SPATIAL AND VOLUMETRIC DISTRIBUTION OF ORGANIC CARBON IN URBAN TIDAL MARSH SEDIMENTS

By

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ABSTRACT OF THE THESIS

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Tidal marshes are important habitats for wildlife, and they provide a wide variety of ecosystem services, one of the most important of which is carbon storage and sequestration. Studying and modeling carbon storage in tidal marshes is very difficult due to the highly variable, highly site-specific biogeochemical processes that occur within them. Many studies attempt to understand the environmental factors that impact carbon storage in tidal marshes, but few assess marsh sediments at depths below 1 meter; therefore, this study seeks to understand the influence of environmental factors (spatial location, elevation, vegetation/sediment type) on carbon storage and to estimate total carbon stored throughout the entire depth of the marsh sediments. 16 cores were collected to refusal in a small urban tidal marsh, and percent organic carbon and organic carbon density were assessed along the full core depth. Interpolation maps of sediment thickness and carbon storage were generated to estimate total carbon stocks. Average carbon stocks per unit volume were similar to those collected by previous studies, but when summed across the entire vertical profile, total carbon stock estimates were over three times higher than the assessment that relied solely on stock estimates for the top 1 meter of sediment. While studies that only assess the top meter may be useful, assessing the true depth of marsh sediments could be key to gauging the potential of tidal marshes in sequestering and storing carbon. Trajectories of percent organic matter throughout each core depth suggested that the landward portion of the study site may have vegetated first; this is unusual, as seaward marshes are generally older, since marsh systems migrate inland with sea level rise. The landward portion of the study site likely originated as a freshwater riparian wetland, while the seaward portion may have formed later under the influence of sea level rise and tidal regimes; as sea level gradually increased over time, the entire study site transitioned into a tidal marsh system. Surface elevation and distance from creek showed no relationship to organic matter or carbon density, while both percent organic matter and organic carbon density showed significant variation when grouped by sediment type. Percent organic matter was significantly higher in areas covered by *Spartina patens* than areas covered by *Phragmites australis*. Further research is needed to clarify the relationship between tidal marsh carbon storage and environmental factors such as sea level, tidal regimes, vegetation, elevation, spatial distribution, salinity, and other factors that may add to the complexity of biogeochemical interactions. If we can better understand the true depth of tidal marsh sediments, as well as how environmental factors may have impacted organic matter storage in the historic past, then we may be better able to predict how changing environmental conditions may alter carbon storage potential in the future. Now more than ever, it is essential to study the dynamics of these important blue carbon systems so that we can better approach tidal marsh management in the face of global climate change.

Acknowledgments

I am grateful to Laura Reynolds for her invaluable contribution to the field and laboratory work required for this project, as well as her unwavering willingness to provide overall project support and to consult with me regarding tidal marsh geological processes. Thank you to the Rutgers Raritan River Consortium for providing the mini-grant funding required for field data collection. I appreciate being granted the National Science Foundation's Coastal Climate Risk and Resilience (C2R2) Fellowship, which gave me the opportunity to pursue a Master's degree at Rutgers University. Thank you to the Rutgers Geologic Core Repository and the Gary Taghon Lab in the Department of Marine and Coastal Sciences for providing us with facilities to store cores and complete lab work. I am grateful to Myla Aronson and Jean Marie Hartman, the members of my Master's committee, for providing me with prompt and helpful comments and support. Finally, I would like to thank Richard Lathrop, my advisor, for providing support throughout my time at Rutgers and for giving me helpful advice whenever I needed it.

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Introduction

Tidal marshes, wetland environments inundated by ocean water on a daily basis, are highly productive coastal systems that provide numerous ecosystem services. These marshes are important habitats for a variety of wildlife species, including those that are threatened and endangered; in the United States, they provide food, refuge, or nursery habitat for over 75 percent of commercial fisheries species (NOAA 2018). They also protect coastal communities from flooding and storm damage; in New Jersey, $625 million in storm damage was prevented by tidal marshes during Hurricane Sandy (Narayan 2017).

One of the most important ecosystem services provided by tidal marshes is carbon sequestration and storage. Tidal marsh systems sequester and store carbon from the atmosphere much more efficiently than even the most productive terrestrial forests (Mcleod et al. 2011). Tidal marsh vegetation sequesters carbon through photosynthesis, in a manner similar to that of forests; however, the saturated, anaerobic environment also causes the decomposing biomass to build up as peat. This peat accumulates over time and can serve as long-term carbon storage for hundreds, or even thousands, of years. This type of “blue carbon” is an essential tool in the fight against climate change (McLeod et al. 2011); understanding the dynamics of carbon sequestration and storage in tidal marsh environments will help to guide management priorities and marsh restoration practices.

Tidal marshes, especially those in highly developed areas, are increasingly subjected to a variety of human impacts that lead to complex changes in carbon flux cycles as well as significant degradations in marsh health. Coastal states in the NY/NJ metropolitan area are experiencing rapid urbanization; so much urban land development has occurred in New Jersey that in recent years, the rate of urban growth outpaced the rate of population growth by a factor of four (Hasse and Lathrop 2010). When stormwater runs off the impervious surfaces of a densely developed landscape, nutrients and organic waste end up in nearby waterways and oceans in excessive amounts (Savidge et al. 2016). Ordinarily, this excess nutrient runoff is filtered by marsh vegetation and buried by the accumulating marsh soils, which buffers oceans and estuaries from nutrient enrichment (Nelson and Zavaleta 2012; Valinsky et al. 2017); however, some studies suggest that a high nutrient influx may negatively impact above- and belowground biomass, thus limiting nutrient filtration, reducing carbon sequestration rates, and destabilizing marsh sediments enough to release stored carbon back into the system through increased erosion (Wigand et al. 2014; Alldred et al. 2017; Wedge and Anderson 2017; Logan 2018; Matzke and Elsey-Quirk 2018; Martin et al. 2018). Few studies have investigated carbon sequestration dynamics in highly urbanized marsh systems and the environmental factors that may alter carbon storage and sequestration regimes.

Climate change can also have a significant impact on tidal marshes and their carbon fluxes. Sea level change influences sediment accretion rates, causes inland marsh migration, and increases likelihood of submersion; these changes have the potential to influence carbon sequestration rates (Morris et al. 2002, Kirwan et al. 2016, Rogers et al. 2019). The potential increase in frequency of severe coastal storms may increase the likelihood of erosion, thus exacerbating the release of stored carbon (IPCC 2019; Lane et al. 2016). In the future, understanding the impacts of climate change will grow increasingly important to the health of tidal marsh systems.

A wide variety of local factors have been known to influence greenhouse gas fluxes in tidal marsh sediments, including vegetation type, salinity, nutrient and sediment availability, accretion rates, and tidal regimes; however, interactions between these biogeochemical and geomorphological processes are complex and not well understood (Holmquist et al. 2018; Sheng et al. 2015; Reid et al. 2013; Poffenbarger et al. 2011; Kirwan et al. 2016). As a result, the processes governing tidal marsh carbon storage and sequestration are incredibly site-specific, and this makes carbon modeling difficult and often inaccurate (Holmquist et al. 2018). Many blue carbon studies address site-specific carbon storage in tidal marsh sediments, but most of these studies only analyze sediments to 1 meter depth, leaving carbon variation at greater depths virtually unexplored (Holmquist et al. 2018). In many tidal marshes, sediments have accumulated due to relative sea level rise over the thousands of years that followed the last ice age (Kemp et al. 2013). These post-glacial tidal marsh sediments can extend much deeper than 1 meter, potentially storing much larger amounts of carbon than previous research has tabulated.

The goal of this project is to better understand the influence of several environmental factors on carbon density and sequestration rates in urban tidal marsh sediments. Understanding carbon sequestration in these dynamic urban wetland systems has important implications for tidal marsh management in the face of climate change. The following research questions were posed using a little-studied tidal marsh system on Staten Island, New York.

Research Questions

1) How much organic carbon is stored in the sediments of a small, urbanized estuary along the Raritan Bay?
2) How much carbon is stored in the tidal marsh sediments of the top 1 meter (the usual limit for blue carbon studies) as compared to the full vertical depth profile? I.e., how much carbon is missed when we only account for the top meter of sediment?
3) Does the amount of organic carbon stored in tidal marsh sediments vary according to:
    a) Spatial distribution (e.g. distance from tidal creek)
    b) Dominant vegetation
    c) Surface elevation
    d) Sediment age/depth
    e) Sediment type

Methods

Study Site

The study site is a portion of a tidal marsh located in Lemon Creek Park, a property located on Staten Island, New York and owned by New York City Parks (Figure 1). Based on permitting and accessibility restrictions, a 7 hectare section located about 600 meters landward of the bay was selected as the study area. *Phragmites australis* dominated the northernmost quarter of the study site, with additional narrow strips located along the western, eastern, and southern fringes. The remainder of the study site was dominated by tall-form *Spartina alterniflora* with mixed patches of *Spartina patens* and *Distichlis spicata* in areas of slightly higher elevation between channels and mosquito ditches. A few small locations within the marsh were dominated by other vegetation such as *Bolboschoenus maritimus*.

Based on a visual assessment of available aerial imagery (USGS Earth Explorer), the area surrounding Lemon Creek was sparsely residential and mostly forested in the early-to-mid 20th century. In the 1970s, residential development density started to increase until mostly leveling off to its current state by the mid-1990s. Currently, the study site is predominantly surrounded by medium- and low-intensity development, with the exception of the northeastern corner, which is bordered by deciduous forest (NLCD 2016).

According to the National Wetland Inventory (USFWS 2020), the northern and western portions of the study site are classified as estuarine intertidal emergent wetland, irregularly flooded, and dominated by *Phragmites australis* (E2EM5P). The southern and eastern portions of the study site are classified as estuarine intertidal emergent wetland, irregularly flooded, dominated by persistent vegetation, and partially drained/ditched (E2EM1Pd). The USDA Web Soil Survey (NRCS 2020) classifies the soil as Ipswich mucky peat, 0-2 percent slopes, and very frequently flooded (IwA).

Sediment Core Collection

Sediment cores were collected to assess water content, bulk density, and organic matter content to determine the carbon stocks contained within the sediments. Sediment cores were collected using a Russian Peat Corer at 16 locations throughout the study site between October 3 and November 21, 2019. Cores were collected within 3 hours of low tide to avoid flooded conditions at sites (with the exception of core 2, which was collected within an hour of high tide). Core sites were selected based on accessibility, but also to evenly sample differing parts of the marsh based on vegetation cover and spatial distribution. In most cases, 2 cores were collected at each site: 1) a short core, typically reaching down to 130 cm from the surface, and 2) a long core, collected to refusal. At this site, refusal was reached by encountering sand layers or very dense clays. Long core depths ranged between 330 and 770 cm in depth. Cores were collected in 50 cm segments, alternating between two adjacent holes (typically about 0.5-1 m apart) in which the segments overlapped in depth by 10 cm to replicate the portions of each core that were disturbed by the corer's tip. Core segments were stored in 50 cm lengths of Schedule 40 2-in. PVC pipe, halved lengthwise. Each tube was wrapped in plastic wrap, secured on the ends with duct tape, and stored in a refrigerator upon returning from the field.

Figure 1. Lemon Creek Marsh study site located in Staten Island, NY. Study site boundary (labeled as AOI) outlined in cyan.

Core Descriptions, Sampling, and LOI

All sediment cores were visually described, including sediment type (Peat = > 75 % organic fragments; Muddy Peat = > 50% organic fragments; Peaty Mud = < 50% but > 25% organic fragments; Mud = < 25% organic fragments), sediment color (Brown, Dark Brown, Orange Brown, Dark Gray, etc.), grain size (Clay, Silt, Sand), type of organic matters (fibers vs. coherent fragments of stems or leaves, etc.) and other items of note such as large rhizomes, cedar pieces, and shell fragments. The majority of the cores (1, 2, 4, 5, 7, 10, 11, 12, 13, 16) were sampled at 5 cm resolution. Variability in the organic material was determined to be low enough to reduce sampling resolution; therefore, the remaining cores (3, 6, 8, 9, 14, 15) were sampled at 10 cm resolution within the more variable peat layers and 25 cm resolution within the less variable mud layers. Prior to sampling, the top few mm of sediments within each core tube were scraped off to remove any contaminated material on the surface. Sediment samples of 1 cm^3 were retrieved by gently inserting a 5 mL plastic syringe with the tip removed into the sediment, dislodging or cutting any surrounding material, and holding the sample inside with a metal spatula to prevent compaction. Samples were inserted into 15 mL high-form porcelain crucibles and dried for 12 hours at 105°C in a muffle furnace. Using a precision scale (Mettler Toledo AE160 analytical balance), crucibles were weighed 1) empty, 2) with the wet samples, and 3) with the dry samples to determine the dry bulk density. Dried samples were heated to 550ºC for 4 hours and weighed again to measure the organic matter lost (Loss on Ignition, LOI). The LOI value was converted to gC cm^{-3} using established relationships between organic matter and organic carbon content in estuarine marsh soils (Craft, 1991; Holmquist et al., 2018). Samples were dried and burned in batches of 60-90, and the crucibles were wiped clean of sediment and reweighed between each use.

Data Analysis and Interpolation

Organic carbon storage and distribution within the study site was estimated using interpolation techniques similar to those utilized by Ardenne et al. 2018. The interpolation method used was Inverse Distance Weighting (IDW) with a distance weight of two. Edge estimate points, which assume a sediment thickness of 0, were manually placed around the border of the marsh soils at distances of 25-50m apart, based on analyzer judgement. A refusal depth interpolation and sediment thickness interpolations for both peat and mud/sand sediment types were completed both with and without edge estimates to compensate for potential bias in edge estimate results. Total carbon stocks were estimated for each sediment type by averaging carbon density at each core site for each sediment type, creating carbon interpolations from these averages, and multiplying the carbon interpolation rasters by the sediment depth interpolation rasters. The final carbon values within each cell for each sediment type were then added together to generate an estimate of total carbon stock within the study site.

After assessing percent organic matter throughout each core depth, cores were grouped based on visual similarities in their trajectories and similar spatial location. These groups were established based on the assumption that similar spatial and volumetric patterns between cores may indicate wetland environments that formed under similar conditions; the groups were then analyzed to ascertain possible environmental factors that could have guided marsh development.

Variations in organic carbon within individual cores were analyzed in conjunction with sediment type, sediment depth, surface elevation, surface distribution, and vegetation type to assess whether any of these factors could explain variation in carbon storage across this site. Mixed model Nested ANOVA and Tukey Multiple Comparisons

Post-Hoc tests (where applicable) were performed in R to determine statistically significant differences ($\alpha = 0.05$) when grouping percent organic matter and carbon density by vegetation type and sediment type.

Results

Stratigraphy

The stratigraphy indicated by the collected cores was predominantly characterized as follows (from marsh surface to depth):

a) a thick layer of interspersed brown, dark brown, and red-brown peat near the top of the cores,

b) smaller layers of brown muddy peat directly below or interspersed within the lower portions of peat,

c) a rapid transition to a small brown or gray-brown peaty mud layer,

d) a thick layer of dark gray mud, and in some cases, and

e) thin layers of dark gray sand at refusal (Figures 2-7).

Some cores reached refusal (i.e., greatest depth of core penetration) upon reaching a sand layer (3, 4, 5, 9, 10, 11, 14, 16), while others reached refusal after encountering a layer of wood chips (7) or other unknown dense materials, such as thick mud (1, 6, 8, 12, 13, 15; Table 2). Some core sections were not collected due to time constraints in the field (13, 14) or difficulty with extraction (4, 12).

Percent organic matter and organic carbon density variation

The average percent organic matter across all core samples was approximately 28.89 ± 19.08%. Organic carbon density across all core samples was much less variable at 0.028 ± 0.008 (Table 1, Figure 8). In the top 1 meter of sediments, both organic matter and carbon density values were higher than the overall average and the values from the depths below 1 meter were similar to the overall average (Table 1). Organic carbon density showed a slight negative linear trend, with carbon density decreasing as depth increased (Figure 8; $R^2 = 0.2263$).

