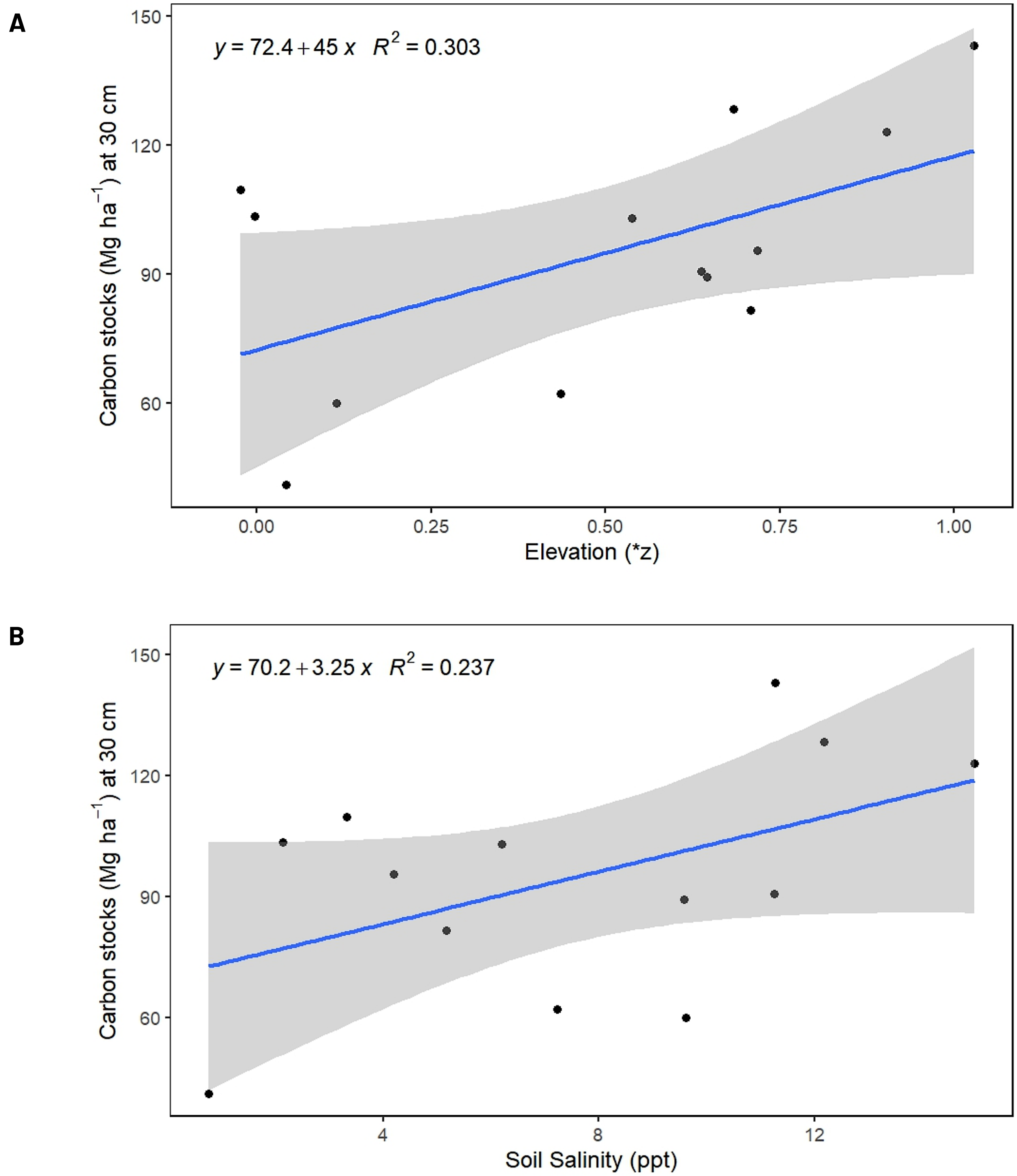


Figure B3. Carbon stocks at 30 cm compared to (A) elevation and (B) soil salinity, with linear regression equations and R^2 displayed for each relationship.



Note. Elevation was converted to a relative tidal elevation using mean tide level (MTL) and mean higher high water (MHHW) and the following formula: z* = (elevation – MTL) / (MHHW-MTL) per Janousek et al. (2025a). For interpretation, z* = 0 equates to the local MTL, and z* = 1 equates to local MHHW.

Table B1. Statistical summary of differences in soil properties between sampled sites in the Siuslaw River Estuary.

Soil property	Depth	F, df	*p*	Cox Island	S59	NFB
Bulk density	All depths	6.91 (2,106)	0.002	a	b	b
	0-30 cm	8.08 (2,11)	0.007	a	a	b
	30-50 cm	6.57 (2, 9)	0.017	a	b	ab
	50 cm-1 m	10.2 (2, 9)	0.615	-	-	-
Percent organic matter	All depths	0.87 (2,106)	0.423	-	-	-
	0-30 cm	1.22 (2, 11)	0.333	-	-	-
	30-50 cm	3.85 (2, 9)	0.062	-	-	-
	50 cm-1 m	0.15 (2, 9)	0.86	-	-	-
Percent carbon	All depths	1.11 (2,106)	0.335	-	-	-
	0-30 cm	0.74 (2,11)	0.499	-	-	-
	30-50 cm	3.37 (2,9)	0.081	-	-	-
	50 cm-1 m	0.35 (2,9)	0.714	-	-	-
Percent nitrogen	All Depths	0.70 (2,106)	0.497	-	-	-
	0-30 cm	0.50 (2,11)	0.619	-	-	-
	30-50 cm	0.96 (2,9)	0.42	-	-	-
	50 cm-1 m	0.49 (2,9)	0.625	-	-	-
Total C:N	All depths	51.4 (2,106)	< 0.001	a	b	c
	0-30 cm	58.1 (2,11)	< 0.001	a	b	c
	30-50 cm	33.47 (2,9)	0.003	a	b	b
	50 cm-1 m	4.625 (2,9)	0.042	a	ab	b

Note. F, df, and *p* values are from Welch's analysis of variance (ANOVA) tests. NFB = North Fork Bend. Letters under site names indicate groupings based on Tukey's Honestly Significant Difference (HSD) comparisons.

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