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Spatial dynamics of sediment accumulation and soil carbon storage in a restored wetland

A Thesis submitted in partial satisfaction of the
requirements for the degree Master of Arts
in Geography

by

Jessica Jayne Landesman

Committee in charge:
Professor Jennifer King, Chair
Professor Vamsi Ganti
Professor Oliver Chadwick

September 2024

The thesis of Jessica Jayne Landesman is approved.

Vamsi Ganti

Oliver Chadwick

Jennifer King, Committee Chair

September 2024

Spatial dynamics of sediment accumulation and soil carbon storage in a restored wetland

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by

Jessica Jayne Landesman

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To Iris Holzer and Nina Bingham – thank you for inspiring me to be a soil scientist and pursue graduate school in the first place! To my parents, thank you for teaching me the value of education and the natural world! What a combination! Thank you to my housemates, cohort, friends, and partner for the endless support and laughs! There is so much to be grateful for!

ABSTRACT

Spatial dynamics of sediment accumulation and soil carbon storage in a restored wetland

by

Jessica Jayne Landesman

Coastal wetlands are being lost at an alarming rate and thus wetland restoration is an important way to recruit coastal wetlands as an ally in our fight against climate change. To better understand and maximize the effectiveness of wetland restoration, it is important to evaluate the success of these restoration projects. In this study, we measured sediment accumulation and soil carbon density in North Campus Open Space, a recently restored wetland near the campus of UC Santa Barbara. The objectives of this study were to 1) assess rates of sediment accumulation since restoration, 2) evaluate spatial heterogeneity in sediment accumulation and soil carbon density, and 3) use this information to better understand the mechanisms that define the relationship between sediment accumulation and surface soil carbon storage to better predict carbon accumulation. Sediment accumulation rate averaged 2.16 mm/year, with a range of 0.4 mm/yr to 5.4 mm/yr. Sediment accumulation, surface soil carbon density, and subsurface carbon density all varied significantly by plot location. The spatial dynamics of vertical accretion were primarily driven by mineral rather than organic material, whereas surface soil carbon was primarily driven by aboveground plant biomass. Sediment accumulation was greatest downstream, whereas soil carbon accumulation was greatest upstream at the freshwater stream inputs. Some areas showed a negative relationship between sediment accumulation and soil carbon density, with high sediment accumulation associated with low surface soil carbon density. Although wetlands are touted to mitigate sea level rise and climate change through sediment accretion and carbon sequestration, these results suggest that sediment accumulation and carbon accumulation do not necessarily co-occur. The results imply that sediment accumulation alone cannot reliably predict carbon accumulation.

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I. Introduction

Coastal wetlands act as nature-based solutions to climate change in two ways – as an adaptation service, they accumulate sediment to keep pace with sea level rise, and as a mitigation service, they store a disproportionate amount of carbon for the small area they occupy (Perillo et al., 2019; Nahlik & Fennessy, 2016; Weston et al., 2023; Lal, 2004). Frequent inundation is characteristic of these ecosystems and promotes sediment accumulation and increased carbon sequestration due to the slowing of decomposition (Nahlik & Fennessy, 2016; Perillo et al., 2019). In recent years, the concept of "blue carbon," or the organic carbon that accumulates in tidal wetlands over time, has been a popular topic to study. Globally, blue carbon sequestration is estimated between 65 and 215 Tg OC per year (Hopkinson et al., 2012; Perillo et al., 2019).

These beneficial ecosystem services make coastal wetlands increasingly important as climate change progresses. However, anthropogenic activities such as housing development threaten coastal wetlands and the services they provide. Half of coastal wetlands globally were lost in the 20th century (Li et al., 2018). Protecting and restoring coastal wetlands is a crucial strategy to promote climate resiliency in coastal communities. To better understand and maximize the effectiveness of restoration, it is important to evaluate the success of these restoration projects, specifically in regards to the nature-based solutions that wetlands provide.