Table 1. Average organic matter and organic carbon density of all analyzed core samples.

		Average	**SD**
Organic matter (%)	Overall	27.89	19.08
	Top 1 meter	30.23	12.78
	Below 1 meter	27.20	20.42
Organic carbon density (gC cm^{-3})	Overall	0.028	0.008
	Top 1 meter	0.034	0.007
	Below 1 meter	0.027	0.006

Percent organic matter varied greatly relative to depth throughout each sediment core (Figure 9). Overall, the peat and muddy peat layers exhibited a high variability in organic matter, while the peaty mud and mud layers showed very little variation. Cores were grouped together to elucidate differing trajectories in organic matter variation that occurred in different spatial locations (Figures 9-10). Cores with similar trajectories were grouped together when their spatial locations were also similar, with Groups A and B near the landward end, Groups C and D in the middle, and Group E at the seaward end (Figure 10). Group A cores (2, 4) show highly variable percent organic matter in the peat layers between 0 and 200 cm; then they show sudden transition to mud at 300 cm and a decrease in organic matter to about 10% with low variability. Group C cores (5, 11, 12, 13) have approximately 20% organic matter in the peat layers, which increases to 60% at a depth of 300 cm, decreases to about 10% at 500cm, and levels off once the sediment type changes to pure mud. Group B cores (core 3 only) follow a similar trend as that of group C cores until 500 cm, at which depth the peat layer continues instead of tapering off, causing the percent organic matter to rise to about 70%. Group D cores (10, 14, 15, 16) follow a very similar organic carbon trajectory as that of the group A cores, but they are located further south and separated from Group A by Groups B and C; therefore, they were placed into their own category. Group E cores (1, 6, 7, 8, 9) exhibit high-variability peat layers until about 200 cm, at which depth organic matter gradually decreases until leveling off at 200 cm at approximately 10%, with little variability.

Table 2. General information collected at each core site.

Core Number	Collection Date	Lat	Long	Surface Elevation (m above NAVD88)	Final Core Depth (cm)	Reason for Refusal	Dominant Vegetation
1	10/12/19	40.51906	-74.20334	0.8497	410	Unknown Refusal	*Spartina patens*
2	10/3/19	40.52241	-74.20242	3.4382	170	Short core/no refusal	*Phragmites australis*
3	10/15/19	40.52165	-74.20376	0.935	770	Sand (850 cm)	*Phragmites australis*
4	10/24/19	40.52143	-74.20402	0.8308	500	Sand	*Phragmites australis*
5	10/24/19	40.52168	-74.20357	0.9042	530	Sand	*Phragmites australis*
6	11/6/19	40.51756	-74.20284	0.672	333	Unknown Refusal/Mud	*Spartina alterniflora*
7	11/9/19	40.51793	-74.20229	0.6233	450	Wood chips	*Spartina patens*
8	11/14/19	40.518	-74.20159	0.7543	330	Unknown Refusal/Mud	*Spartina alterniflora*
9	11/14/19	40.51878	-74.2028	0.7405	410	Unknown Refusal/Sand	*Spartina patens*
10	11/14/19	40.51896	-74.20227	0.8233	530	Sand	*Spartina patens*
11	11/16/19	40.52097	-74.20339	0.6891	630	Sand	*Bolboschoenus maritimus*
12	11/16/19	40.52081	-74.20383	0.9275	335	Unknown Refusal/ Hard	*Spartina patens*
13	11/16/19	40.52094	-74.20353	0.8175	700	Unknown Refusal	*Spartina alterniflora*
14	11/21/19	40.51995	-74.20347	0.9508	430	Sand	*Spartina patens*
15	11/21/19	40.52003	-74.20319	0.932	490	Unknown Refusal	*Spartina patens*
16	11/21/19	40.52032	-74.20273	0.8676	570	Sand	*Spartina patens*

According to the nested ANOVA, organic carbon density did not vary depending on the dominant surface vegetation type; however, after removing *B. maritimus* from the analysis due to small sample size, sites with *S. patens* were found to be significantly higher in percent organic matter than sites with *P. australis* (Table 3; Figures 12-13). Only the top 50 cm of data were included in these analyses, because the deeper layers were unlikely to be influenced by the current vegetative environment. Surface elevation showed little evidence of influence on the organic matter or carbon density, neither within the complete core nor within the top 50 cm (Figures 14-15). When grouped by sediment type, however, potential dependencies were more apparent; the nested ANOVA and post-hoc showed significant differences between all sediment types for both percent organic matter and organic carbon density (Figure 3). Peat-rich sediments showed the highest organic matter and carbon density; both values decreased as the sediment type became more dominated by mud and sand (Figures 16-17). Variation in the percent organic matter also dramatically decreased as the sediment type changed from pure peat to pure mud, although this trend was less apparent in the organic carbon density. The distance of each core site from the main creek did not appear to have any influence over percent organic matter or organic carbon density, with neither the top 50 cm nor the full core depth showing any apparent dependencies (Figures 18-19).

Table 3. Mixed model nested ANOVA (analysis of variance) statistical tests analyzing the variation in organic matter and carbon density according to vegetation type and sediment type. (Significance codes: 0 = ****; 0.001 = ***; 0.01 = **; 0.05 = *)

VEGETATION TYPE - NESTED ANOVA (MIXED)			
Organic matter (%)		Carbon density	
F-value	p-value	F-value	p-value
3.5701	**0.0313 ***	0.0972	0.9083
Multiple Comparisons of Means: Tukey Contrasts – Significance – Organic matter (%)			
S. alterniflora – P. australis	0.58980		
S. patens – P. australis	**0.00363 ****		
S. alterniflora – S. patens	0.36113		

SEDIMENT TYPE - NESTED ANOVA (MIXED)			
Organic matter (%)		Carbon density	
F-value	p-value	F-value	p-value
3.5701	**<.0001**	0.0972	0.9083
Multiple Comparisons of Means: Tukey Contrasts – Significance – Organic matter (%)			
Muddy Peat – Mud	**<0.00001 ******		
Peat – Mud	**<0.00001 ******		
Peaty Mud – Mud	**<0.00001 ******		
Sand – Mud	**<0.00001 ******		
Peat – Muddy Peat	**<0.00001 ******		
Peaty Mud – Muddy Peat	**<0.00001 ******		
Sand – Muddy Peat	**<0.00001 ******		
Peaty Mud – Peat	**<0.00001 ******		
Sand – Peat	**<0.00001 ******		
Sand – Peaty Mud	**<0.00001 ******		
Multiple Comparisons of Means: Tukey Contrasts – Significance – Carbon density (gC cm^{-3})			
Muddy Peat – Mud	**<0.001*****		
Peat – Mud	**<0.001*****		
Peaty Mud – Mud	**0.00132 ****		
Sand – Mud	**<0.001*****		
Peat – Muddy Peat	**<0.001*****		
Peaty Mud – Muddy Peat	**<0.001*****		
Sand – Muddy Peat	**<0.001*****		
Peaty Mud – Peat	**<0.001*****		
Sand – Peat	**<0.001*****		
Sand – Peaty Mud	**<0.001*****		

Figure 2. Texture and color symbols representing sediment type and sediment color at each depth within all collected sediment cores.

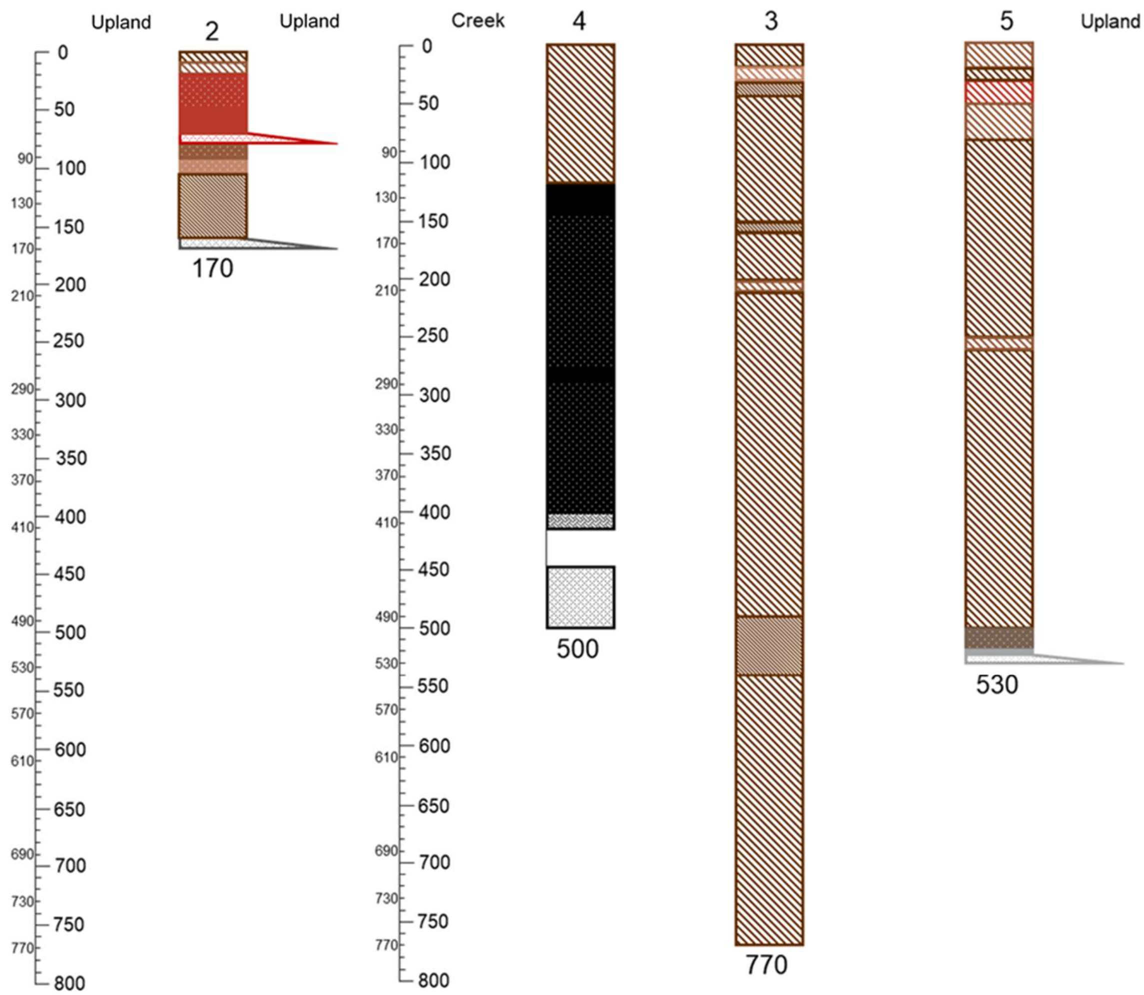


Figure 3. Stratigraphy of sampled cores 2, 3, 4, and 5. Cores in figure are oriented west to east with indication of adjacency upland or creek. Empty sections indicate that no sample was collected. Black sections indicate that no color was recorded due to time constraints in the lab. See Figure 2 for legend. Y axis represents depth relative to ground surface in centimeters. Bar width represents grain size, with a wider bar indicating sandy sediments. All other sediments are silty mud. Normal grading (gradual upwards fining of grain size) is indicated by sloped boxes.

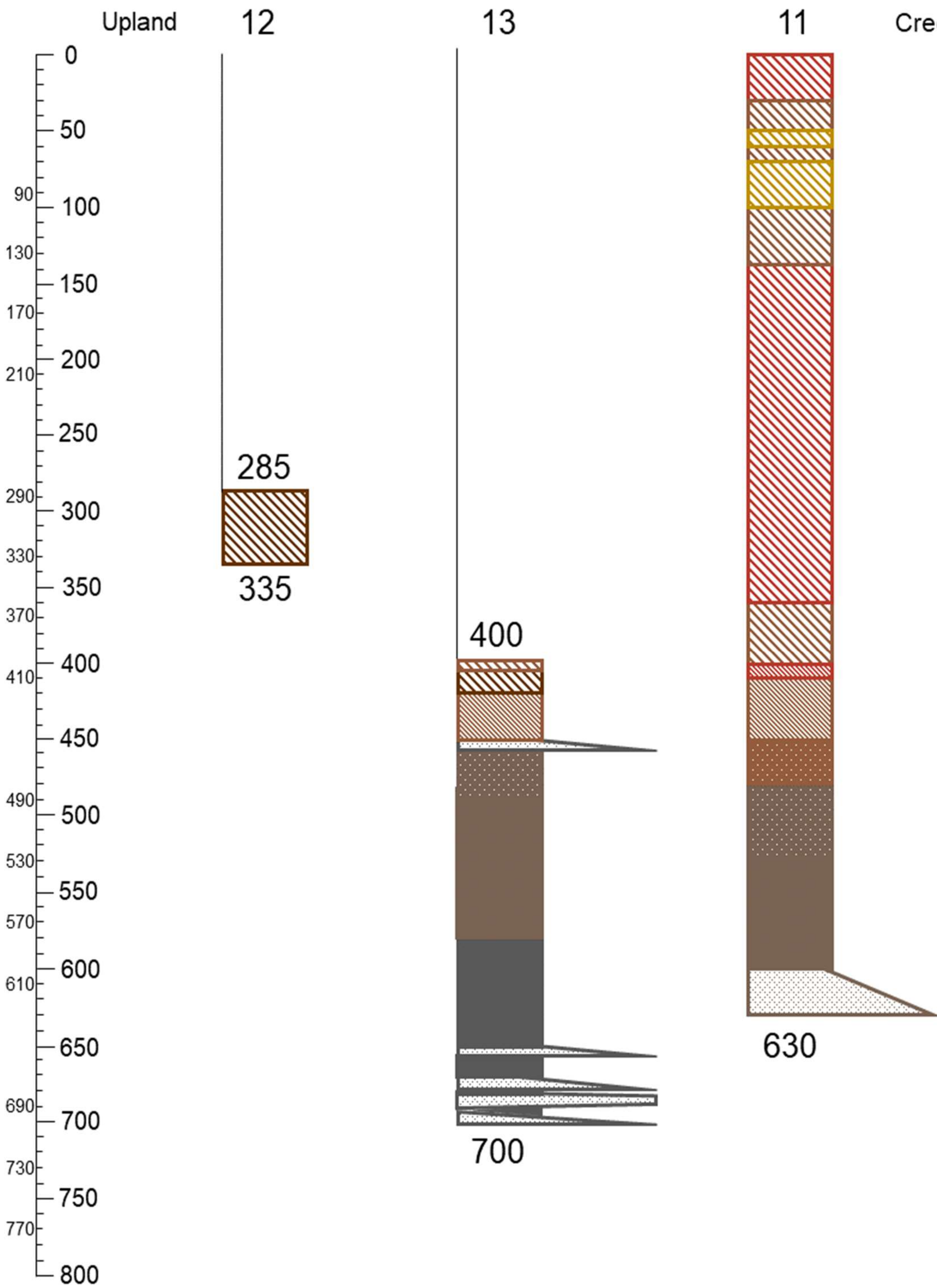


Figure 4. Stratigraphy of sampled cores 11, 12, and 13. Cores in figure are oriented west to east with indication of adjacency upland or creek. Empty sections indicate that no sample was collected. See Figure 2 for legend. Y axis represents depth relative to ground surface in centimeters. Bar width represents grain size, with a wider bar indicating sandy sediments. All other sediments are silty mud. Normal grading (gradual upwards fining of grain size) is indicated by sloped boxes.

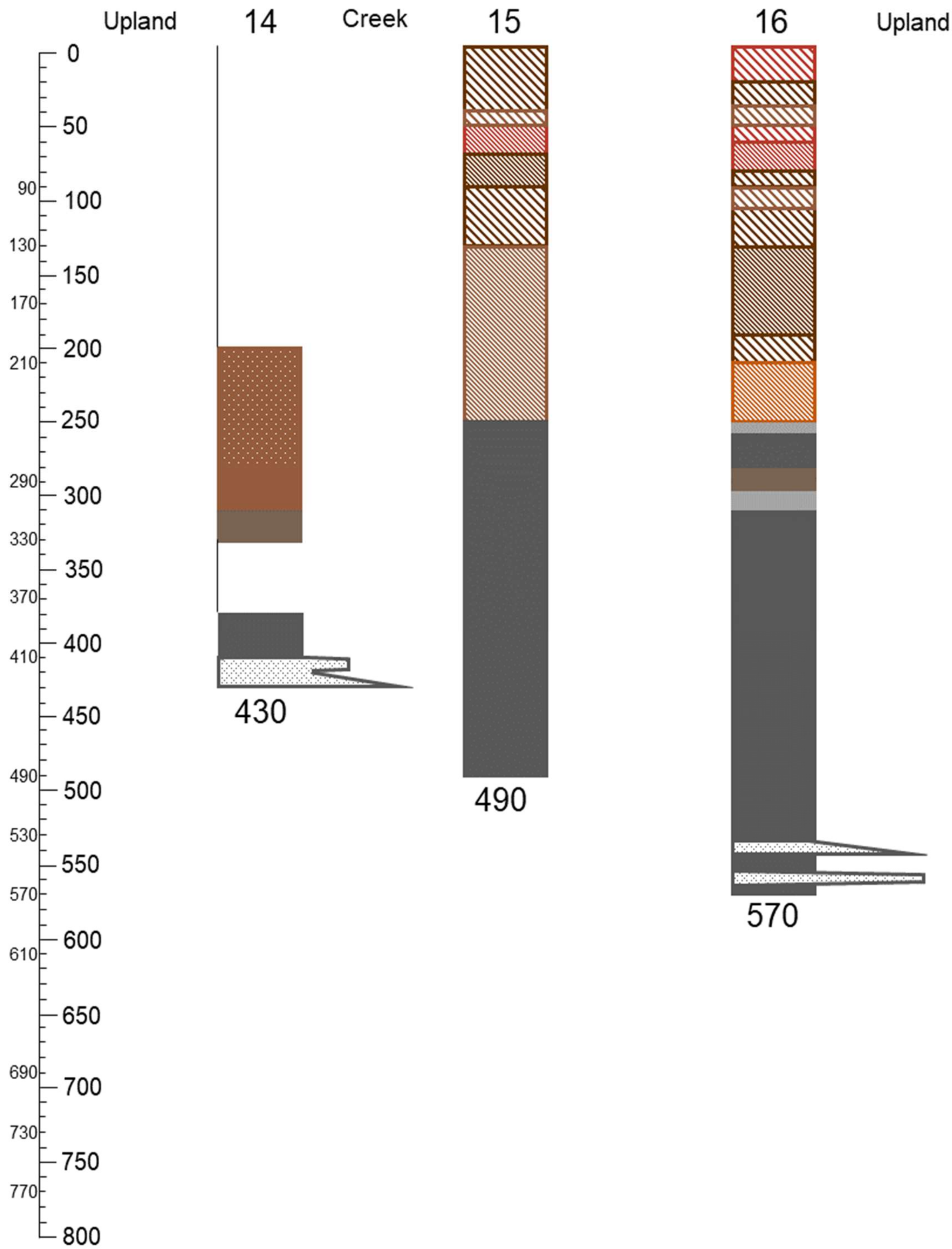


Figure 5. Stratigraphy of sampled cores 14, 15, and 16. Cores in figure are oriented west to east with indication of adjacency upland or creek. Empty sections indicate that no sample was collected. See Figure 2 for legend. Y axis represents depth relative to ground surface in centimeters. Bar width represents grain size, with a wider bar indicating sandy sediments. All other sediments are silty mud. Normal grading (gradual upwards fining of grain size) is indicated by sloped boxes.

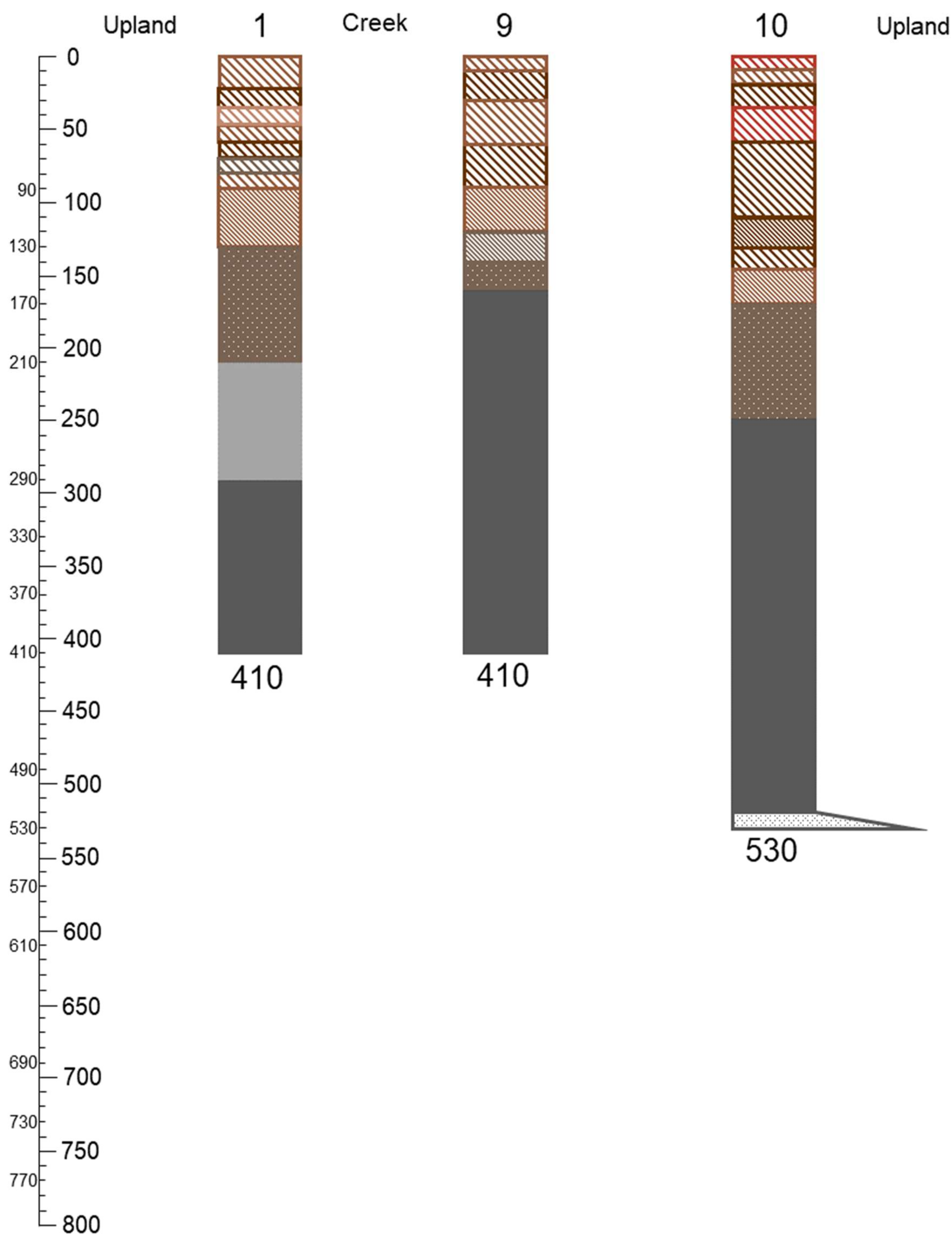


Figure 6. Stratigraphy of sampled cores 1, 9, and 10. Cores in figure are oriented west to east with indication of adjacency upland or creek. Empty sections indicate that no sample was collected. See Figure 2 for legend. Y axis represents depth relative to ground surface in centimeters. Bar width represents grain size, with a wider bar indicating sandy sediments. All other sediments are silty mud. Normal grading (gradual upwards fining of grain size) is indicated by sloped boxes.

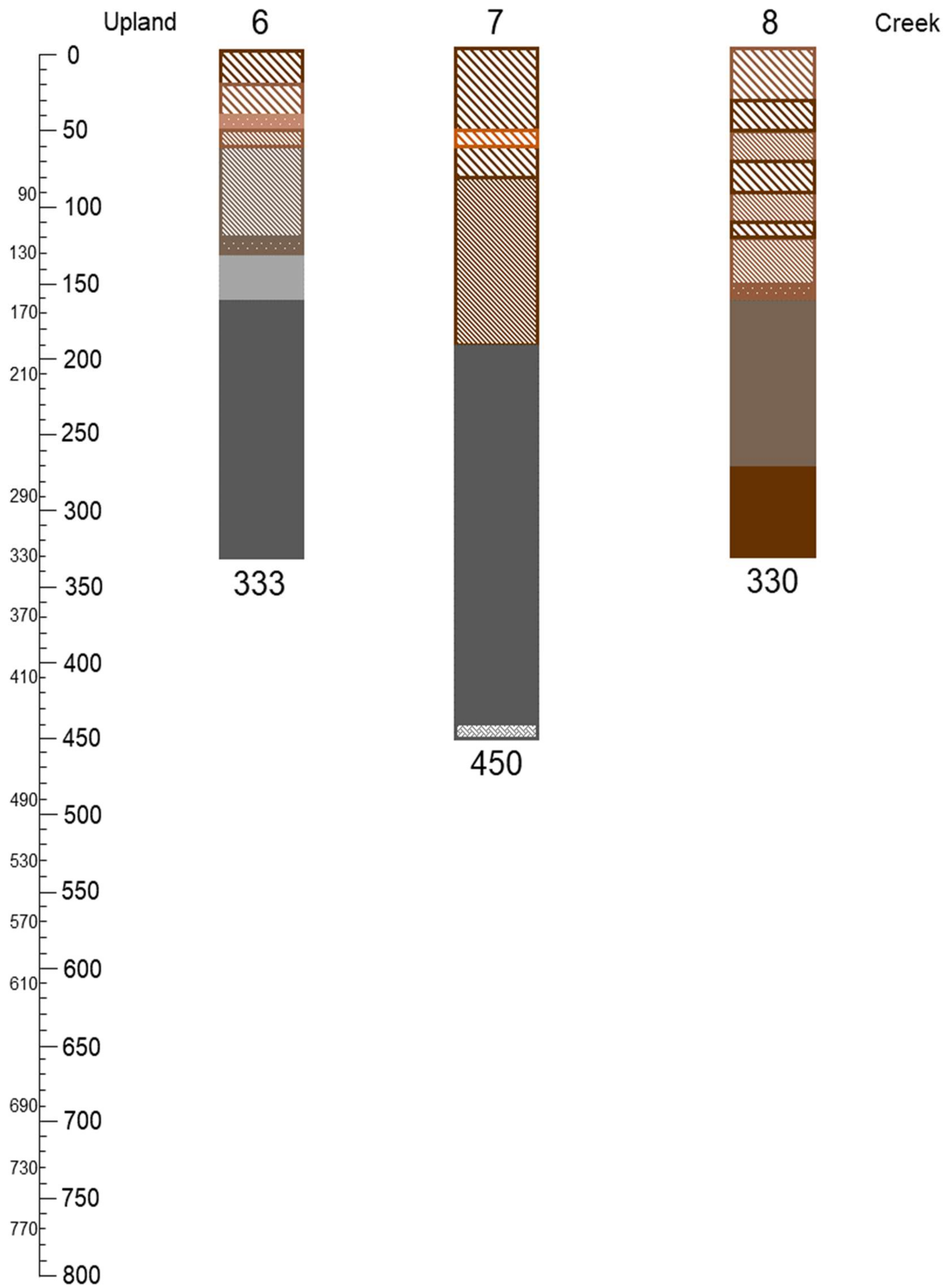


Figure 7. Stratigraphy of sampled cores 6, 7, and 8. Cores in figure are oriented west to east with indication of adjacency upland or creek. Empty sections indicate that no sample was collected. See Figure 2 for legend. Y axis represents depth relative to ground surface in centimeters. Bar width represents grain size, with a wider bar indicating sandy sediments. All other sediments are silty mud. Normal grading (gradual upwards fining of grain size) is indicated by sloped boxes.

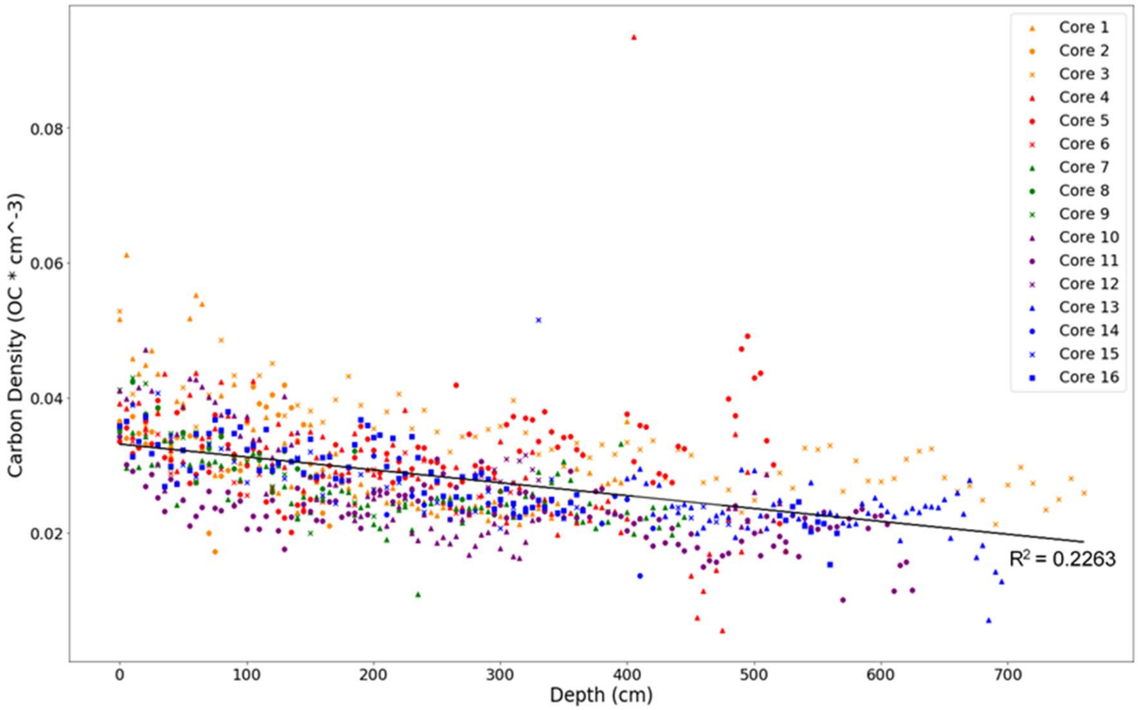


Figure 8. Carbon density per cubic centimeter at each sampled depth at all core sites. Extreme outlier removed for visualization.