Many studies have focused on differences in sediment accumulation and carbon storage *between* wetland systems (Weston et al., 2023; Peck et al., 2020; Callaway et al., 1997), but there is a lack of understanding of spatial heterogeneity *within* wetland systems. The importance of water and inundation led us to hypothesize that lower elevations within a wetland system would be inundated more and thus have higher rates of sediment accumulation and carbon storage (Vandenbruwaene et al., 2011). In testing this hypothesis, we discovered the complexity and interrelatedness of many variables within the wetland system. This study focuses on quantifying spatial variation in sediment accumulation and carbon storage and examines potential factors that may drive spatial variation. Though there is no clear consensus on what predictor variables drive sediment accumulation and carbon storage in coastal wetland systems, past studies have found that sediment availability, vegetation, elevation, and distance to river channels are important in predicting variation in these outcome variables (Vandenbruwaene et al., 2011; Liu et al., 2021; Morris et al., 2002).

As proposed by Mitsch and Gosselink (2015, Figure 1), wetlands are designated by a combination of biotic, hydrologic, and physiochemical environmental factors. These same factors are used to predict sediment accumulation and carbon storage within a wetland system. For example, aboveground biomass is an important control for both sediment accumulation and carbon storage because of biomass trapping and direct carbon inputs to the soil (Morris et al., 2002; Choi et al., 2001). Sediment availability is an important physiochemical factor in controlling sediment accumulation (Liu et al., 2021). Flooding frequency or inundation, a hydrologic component, is important as well, as it slows decomposition and allows coastal wetlands to sequester a disproportionate amount of carbon and leads to greater sediment deposition (Nahlik & Fennessy, 2016). It is important to note that these three categories do not act independently of each other and there are many feedbacks among the variables (Mitsch & Gosselink, 2015).