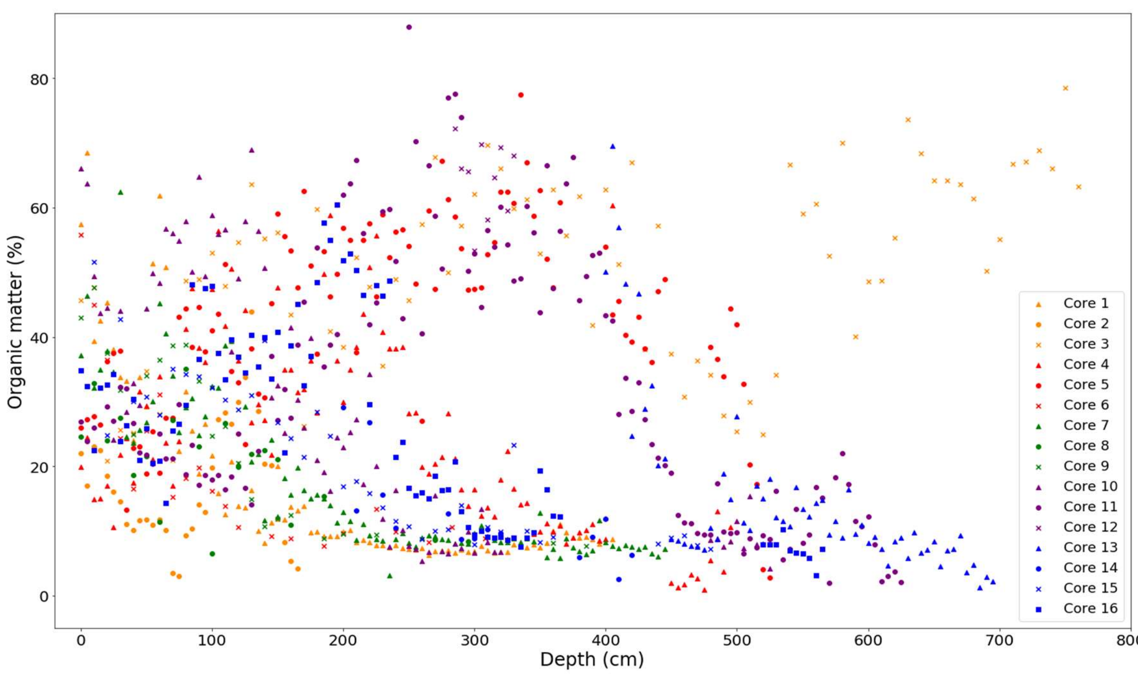


Figure 9. Percent organic matter at each sampled depth at all core sites.

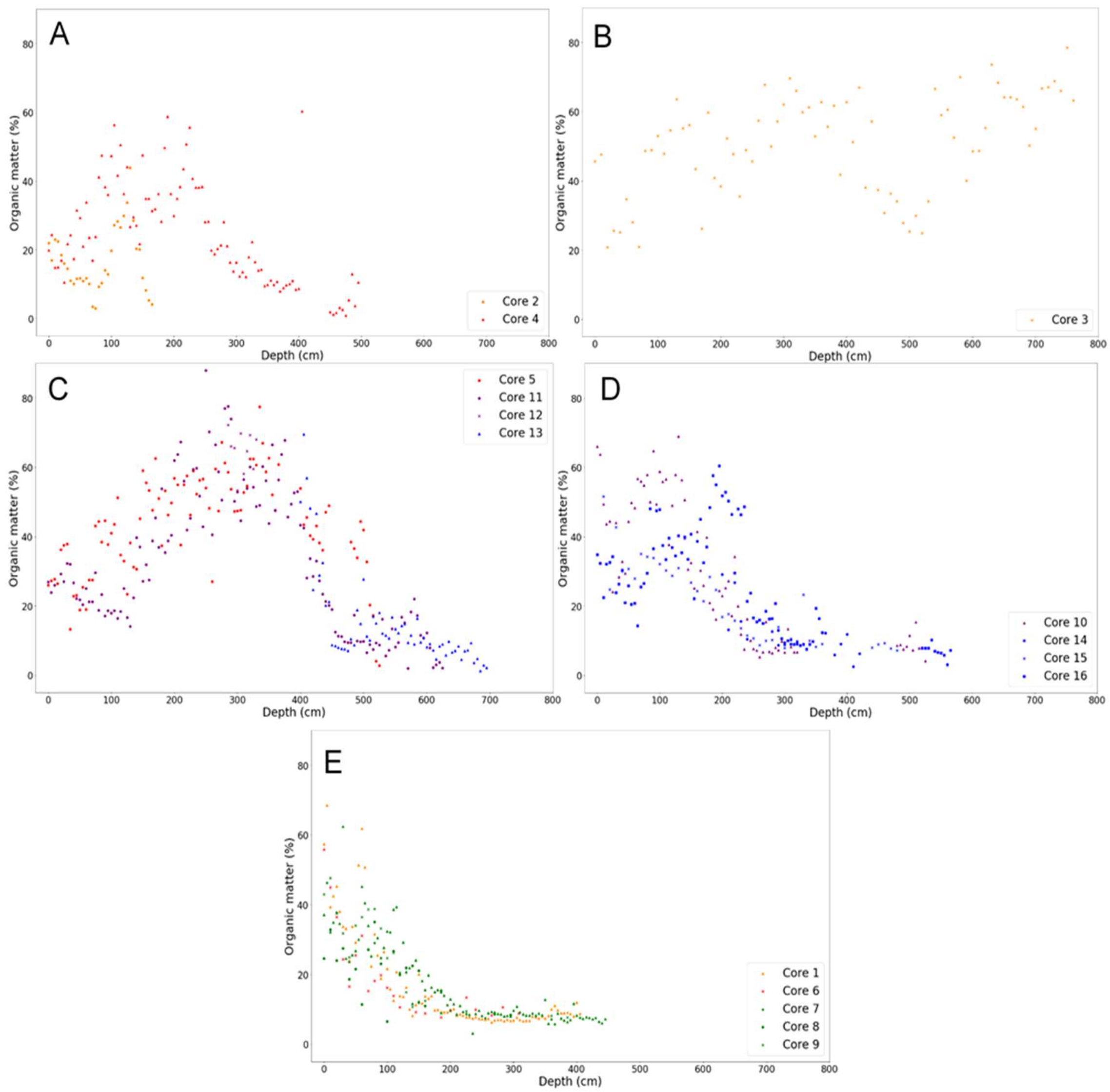


Figure 10. Core groups characterized by similar spatial location and similar trajectories in percent organic matter throughout core depth.

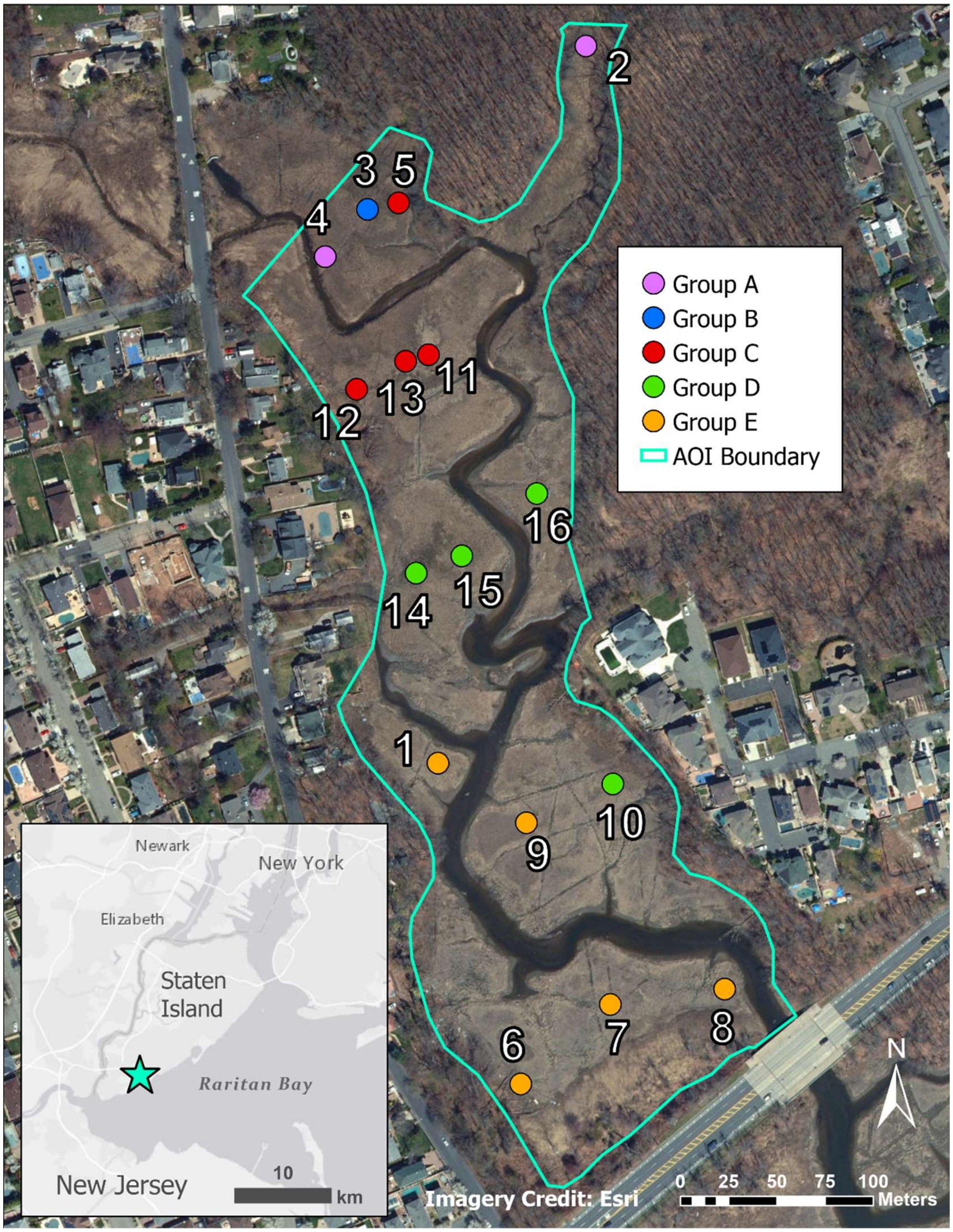


Figure 11. Core groups characterized by similar trends in organic matter throughout core depth. Study site (labeled as AOI) outlined in cyan. Grouped by organic content trajectories and spatial location.

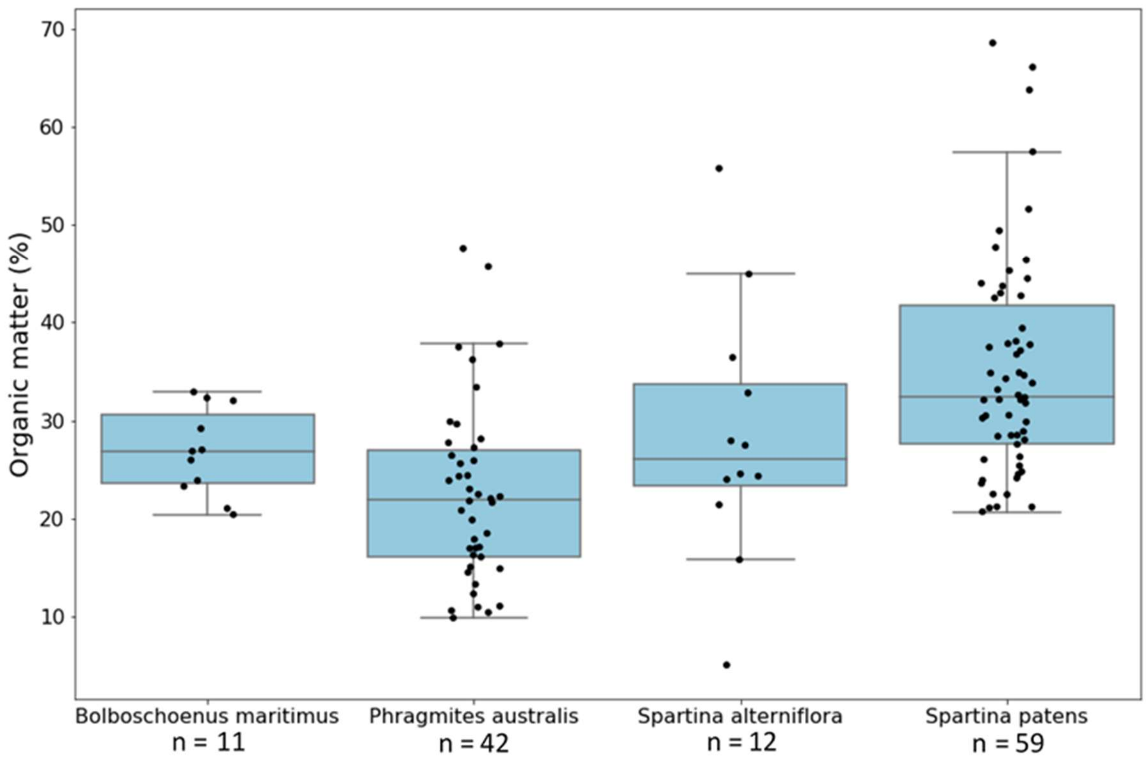


Figure 12. Percent organic matter within the top 50 cm, grouped by dominant vegetation type. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum.

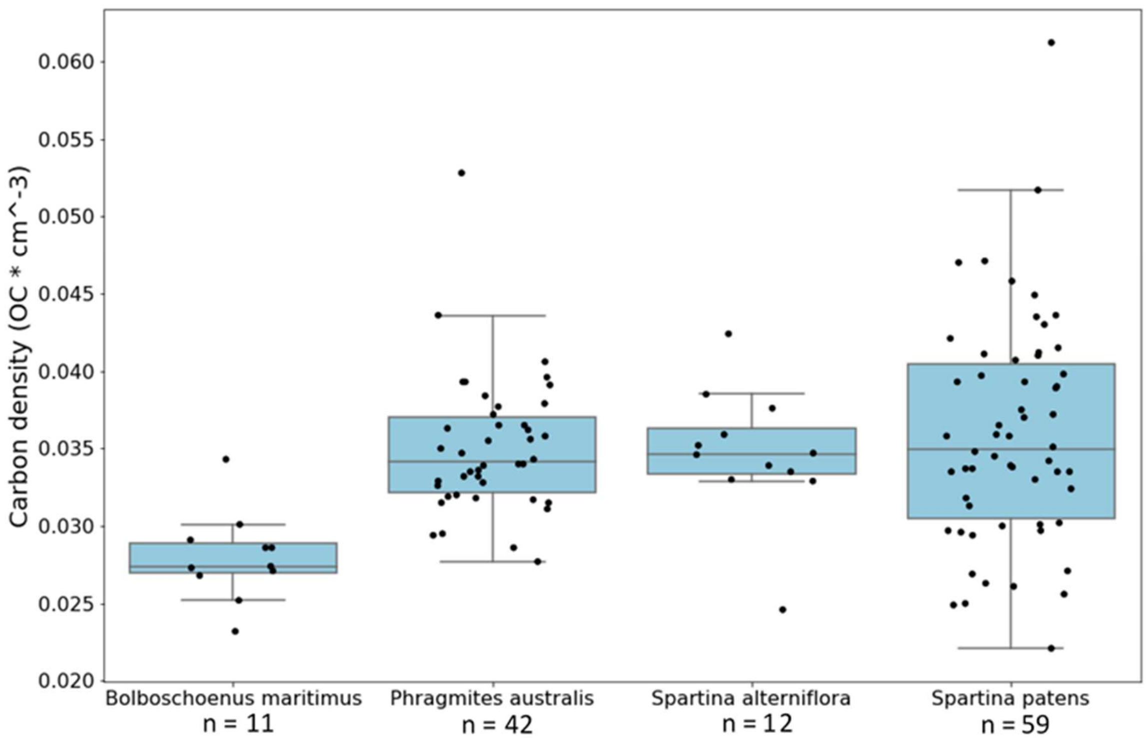


Figure 13. Carbon density within the top 50 cm, grouped by dominant vegetation type. Extreme outlier removed for visualization. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum.

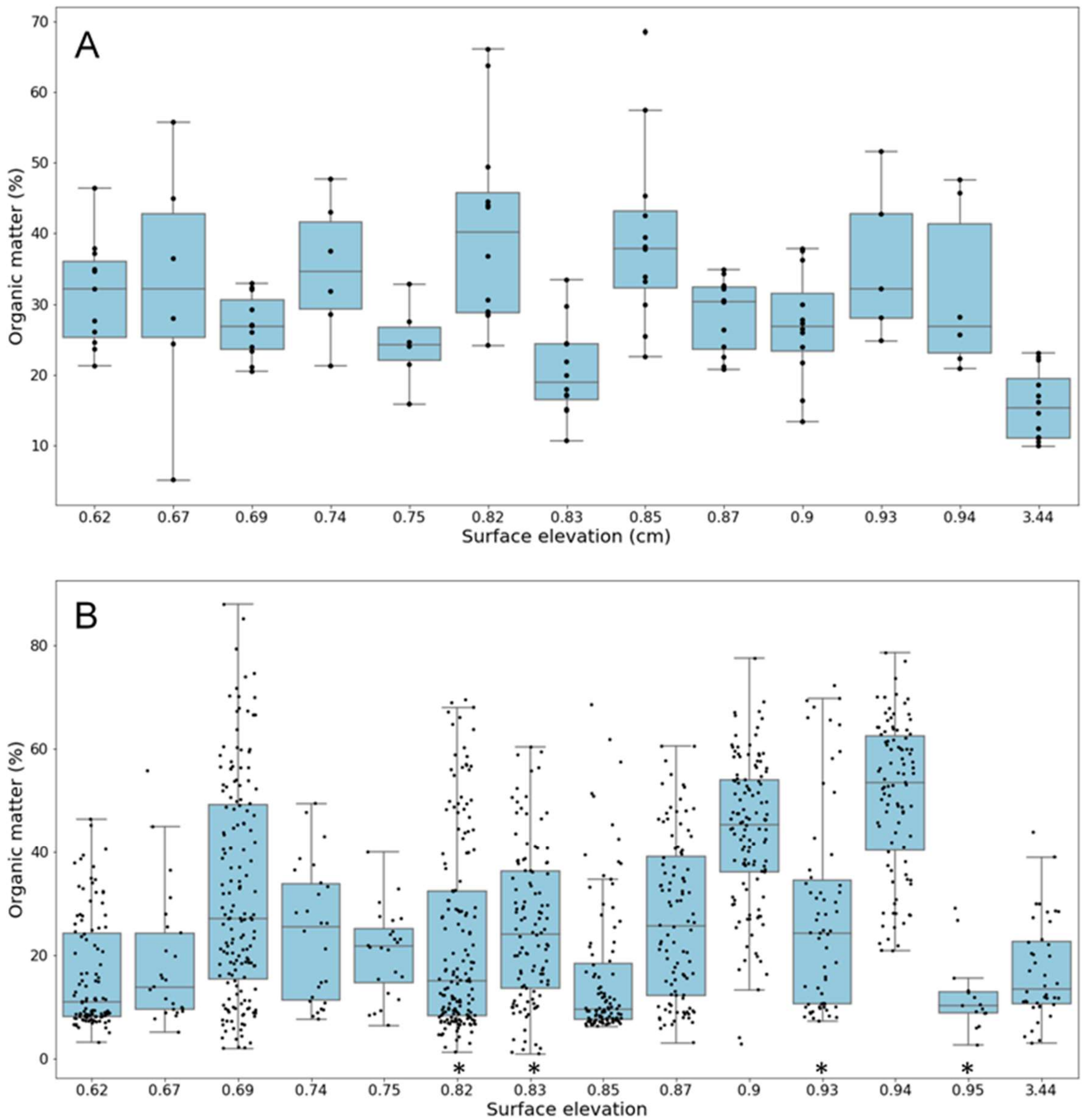


Figure 14. Percent organic matter a) within the top 50 cm and b) throughout entire core depth, grouped by core and sorted by surface elevation. Extreme outlier removed for visualization. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum. Asterisks (*) indicate incomplete cores (cores missing samples at some depths).

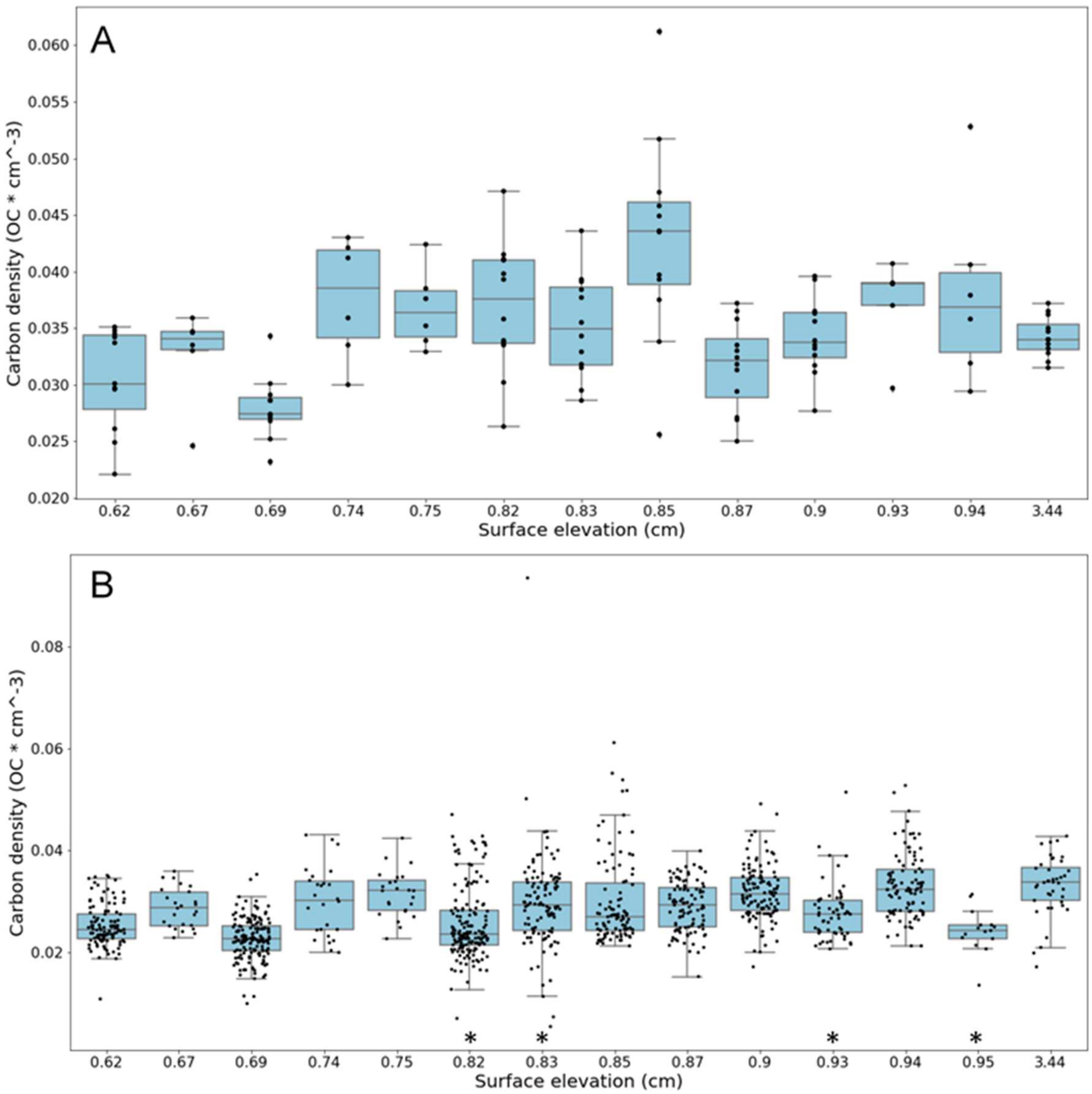


Figure 15. Organic carbon density a) within the top 50 cm and b) throughout entire core depth, grouped by core and sorted by surface elevation. Extreme outlier removed for visualization. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum. Asterisks (*) indicate incomplete cores (cores missing samples at some depths).

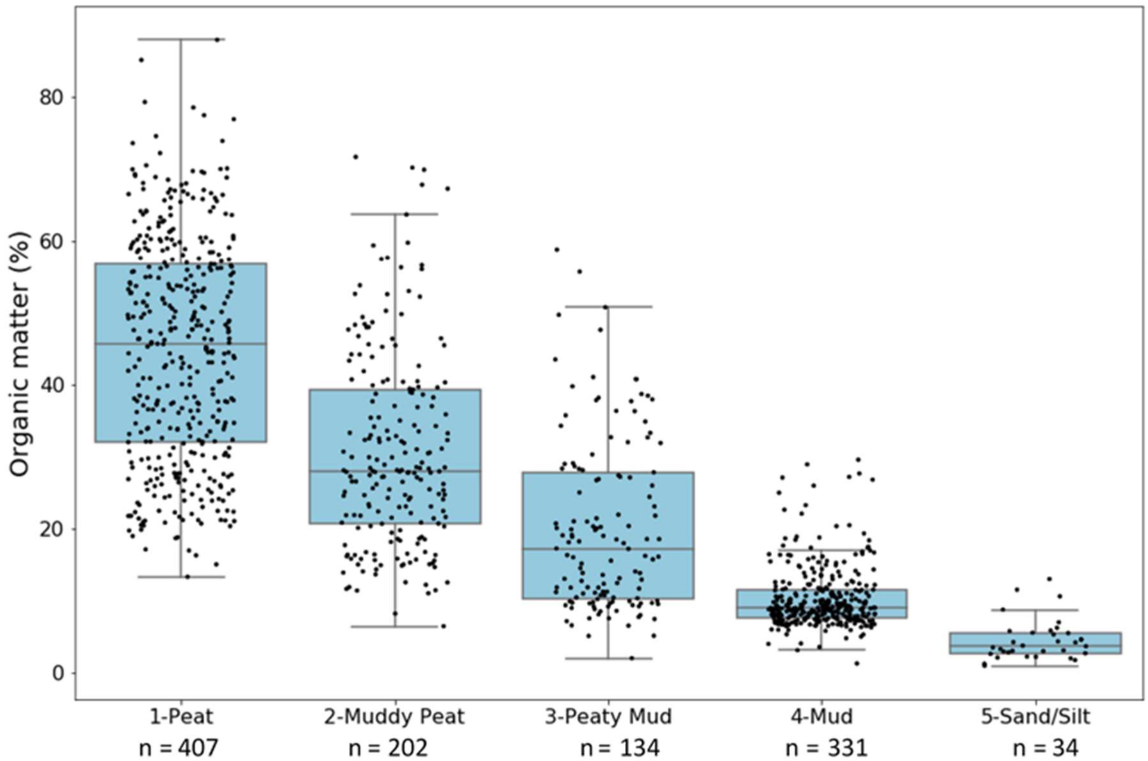


Figure 16. Percent organic matter throughout entire core depth, grouped by sediment type. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum.

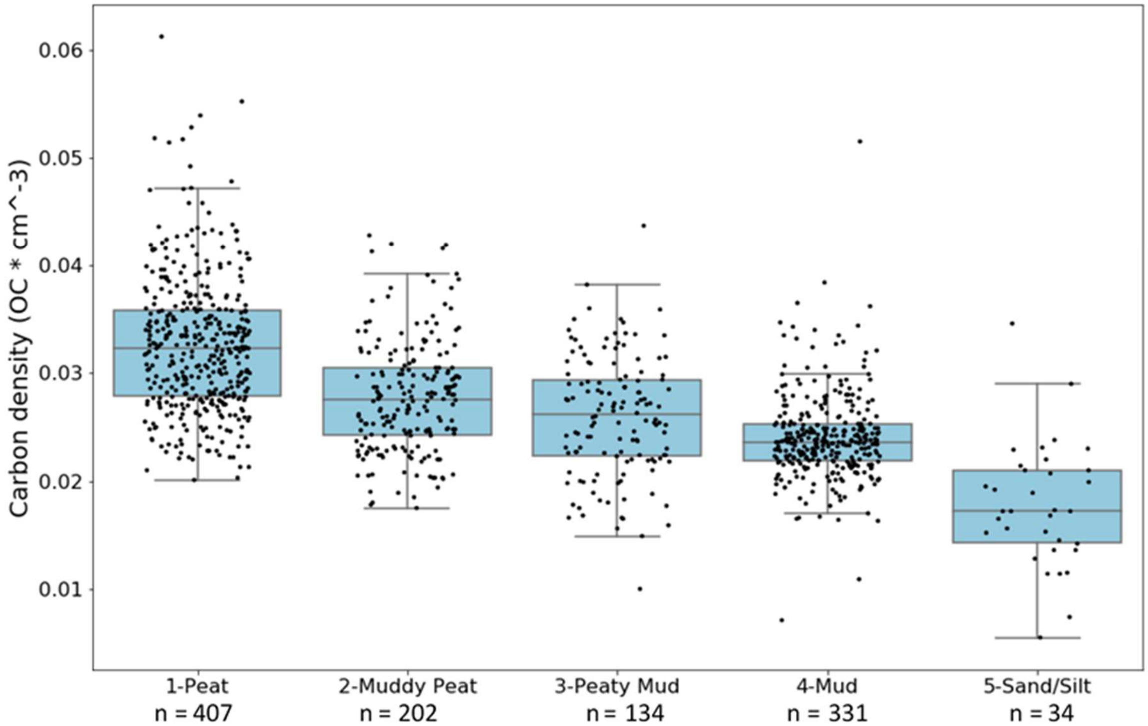
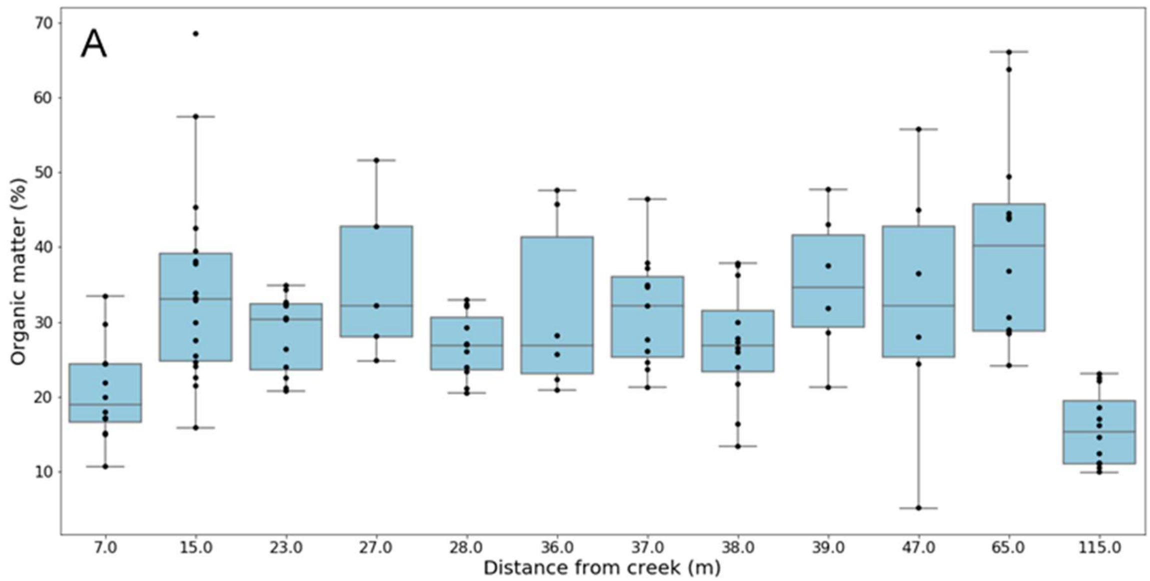


Figure 17. Organic carbon density throughout entire core depth, grouped by sediment type. Extreme outlier removed for visualization. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum.