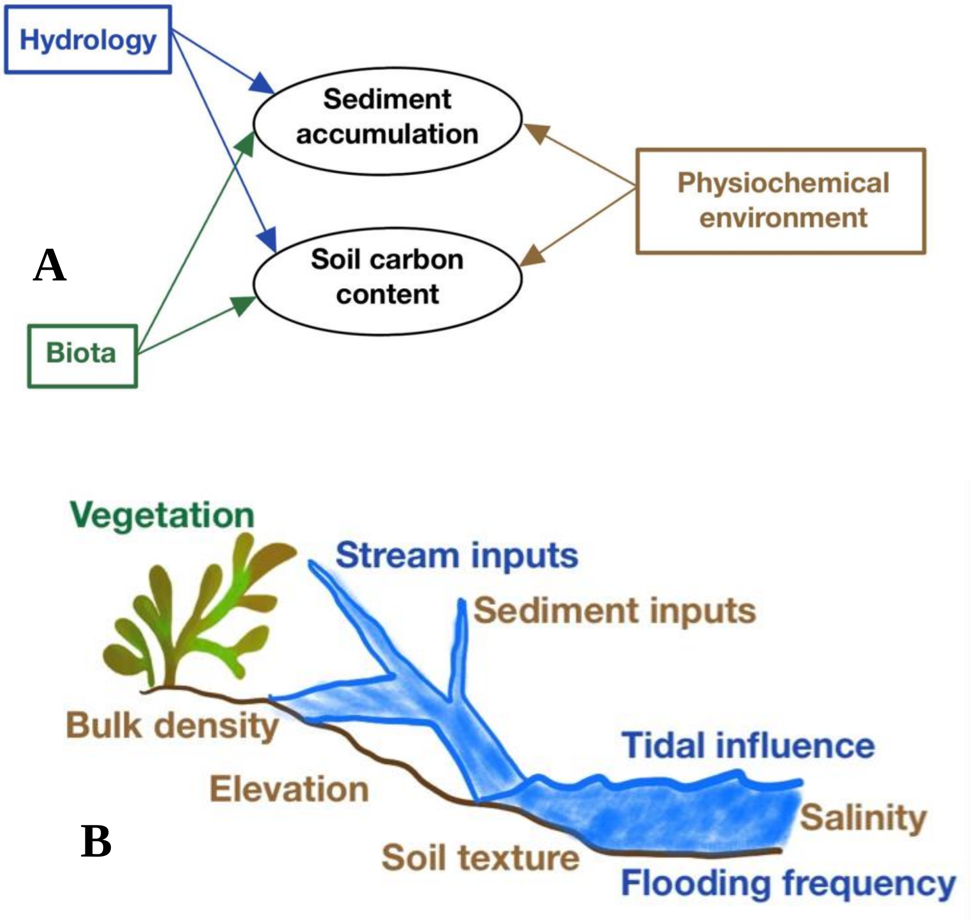


Figure 1: A) Conceptual diagram showing how factors in three main categories, hydrologic, biotic, and physiochemical, affect the variation of the two main outcome variables in this study, sediment accumulation and soil carbon content, in both the surface and subsurface. B) Conceptual diagram that highlights the different specific hydrologic, biotic, and physiochemical factors in this study. Color corresponds to the type of driver (Figure adapted from the three-component basis of a wetland definition diagram in Mitsch & Gosselink, 2015).

Oftentimes in the literature, models that predict carbon sequestration in wetlands assume that increasing sediment accumulation increases surface soil carbon (Lolu et al., 2020; Chmura et al., 2003; Connor et al., 2001). However, results from this study show that this is not always the case. Understanding the nuances and spatial dynamics of the relationship between sediment accumulation and surface soil carbon storage is essential for gaining insight into the mechanisms behind carbon storage and its stability. Amending this assumption used in wetland carbon sequestration models may prove beneficial in designing effective wetland restoration projects to maximize both sediment accumulation and carbon sequestration. A better understanding of this relationship will also allow modelers to make better estimates of the rate of change of blue carbon.

Biotic, hydrologic, and physiochemical factors influence the spatial variation in sediment accumulation and soil carbon storage in wetland systems (Zhang et al., 2002; Spencer & Harvey, 2012). This is particularly important and interesting to assess in restored wetlands, where these three categories of factors are heavily manipulated. Our study looked at sediment accumulation and soil carbon storage at four elevations in six different locations in North Campus Open Space (NCOS), a recently restored wetland near the campus of UC Santa Barbara. Our objectives were to 1) assess rates of sediment accumulation since restoration, 2) evaluate spatial heterogeneity in sediment accumulation and soil carbon content, and 3) use this information to better understand the mechanisms that define the relationship between sediment accumulation and surface soil carbon storage to better predict carbon accumulation.

II. Materials and Methods

Study area

The study was conducted at North Campus Open Space (NCOS), just west of the University of California, Santa Barbara campus, located approximately 175 km northwest of Los Angeles, CA. NCOS is a 40.5-hectare area that includes about 16 hectares of intermittently tidal salt marsh wetlands which were restored in 2017. The original wetlands were destroyed in the 1960s to create a golf course. Measurement sites were also located adjacent to NCOS in Coal Oil Point Reserve (COPR), part of the UC Natural Reserve System and one of the best remaining examples of a natural coastal-strand environment in Southern California. A total of 51 plots were placed in NCOS and COPR after restoration of NCOS from a golf course back into a coastal wetland system in 2017. Plots were placed at different elevations and distances to the main water channel, with the lowest elevation located at 1.98 meters above sea level and the highest elevation of 2.44 meters above sea level, using the NAVD88 datum.