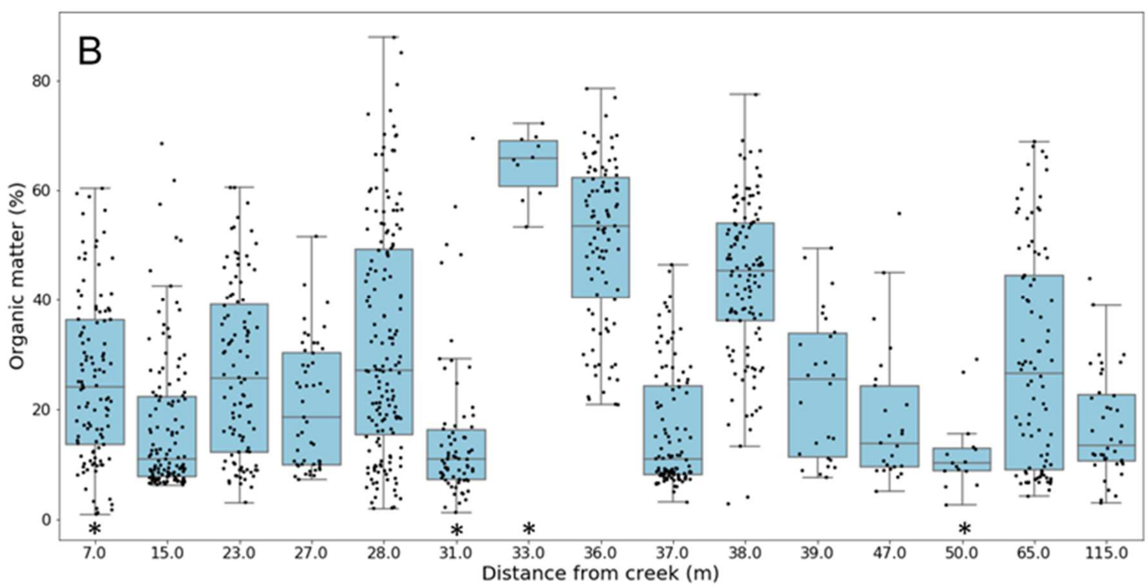


Figure 18. Percent organic carbon a) within the top 50 cm and b) throughout entire core depth, grouped by core and sorted by distance from tidal creek. Extreme outlier removed for visualization. Two cores are grouped together at 15 m distance from creek in figures A and B. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum. Asterisks (*) indicate incomplete cores (cores missing samples at some depths).

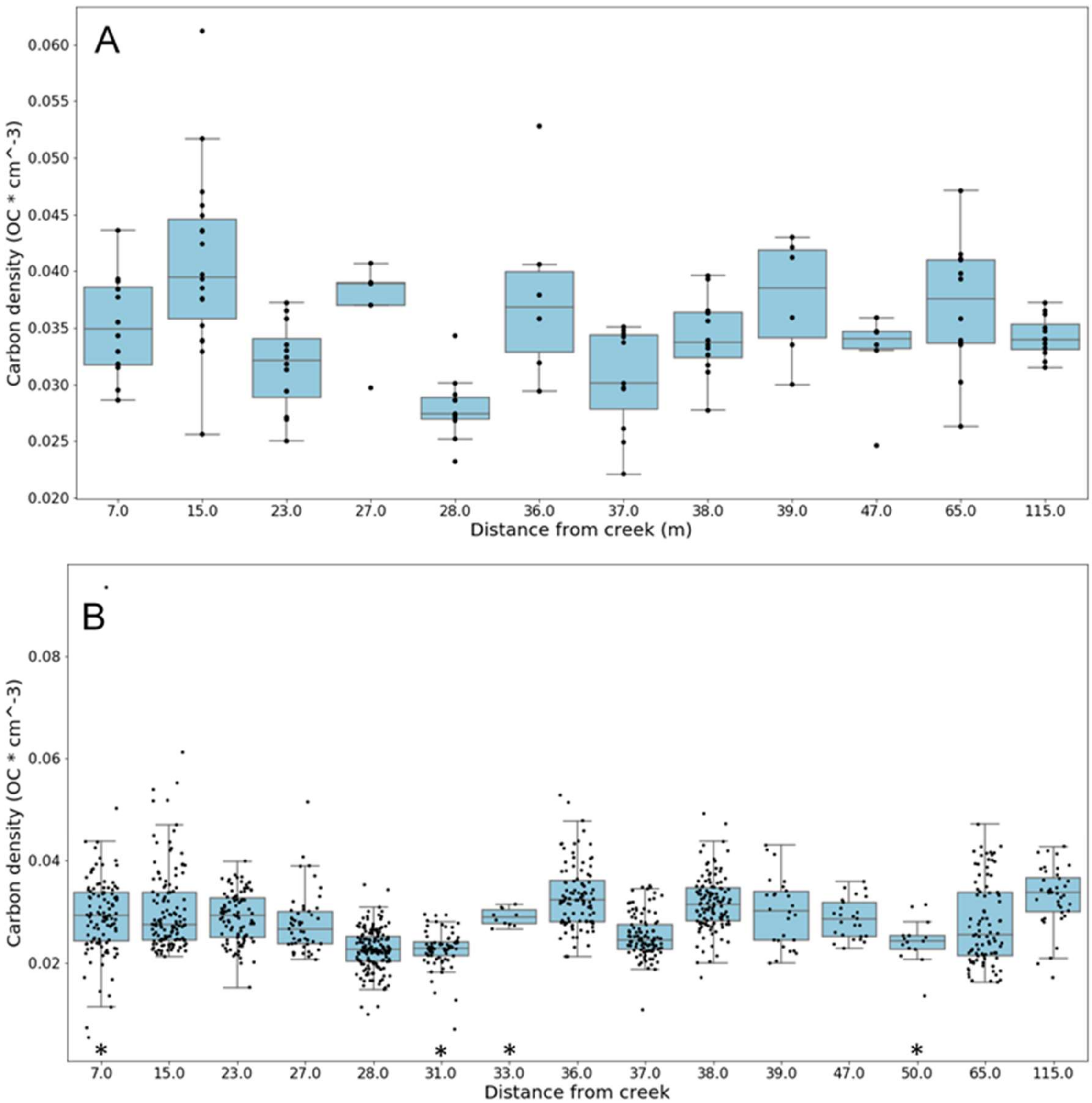


Figure 19. Carbon density a) within the top 50 cm and b) throughout entire core depth, grouped by core and sorted by distance from tidal creek. Extreme outlier removed for visualization. Two cores are grouped together at 15 m distance from creek in figures A and B. Horizontal line represents median, box represents IQR, and whisker caps represent minimum and maximum Asterisks (*) indicate incomplete cores (cores missing samples at some depths).

Interpolation analysis

The refusal depths of each core extended greatly past 1 meter, with the shortest complete core extending to 330 cm below ground surface and the longest extending to 770 cm below ground surface (Table 2). When estimating the depth of the AOI's marsh sediments through Inverse Distance Weighting (IDW) interpolation, the average depth of the surface generated using no edge estimations was more than double that of the surface with edge estimations (Table 4); the interpolations for peat thickness and mud/sand thickness were also drastically different when calculated with and without edge estimations, thus leading to large differences between the total organic carbon calculations completed with and without edge estimations (Table 4, Figure 20).

If refusal depth is assumed to be located at the bottom of the estuarine sediments, then according to the interpolation outputs, the total volume of the AOI sediments was approximately 121,000 m^3 with edge estimations (Table 4). The total organic carbon was approximately 3266 gC with edge estimations, and peat layers made up more than half of the total carbon in both interpolation methods (Table 4). For interpolations with and without edge estimations, the total organic carbon located at 1 meter or above was less than a third of the total carbon throughout the entire sediment depth (Table 4).

According to the interpolation outputs, total organic carbon was highest in the most landward section of the marsh, possibly due to the fact that the peat layers were thickest in that location (Figure 22); this phenomenon was not as apparent in the interpolation that only included 1 meter and above, since large portions of the deepest peat were not assessed (Figure 23). The interpolation outputs including only peat layers shows the same tendency more clearly, with the highest total organic carbon values highly concentrated at the landward end (especially around core 3, which had the thickest peat), and progressively lower values approaching the seaward end (Figure 24). Inversely, the interpolations including only mud layers showed the opposite trend, with higher total organic carbon values concentrated at the seaward end, where the mud layers were thicker (Figure 25).

Table 4. Total organic carbon calculated by summing the outputs of inverse distance weighting (IDW) interpolation, both with and without edge estimations. Units are grams of carbon (gC) and Megagrams of carbon (MgC).

		Min (gC)	Max (gC)	Mean (gC)	SD (gC)	Sum (MgC)
Total	no edge	5.63	25.56	12.74	2.34	7721.92
	w/ edge	0.00	25.56	5.39	4.04	3265.85
Top 1 meter only	no edge	2.59	4.17	3.38	0.26	2049.16
	w/ edge	0.00	4.17	1.40	0.93	846.47
Peat only	no edge	0.71	25.56	7.60	3.43	4607.20
	w/ edge	0.00	25.56	3.26	3.22	1976.87
Mud/Sand only	no edge	0.00	10.15	5.14	1.72	3114.73
	w/ edge	0.00	10.14	2.13	1.69	1288.99
		Min (cm)	**Max (cm)**	**Mean (cm)**	**SD (cm)**	**Volume (m^3)**
Refusal Depth	no edge	170.00	769.96	468.24	86.72	283704.64
	w/ edge	0.00	769.90	200.17	150.25	121280.79

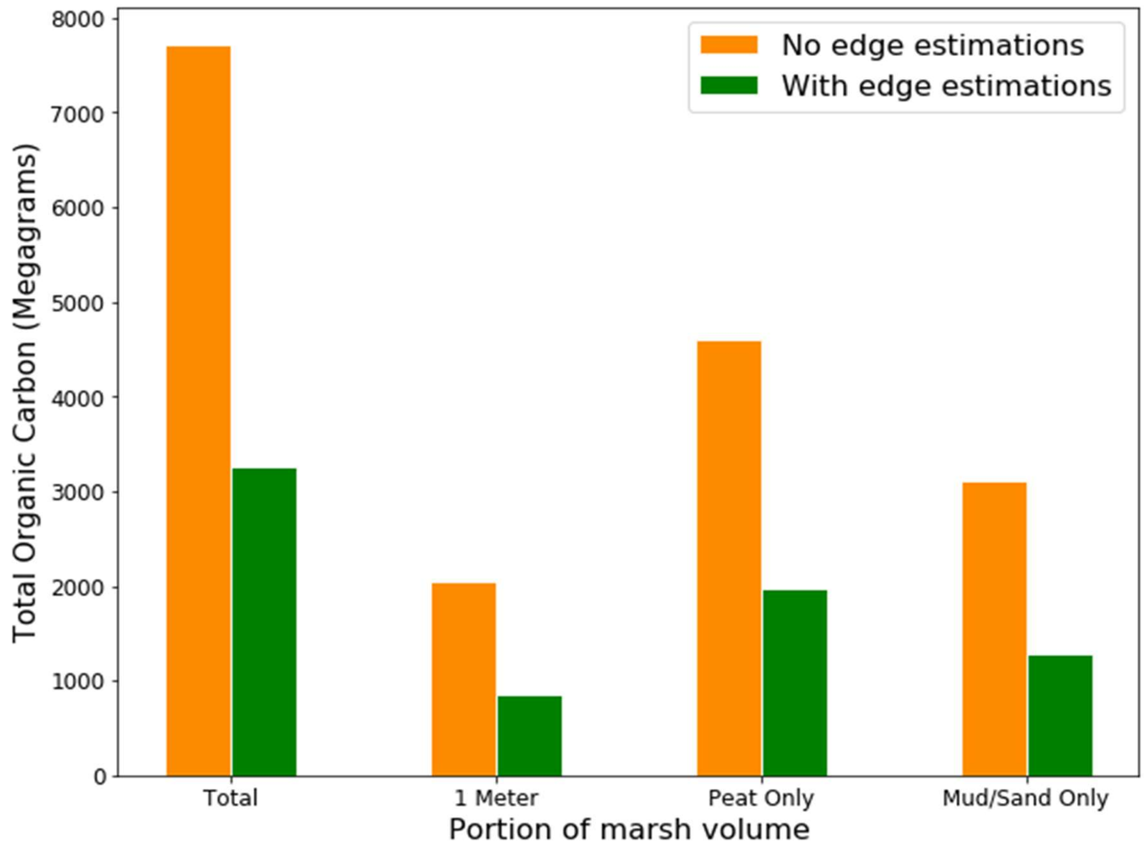


Figure 20. Total organic carbon in megagrams as calculated by summing the outputs of inverse distance weighting (IDW) interpolation, both with and without edge estimations.

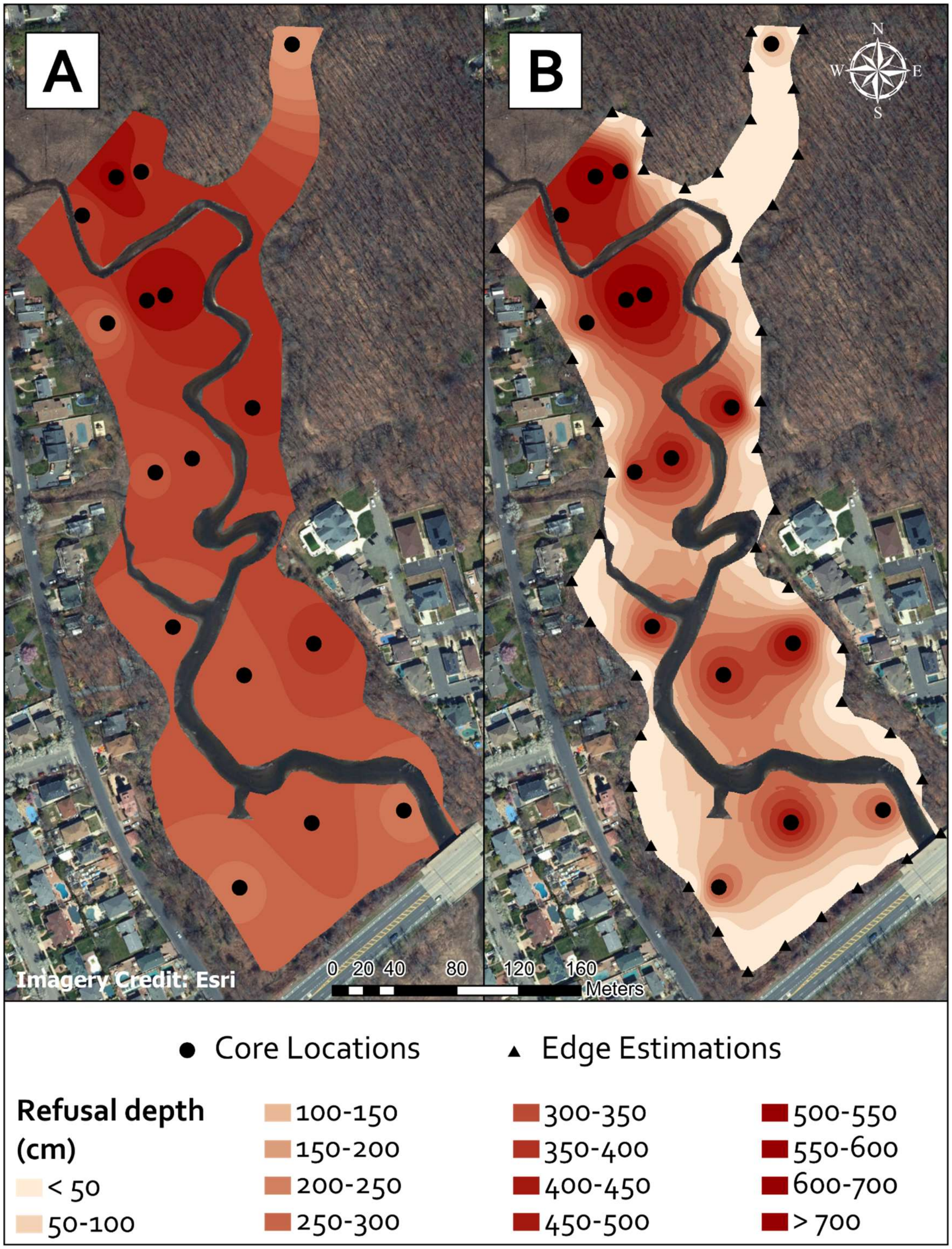


Figure 21. Inverse Distance Weighted (IDW) interpolations showing core refusal depth in cm below ground surface, both a) without and b) with edge estimations (estimated depth of 0).

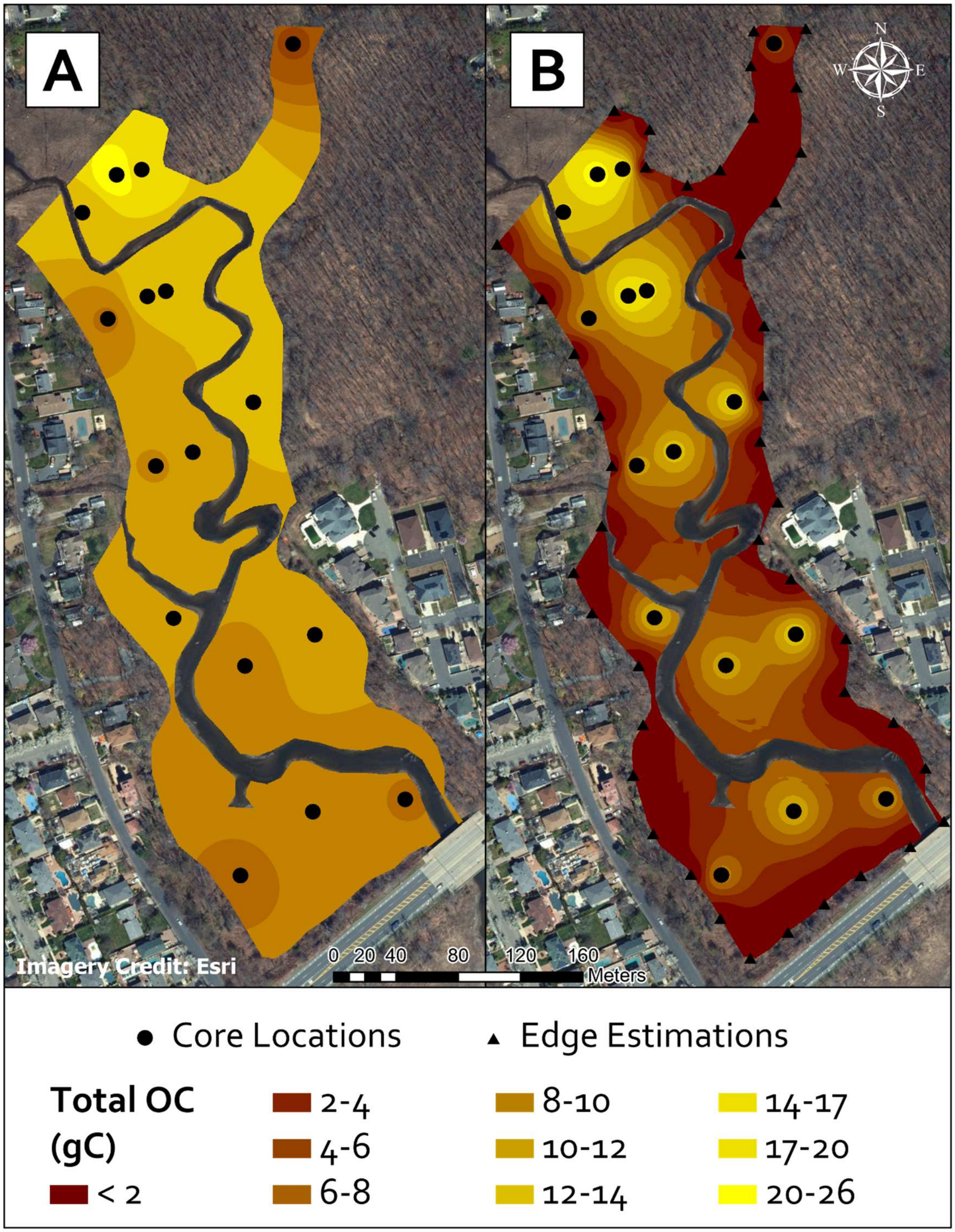


Figure 22. Inverse Distance Weighted (IDW) interpolations showing total organic carbon in grams of carbon, both a) without and b) with edge estimations (estimated depth of 0).

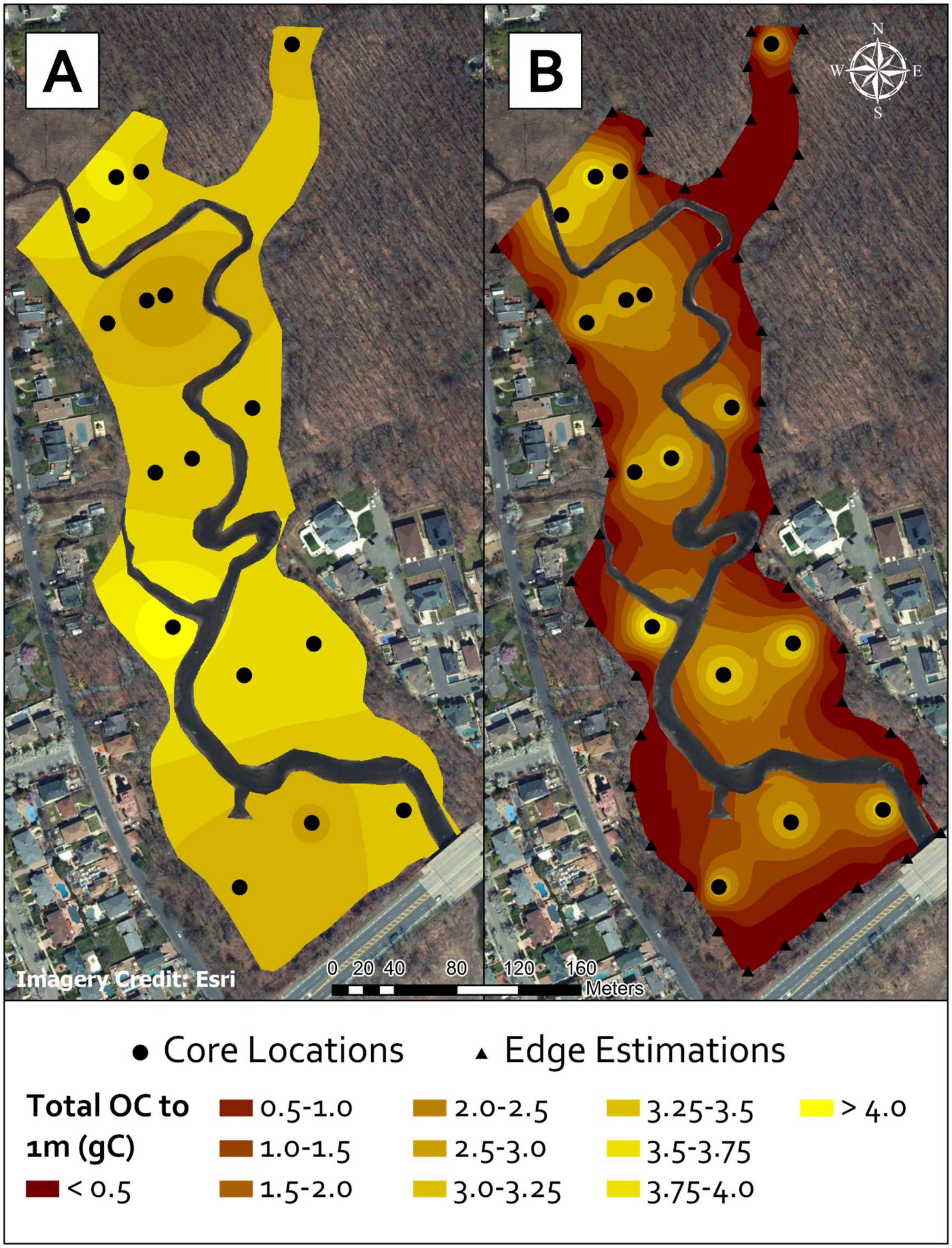


Figure 23. Inverse Distance Weighted (IDW) interpolations showing total organic carbon down to 1 meter depth, both a) without and b) with edge estimations (estimated depth of 0).

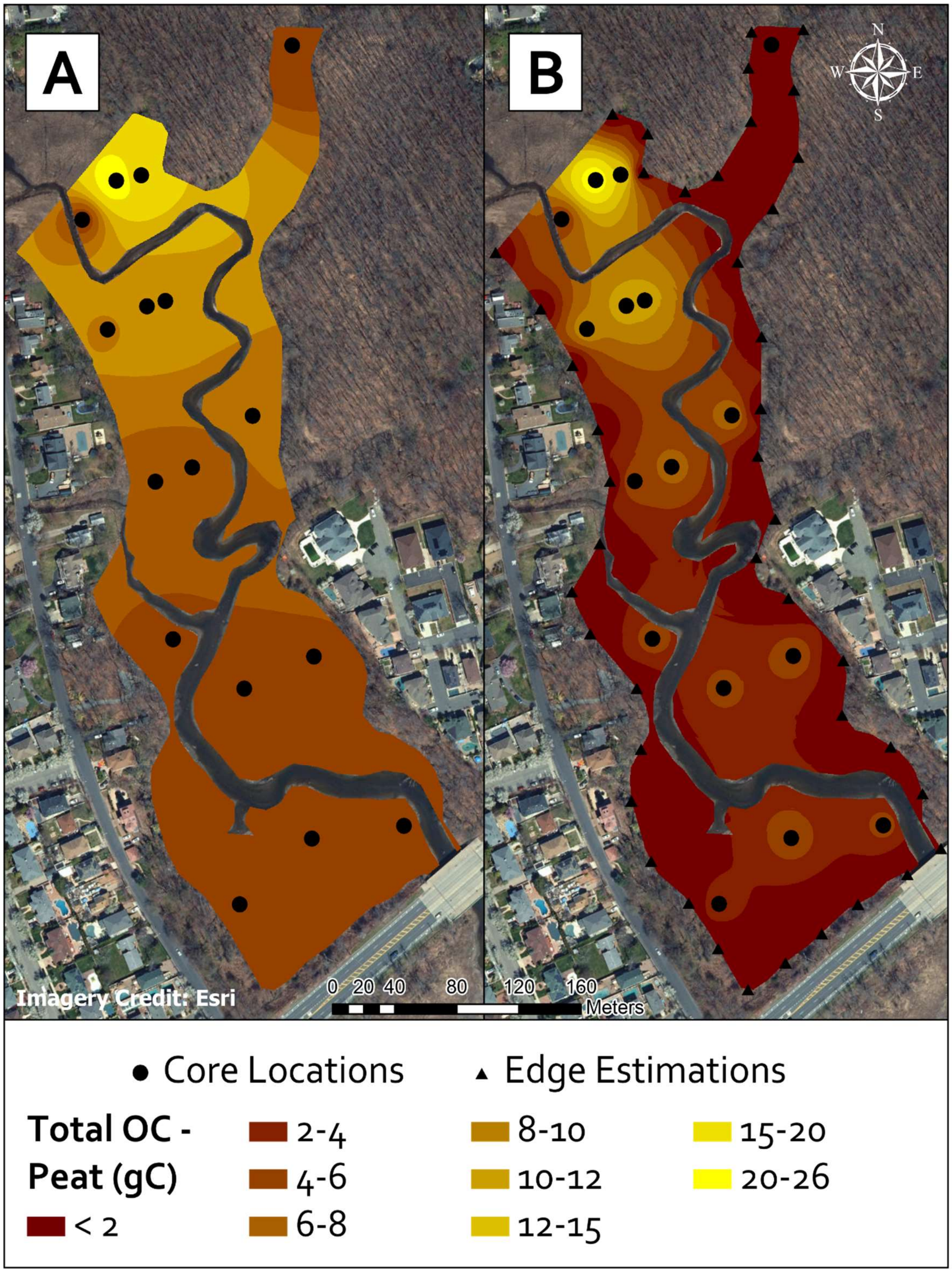


Figure 24. Inverse Distance Weighted (IDW) interpolations showing total organic carbon within peat layers only, both a) without and b) with edge estimations (estimated depth of 0).

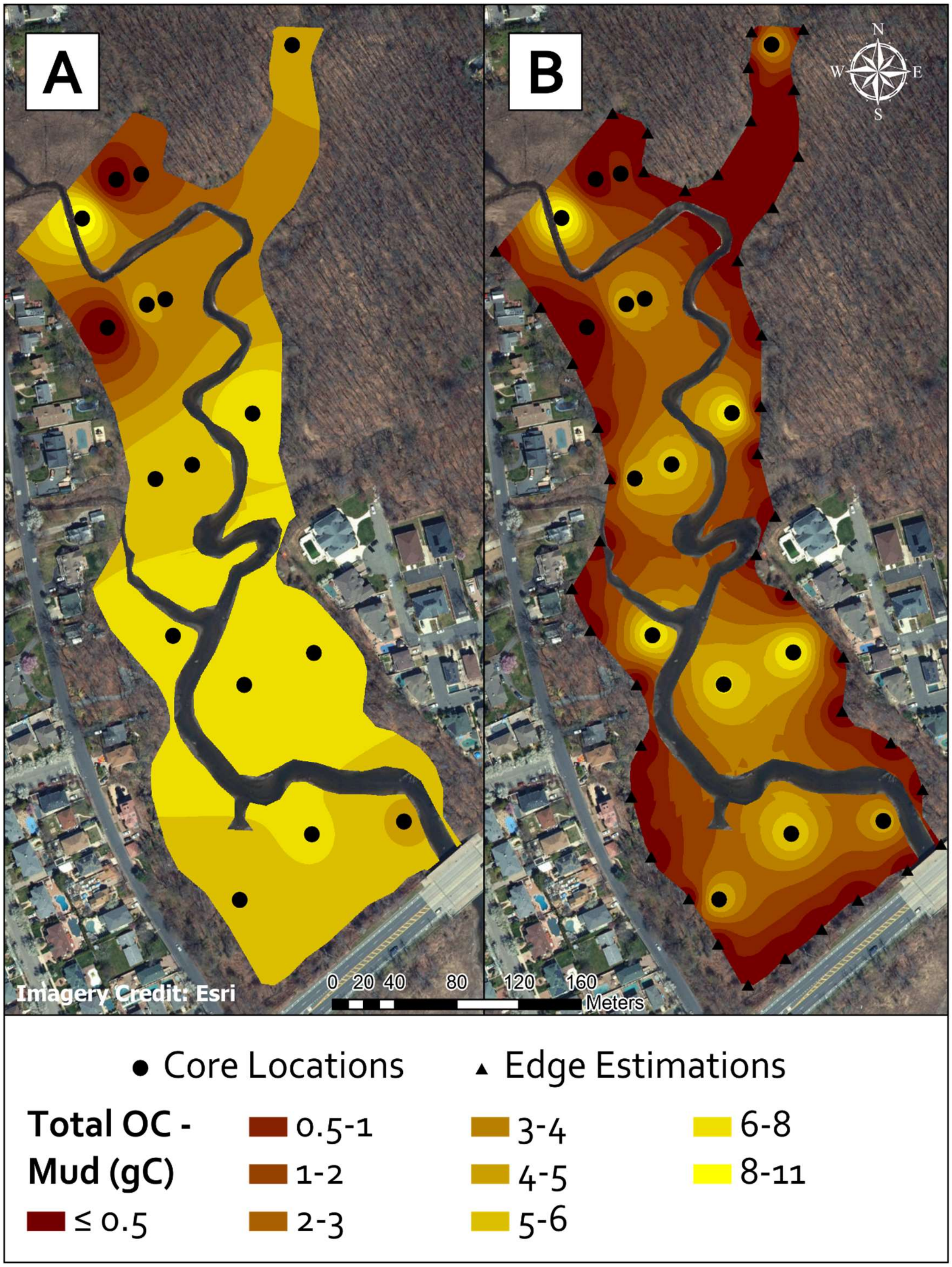


Figure 25. Inverse Distance Weighted (IDW) interpolations showing total organic carbon within mud layers only, both a) without and b) with edge estimations (estimated depth of 0).