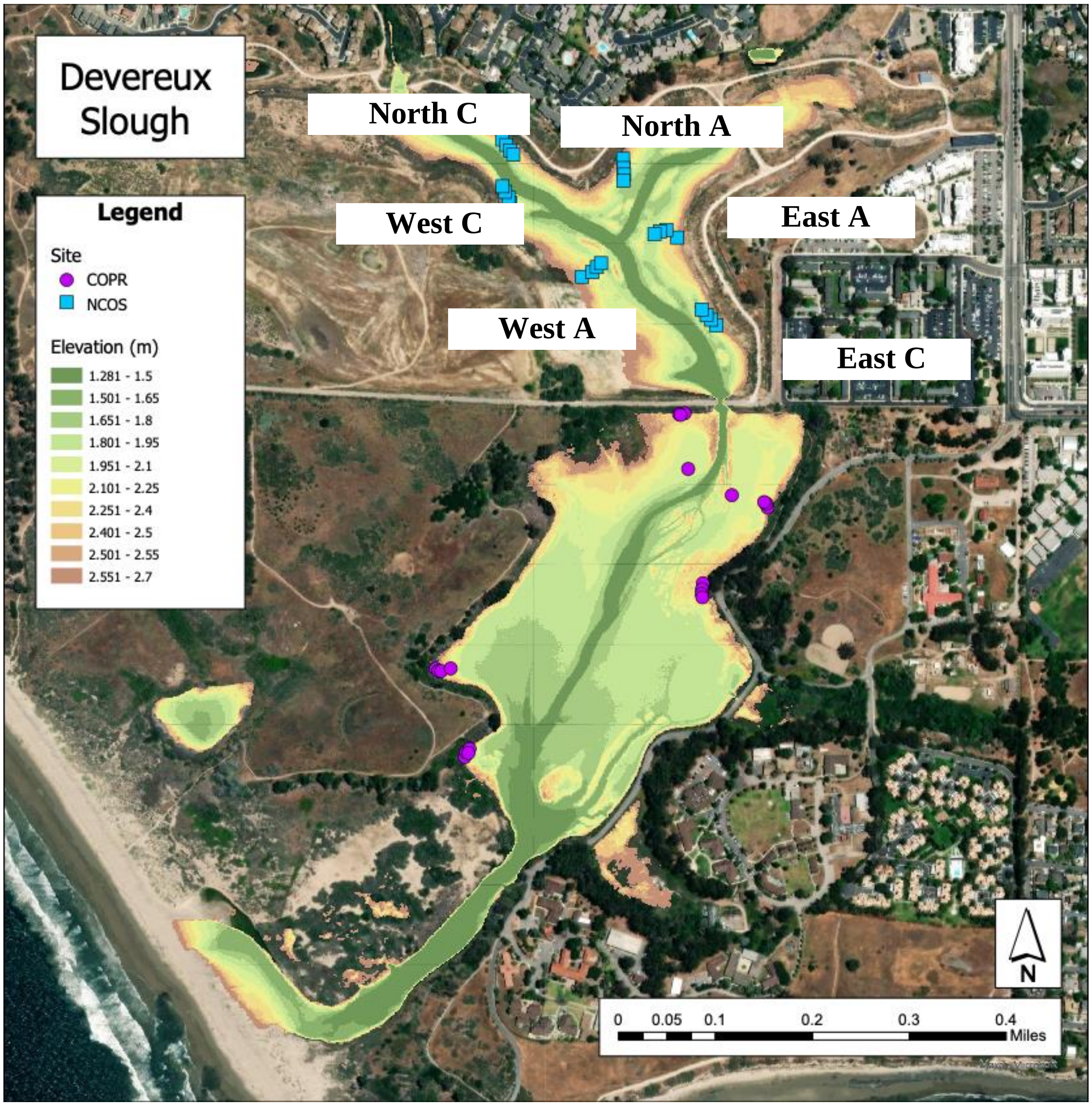


Figure 2: Feldspar plot locations in NCOS (blue squares) and COPR (purple circles) overlayed on a digital elevation model. NCOS plots are labelled for reference.

Sediment accumulation:

The feldspar marker technique was used to quantify the average amount of sediment that has accumulated in NCOS and COPR over the past five years (Cahoon & Turner, 1989). After restoration of NCOS in 2017, 51 square plots of feldspar (in 0.25 m^2 quadrats) were placed in NCOS and COPR with one corner oriented due north and marked with rebar and PVC pipe. In 2023 the sites were sampled. After removing aboveground vegetation from each plot, a 30-cm transect line was cut from the western side of the plot and five measurements above the feldspar marker were taken from this transect. This process was repeated, with ten measurements recorded at the 45-cm transect, 15 measurements from the 60-cm transect, and 20 measurements taken from the 75-cm transect across the center of the plot. Two people recorded a total of 100 measurements of sediment accumulation per plot. An average was then taken for the 100 measurements.