Discussion

Percent Organic matter and organic carbon: Averages

The average organic carbon density (0.028 gC cm^{-3} ± 0.008) found in this study was very similar to the values found by a national inventory study by Holmquist et al. 2018 (0.027 gC cm^{-3} ± 0.013). The Holmquist et al. 2018 study included a total of 8280 samples collected in tidal marshes across the country and only surveyed marsh sediments down to a depth of 1 meter. Conversely this study included a total of 16 samples located within a 7-hectare area and surveyed both marsh (peat) and estuarine (muds and sand) sediments down to a maximum of 7.7 m. The high similarity of the average carbon density values between these two drastically different studies suggests that despite the highly site-specific, highly variable nature of tidal marsh carbon fluxes, trends in carbon storage may still be closely related when averaged. The average percent organic matter of cores in the Holmquist study decreased with depth until reaching 1 meter, ranging from 29 ± 0.5% to 15 ± 1.1%; the average percent organic matter of the Lemon Creek study was much more variable (27.89 ± 19.08%), and in most cores, the average increased with depth rather than decreasing, both to 1 meter depth and below (Figure 10). This difference suggests that despite similar carbon values, there may be differing mechanisms behind accumulation of organic material at Lemon Creek.

Ardenne et al. 2019 completed a study of marsh sites in Maine and Canada at a much finer scale in order to investigate carbon storage deeper than 1 meter. Ardenne et al. (2019) found the average carbon density above 1 meter (0.025 ± 0.009) was similar to the average carbon density below 1 meter (0.026 ± 0.008). While the Lemon Creek site had a larger difference in average carbon density between above and below 1 meter

(0.034 ± 0.007; 0.027 ± 0.006), the standard deviation suggests that these results may align with Ardenne's findings. Despite coring to refusal, the cores in Ardenne et al. 2019 did not exceed 2 meters, in contrast with the 7.7 meter maximum depth of the Lemon creek cores (Table 2); this demonstrates the high variability of marsh sediment depths, and emphasizes the further need to incorporate deeper samples in future research in order to more accurately gauge marsh depth.

Percent Organic matter and organic carbon: Surveying below 1 meter

Results from the Lemon Creek inventory suggest that accounting for only the carbon stored within the top meter greatly underestimates the overall carbon stock. The interpolations with edge estimates are more realistic, so only these will be discussed here. The total organic carbon within the top meter (846 MgC) was less than one third of the total carbon found throughout the entire marsh depth (3266 MgC; Table 4; Figures 22-23). If the average carbon storage figure determined by Holmquist et al. 2018 were to be applied to the total area of the Lemon Creek study site, assuming a depth of 1 meter, the total carbon estimate would be approximately 1896 MgC. Since this quick estimate is only a little more than half the total carbon found in this study, it further supports the idea that understanding the true depth of a given marsh is essential for a more accurate carbon estimation. Another important takeaway is the unexpected thickness of the peat layers, which extended far past 1 meter and accounted for more than half of the total organic carbon stored within the marsh (Table 4). Each of the 16 cores also varied considerably in depth, suggesting that marsh depth can be highly variable even within a localized area (Table 2). While using the 1-meter default value for assessing carbon stocks can provide a great deal of valuable data, especially when conducting broad-scale research, this method does not provide a full accounting of carbon stored in deeper marsh sediments, and important information on tidal marsh carbon stocks and depth variability may be overlooked (Holmquist et al. 2018; Ardenne et al. 2019).

Organic matter: Spatial patterns and depth trajectories

Variation in percent organic matter throughout core depth and among core groups A-E may be caused by a variety of factors, depending on the spatial location and the trajectory of these changes over time. Sea level rise is an important factor controlling rates of organic accumulation due to its influence on vegetation and accretion regimes in tidal marsh environments (Rogers et al 2019); these factors plus a variety of human impacts may have been largely responsible for guiding percent organic matter trajectories in Lemon Creek marsh. Changes in percent organic matter are relative changes rather than total changes; this means that the ratio of organic to inorganic material is reported, but the total volume of each type of material entering or leaving the system cannot be quantified through these data alone. The variation in percent organic matter may be caused by shifts in the total amount or nature of inorganic material in the system, which is controlled by sea level, tidal regimes and fluvial inputs. In addition, these variations in percent organic matter may be influenced by shifts in the total amount or nature of organic material caused by changes in vegetation cover or type through time. The variations we observe likely reflect a combination of these factors, but future work would be required to tease apart the various influences.

Changes in vegetation density and type may also be responsible for spatial and vertical changes in percent organic matter. Assuming that depth is roughly equivalent to age, the spatial pattern of each core group may indicate that the more landward portions of the marsh vegetated earlier than the more seaward portions of the marsh, with the exception of Group A (Figure 11). The landward Groups B and C may have vegetated first, as indicated by the presence of peat at depths of about 770 cm and 450-500 cm respectively, with vegetative cover first increasing from 500 m and then decreasing until present day (Figure 10). This early vegetation may only been able to colonize the landward-most portion of the study site as part of a freshwater wetland influenced by fluvial inputs and freshwater hydrologic regimes rather than tidal regimes. The very deep peat layers present to 770 cm depth in Group B (Core 3) differ from any other group, all of which show only mud and sand layers deeper than 400 m (Figure 10); the area around Core 3 may have vegetated as part of a freshwater riparian wetland much earlier than surrounding cores, potentially due to localized differences in vegetation type or fluvial inputs. Groups D and A may have vegetated next, as indicated by the presence of peat at depths of about 200-250 cm (Figure 10). Group A's very landward position indicates that it may have formed through an expansion of the freshwater wetland environment; however, the more seaward position of group D suggests that the tidal marsh environment may have begun to form by that point, accreting enough to reduce inundation frequency in more seaward areas and allow marsh vegetation to colonize. Group E vegetated last in historical time, indicated by peat that begins at a depth of about 200 cm and increasing until the surface (Figure 10); this is curious, since marshes tend to migrate landward with sea level rise and one would expect the seaward marshes to be older. As mentioned earlier, this discrepancy might be explained by the earlier formation of a more landward freshwater riparian wetland. The continuous increase of organic matter in Group E towards present day suggests that marsh conditions (elevation, inundation, etc.) remained suitable for vegetation growth and increases in vegetation density over time. The decrease in percent organic matter from 150-300 cm to the surface in Groups A-D may be caused by differences in vegetation density or vegetation types. The landward portion of the study site may have gradually converted from freshwater wetland to tidal marsh, thus allowing a transition from freshwater wetland to tidal marsh vegetation species. Also, as tidal regimes or marsh accretion rates changed salinity and marsh elevation relative to sea level, then the more seaward areas may have become vegetated with different high or low marsh species based on changes in tidal inundation frequency (Bertness and Ellison, 1987).

No age constraints were assessed in this study, but based on historic records, sea level in New Jersey 2500 years ago was about 4 m below what it is today, and has steadily risen since the preindustrial period; we expect that approximately the top 3-5 m of sediment in Lemon Creek marsh represent sediments that were deposited during this late Holocene SLR (Kemp et al 2013; Horton et al. 2013). The peak in percent organic matter that occurs at different depths in different core groups may represent changes in the marsh environment due to variations in rates of sea level rise and consequent inundation frequency, tidal range, and tidal energy changes. The peak in organic matter common between core Groups B and C rises represents the greatest change (60-70%) and occurs in deeper, older (300 m) sediments; the oldest sediments in these cores may have been deposited by an organic-rich freshwater wetland environment, with increasing tidal inundation triggering changes in hydrology and sediment type that may have eventually lead to a decrease in the organic/inorganic ratio alongside a transition to tidal marsh. Moving seaward, the peak in core Group D was lower in magnitude (40-60%) and occurred at shallower (more recent) depth (150 m); at this later point in time, tidal influences may have been occurring in that section of the wetland, thus allowing for an increase in inorganic sedimentation rates and a decrease in organic-rich peat accumulation alongside increasing tidal influence. The most seaward group, Group E, also included a shallower/later peak, with a rapid increase in percent organic matter above 200 m; the magnitude of this peak is similar to that of Group D. This trajectory suggests that this location may have never been occupied by a freshwater wetland, or a large pulse of sediment may have been deposited, thus allowing the rapid development of a tidal marsh. The tidally-influenced environment may have allowed a thinner layer of peat to accumulate over time, and inorganic sediment inputs decreased as the marsh accreted, thus allowing density of organics to quickly increase over time. Group A has a similar trajectory to group D, despite being spatially separated, while Group B has a similar trajectory to Group C except for a major increase in percent organic matter between 500 and 800 cm. These discrepancies could imply that despite the similarities, the trajectories of both Group A and Group B were more heavily influenced by the development of a freshwater wetland (e.g. fluvial inputs, overland runoff, and inland vegetation types), with the exception of the shallowest portions that likely formed once the area had converted to tidal marsh. While Group E showed an increase in percent organic matter approaching the surface, all of the other groups decreased from 150-300 m to the surface; this decrease may be explained by the changes in hydrology, salinity, sediment type, and inorganic sedimentation rates that accompanied the conversion from freshwater wetland to tidal marsh and the continued accretion of a tidal marsh system.

Influence of environmental factors on organic matter and carbon density

The available data indicates that neither percent organic matter nor organic carbon density had any dependent relationship with surface elevation and spatial factors such as distance from tidal creek (Figures 14-15, 18-19). This suggests that a) surface elevation and distance from creek did not have any major impact on carbon storage at this study site, or b) other environmental factors may have had a greater influence on carbon, thus masking any relationships that may have existed. Previous studies have suggested that marshes of different elevations have different accretion rates and low marshes on average accrete faster than high marshes (Kirwan et al. 2016); however, studies directly addressing the relationship between elevation and carbon density in tidal sediments are lacking. Since tidal marshes have high spatial variability due to complex geophysical processes, analyzing distance from creek and other spatial factors may only be applicable to very site-specific situations; nonetheless, contributing spatial data of any kind to the body of tidal marsh carbon research can fill important data gaps.

The sediment types compared in this study were linked to percent organic matter by nature; peat has high organic content while mud and sand have very low organic content, and the significant differences in both organic matter and organic carbon density between all of these sediment types were reflected in the results (Table 3; Figure 16). Organic carbon density showed a similar but slightly less significant trend (Table 3; Figure 17). While these results are expected, identifying carbon trends in different sediment types (which reflect different environments of deposition) may be an important tool when comparing carbon storage potential at tidal marsh and other tidal estuarine sites.

Vegetation type was not found to have a significant relationship with organic carbon (Figure 3, Figure 12); however, there was a significant difference in percent organic matter between S. patens and P. australis (Figure 3; Figure 13). Previous research has investigated a variety of potential relationships between organic carbon and surface vegetation and the results have been inconsistent; therefore, although significance was found at Lemon Creek Marsh, the low sample size and the small study site suggest that more extensive research is needed with more samples and at a wider range of sites. Some studies found significant differences in soil carbon between surface vegetation species salt marsh species or low marsh vs. high marsh environments (Ardenne et al. 2019), while others found no differences or asserted that vegetation type was not a reliable predictor of soil carbon (Gorhan et al. 2020; Holmquist et al. 2018). The plant productivity and biomass of different marsh vegetation types may be too heavily influenced by human impacts such as nutrient loading and urban runoff to show an effective relationship with carbon storage, especially at urbanized sites such as Lemon Creek (Matzke et al. 2018; Logan 2018). While surface vegetation itself may not always have a direct relationship with carbon density, some studies suggest that salinity and flooding have a major impact on organic matter decomposition and carbon fluxes (Stagg et al. 2017, Sheng et al. 2015); these factors may be more responsible for altering organic carbon density in tidal marsh sediments than surface vegetation type. Salinity interacts with the plant-microbial-soil system in a manner that clearly impacts carbon fluxes, and some studies find that salinity can increase carbon sequestration; however, these interactions are complex and often inconsistent due to differing periods of exposure to saltwater inundation, as well as differences in carbon flux during different points in the tidal cycle (Nebauer et al. 2013; Chambers et al. 2013; Sheng et al. 2015). Vegetative cover may have more of an impact on methane than organic carbon; during certain months of the year, Reid et al. 2013 found differences in methane fluxes between non-vegetated and vegetated estuarine environments. Despite the lack of an apparent relationship between vegetation type and carbon density in this study, the complex interactions between vegetation and the biogeochemical processes of tidal marsh systems suggest a need to further investigate the potential impacts of vegetation on tidal marshes.

Conclusion

The main conclusions of this study are:

- The Lemon Creek marsh site had a total volume of 121,281 m^3 (with edge estimates) with thick, carbon-rich peat layers that grew thicker approaching the landward end and contained more than half of the site's total organic carbon; the significant depth of these peat layers suggests that assessments of tidal marsh carbon storage that only include depths up to 1 meter can be limited. While results utilizing Holmquist's methodology at Lemon Creek estimate a total organic carbon storage amount of 846 MgC, assessment of the full 3D volume revealed over three times that amount, 3266 MgC (with edge estimations). Broad-scale inventory studies assessing the true depth of marsh sediments could be key to gauging the potential of tidal marshes in combatting climate change.

- Trajectories in percent organic matter throughout core depth suggested that, at the landward end of the study site, the present day tidal marshes are underlain by earlier freshwater wetland environments. Over time, increasing tidal inundation due to sea level rise caused the entire area to transition to tidal marsh. These trends were influenced by a variety of environmental factors such as fluvial inputs, changes in sea level, tidal regimes, sedimentation and accretion rates, vegetative cover, and other human impacts.

- Surface elevation and distance from creek did not show significant relationships with percent organic matter and organic carbon density in marsh sediments; however, organic matter varied significantly when grouped by certain vegetation types, and both organic matter and carbon density varied significantly when grouped by sediment type. Many of these environmental factors have an uncertain degree of influence on carbon storage; therefore, continuing to explore such factors on larger scales may help to close important knowledge gaps in the future.

For future research investigating tidal marsh carbon, a variety of elements can be included to produce more detailed results. A higher number of sediment cores may produce better interpolation results, thus providing a clearer picture of spatial changes in organic matter, organic carbon, and sediment type throughout the entire marsh. Macrofossils, fossil pollen, and carbon isotopes can be utilized to assess the age of sediments at different depths (Kemp et al. 2013); aging the sediments would provide a better sense as to how and when different parts of the marsh may have formed. Another important parameter to consider is salinity (Stagg et al. 2017, Sheng et al. 2015); vegetation dynamics, organic decomposition, as well as methane and carbon fluxes may all be influenced by salinity, so it may be an essential factor to consider when studying blue carbon.

Carbon research in tidal marshes is continually expanding as we try to understand how best to sustain blue carbon resources to mitigate the impacts of global climate change. Identifying those tidal marshes with deep peat layers that are currently housing and sequestering large amount of organic carbon is vital if these blue carbon rich locations are to be properly managed and sustained for the long term. The marshes with the highest carbon stocks are also at the highest risk of releasing CO_2 into the atmosphere if they undergo degradation or shoreline erosion (Lovelock et al. 2017), although it is unclear to what depths carbon can be lost from these systems via erosion and decomposition. In the coming years, climate change and other human impacts will also continue to affect sea level, tidal regimes, accretion rates, and vegetation patterns in tidal marshes. If we can better understand how these factors may have impacted organic matter storage in the historic past, then we may be better able to predict how changing environmental conditions may alter carbon storage potential in the future. Now more than ever, it is essential to study the dynamics of these important blue carbon systems so that we can better approach tidal marsh management in the face of global climate change.

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