Carbon content:

Soil samples were collected from the surface and below the layer of feldspar using shovels and labeled plastic bags. These samples were oven dried for 48 hours at 65°C, ground using a Wiley mill, added to small vials and further ground on a roller mill for 24 hours. Next, ~25 mg of soil was added to tin capsules by weighing on a microbalance scale. These tin capsules were incinerated in an elemental analyzer to get percent of carbon and nitrogen content in each soil sample, from both above and below the feldspar layer. Soil samples were analyzed for total carbon and nitrogen using a Flash 2000 Elemental Analyzer (Thermo Fisher Scientific) and the Eager Xperience computer software. This instrument has an autosampler connected to a steel reactor that heats to 1800°C, combusting the soil in the tin capsule. The gas mixture that is produced by this combustion makes its way to the thermal conductivity detector (TCD) which is converted to electrical signals that the Eager Xperience software is able to convert into elemental carbon and nitrogen (Thermo Fisher Scientific, 2009). Acetanilide (C ~ 70%, N~ 10%) was used as the standard for these analyses.

Carbon accumulation:

Carbon accumulation (CA) was calculated using the following equation:

$$BD * \%C * SA = CA,$$

where BD is the bulk density of the soil in units of grams per cm^3 (described below), %C is the percent carbon in the soil sample, and SA is the sediment accumulation rate, calculated as mm/year.

To evaluate the spatial dynamics that create variation in sediment accumulation, carbon density, and carbon accumulation, we analyzed biotic, hydrologic, and physiochemical variables. Since these three categories are important for defining what makes a wetland, they are also important for establishing the major mechanisms that drive variation in the system. For biotic factors, we sampled vegetation. For hydrologic factors, we analyzed flooding frequency at each plot, which could be attributed to stream inputs or tidal influence. For physiochemical environment variables, we measured bulk density, soil texture, soil pH and electrical conductivity, sediment inputs, and distance from sediment source.

A. Biotic Factors:

Vegetation sampling:

A 0.5 m x 0.5 m quadrat was placed at each feldspar plot location, with the PVC pipe field marker hammered into the soil marking the northernmost point. Using clippers, all aboveground vegetation within the quadrat was collected, including plants with roots in the plot and plants with roots elsewhere that were growing into the area where the quadrat was placed. Vegetation was placed in paper bags and brought back to the lab. In the lab, vegetation was separated into four categories: dead, pickleweed, grass (live and senesced), and herbaceous vegetation. After weighing the separate categories, plant samples were placed in the oven to dry for 48 hours at 65°C. The dry biomass was then weighed again.

B. Hydrologic factors:

Flooding frequency:

We used Planet Labs imagery to measure the number of times plots have been flooded since restoration. A satellite image was collected every month from post-restoration in October 2017 to July 2023, before we started sampling the plots. These images were taken from a combination of Planet Dove satellites, with a resolution of 3m x 3m. Images were selected for having the least amount of cloud cover, covering the full extent, and from the first 10 days of the month, though exceptions occur. We overlaid the plot locations on the true color and false color satellite image to trace the water extent, and then counted the number of plots that were fully submerged. Flooding frequencies were recorded as the total number of times each plot was flooded during 68 months between October 2017 and July 2023 because two months did not have viable satellite images available (June 2019 and September 2020). Plot flooding was likely due to freshwater stream inputs or tidal influence from the ocean when the intermittently tidal wetland becomes tidal for part of the year, but the source of the flooding was not determined in the analysis.

Stream inputs:

For this study, we primarily focused on stream inputs and water level data from Phelps Creek and Whittier storm drain, though Devereux Creek on the west side and Storke Ranch culvert on the east side likely also contribute freshwater stream inputs to this system. NCOS has pressure transducer loggers (YSI EXO1 and Solinist Leveloggers) in both Phelps Creek and Whittier storm drain. These devices record the water level every 15 minutes.

Water level data is converted to water surface elevation (WSE) in feet using the known elevations of the loggers or regular readings of a WSE staff.

Tidal influence:

Since NCOS is an intermittently tidal wetland system, it is influenced by tidal action for a portion of the year. Tidal influence data was collected by the Cheadle Center for Biodiversity and Ecological Restoration (CCBER) using a Solinist pressure transducer which collects data every 15 minutes from Venoco Bridge. These pressure transducers are placed in multiple locations across the Slough, but the Venoco Bridge location is best used to infer when the system is experiencing the influence of the ocean and tides. There are some errors in readings for the Venoco Bridge logger from 2022, so data from the East Channel Bridge was used to measure the days that were tidal and nontidal when the berm was breached.

C. Physiochemical environment factors:

Bulk density:

Soil bulk density was measured by hammering copper rings with a diameter of 5.08 cm and a height of 1.27 cm into the ground. Three replicates were taken of the surface soil and three replicates were taken below the layer of feldspar (generally 5-10 cm depth). These samples were taken back to the lab, weighed, dried for 48 hours at 105°C, and weighed again to record bulk density and moisture content.

Soil texture:

Soil texture measurements were made for the surface soil and the below feldspar-layer soil by combining the bulk density sample replicates after drying and grinding to less than 2 mm. The 2-hour hydrometer method was used: percentage silt and clay that remained in the column was recorded after 40 seconds, and percentage clay that remained in the column was recorded at 2 hours (OSU Soil Fertility Lab, 2020). Sand percentage was calculated by subtracting the percentage silt and clay from 100. Silt percentage was then calculated by subtracting the clay in the column at two hours from the silt and clay in the column at 40 seconds.

Soil pH/EC:

At each plot, soil samples were collected from above the layer of feldspar and below. These samples were sieved and a portion was dried for 48 hours at 65 degrees Celsius. After drying, the samples were ground through a Wiley mill and placed in small plastic containers with metal bars to be placed on the roller mill for 24 hours. Soil slurries were made by adding 5 grams of ground soil to 25 mL of type 1 water and mixing. After the slurries were prepared, an Oakton CON 510 Series conductivity meter was used to get a measurement of soil salinity and a Hach Sension+ MM374 pH meter was used to measure soil pH.

Sediment inputs:

In addition to the pressure transducer loggers that CCBER operates in NCOS, they also employ Teledyne-ISCO brand portable water samplers to collect water samples at chosen intervals, usually during storm periods. These water samples are then stored in the laboratory and analyzed for sediment concentration using either total suspended solids protocol (TSS) (for less visibly turbid samples) and suspended sediment concentrations (SSC) (for more visibly turbid samples). For this study, water samples from the 2023 water year were analyzed for sediment concentration using TSS and SSC techniques.

Distance from sediment source:

Downstream distance was calculated in ArcGIS Pro by following the channel upstream from the mouth of the river, which we labeled here as Venoco Bridge, where the channel narrows and enters the lower part of the Slough, also known as Coal Oil Point Reserve (COPR). Then, a perpendicular measurement from the channel to each plot location was recorded.

D. Data analysis:

Data was analyzed using ANOVA, linear regressions, and multiple linear regressions in R. Spatial visualizations were created in Python using point data and raster data from a digital elevation model of the area. Plots with outlier data, defined as points greater than the 3rd quartile plus 1.5 times the interquartile range, were removed. For model analysis and selection, Bayesian information criterion (BIC) and ΔBIC was used over Akaike information criterion (AIC) because BIC is a more robust, evidence function criterion that works well for data with lower sample sizes (Dennis et al., 2019).

III. Results

Sediment accumulation:

Since NCOS was restored in October 2017, the wetland has accumulated an average of 2.16 mm/yr of sediment, ranging from 0.40 mm/yr to 5.40 mm/yr. Sediment accumulation varies significantly by plot location (Table 1, Figure 2; ANOVA: p-value << 0.001).

Table 1: Sediment accumulation rate (mm/yr) by plot location

Plot location	**Minimum**	**Maximum**	**Mean**	**Sample size**
East A	0.9172414	2.599819	1.8511965	4
East C	2.6689655	5.402299	4.4742816	4
North A	0.687931	1.765517	0.9905172	4
North C	2.2155172	3.346552	2.8926724	4
West A	0.3965517	2.384483	1.1556034	4
West C	0.7827586	2.665517	1.5775862	4

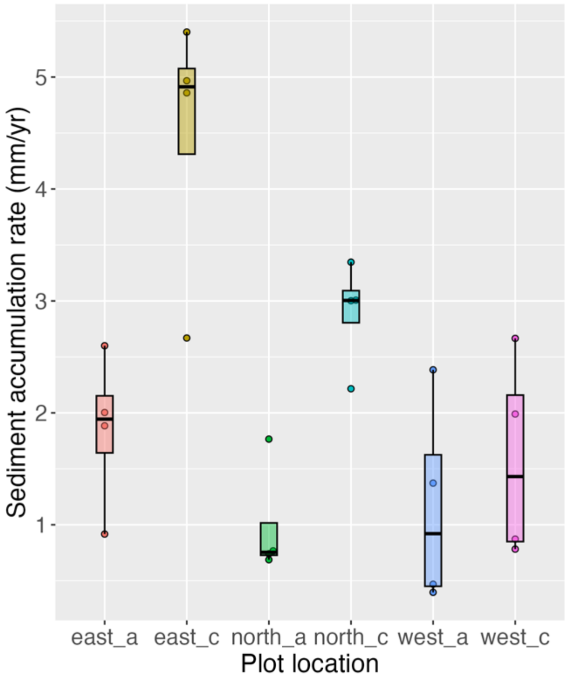


Figure 3: Sediment accumulation rate (mm/yr) recorded at different NCOS plot locations. Sediment accumulation varied significantly by plot location (ANOVA: p-value << 0.001)

Carbon content:

The average amount of carbon in the surface soil in NCOS was 1.39%, with a range from 0.7% to 2.4%. The average carbon density in the surface soil was 0.02 g C/cm^3, with a range from 0.009 to 0.06 g C/cm^3. The average amount of carbon in the subsurface soil is 1.07%, with a range from 0.5% to 1.7%. The average carbon density in the subsurface soil was 0.015 g C/cm^3, with a range from 0.009 to 0.024 g C/cm^3. In the surface soil, carbon content varies significantly by plot location (Table 2, Figure 4; ANOVA: p-value << 0.01). Carbon content in the subsurface soil also varies significantly by plot location (Table 3, Figure 4; ANOVA: p-value = 0.01).

Table 2: Surface soil carbon density (g C/cm^3)

Plot location	**Minimum**	**Maximum**	**Mean**	**Sample size**
East A	0.0134184	0.0218036	0.018233	4
East C	0.0094373	0.0100044	0.0097236	3
North A	0.0183177	0.0264633	0.0228686	4
North C	0.0202641	0.0337509	0.0253849	3
West A	0.014992	0.032035	0.0205926	4
West C	0.0116525	0.0156595	0.0135248	4

Table 3: Subsurface soil carbon density (g C/cm^3)

Plot location	**Minimum**	**Maximum**	**Mean**	**Sample size**
East A	0.0137123	0.0235045	0.0193022	4
East C	0.0091044	0.0161656	0.0122938	4
North A	0.0138588	0.0198371	0.0167705	4
North C	0.0111971	0.0153460	0.0131239	4

West A	0.0152050	0.0209984	0.0170473	4
West C	0.0102967	0.0152868	0.0131457	4

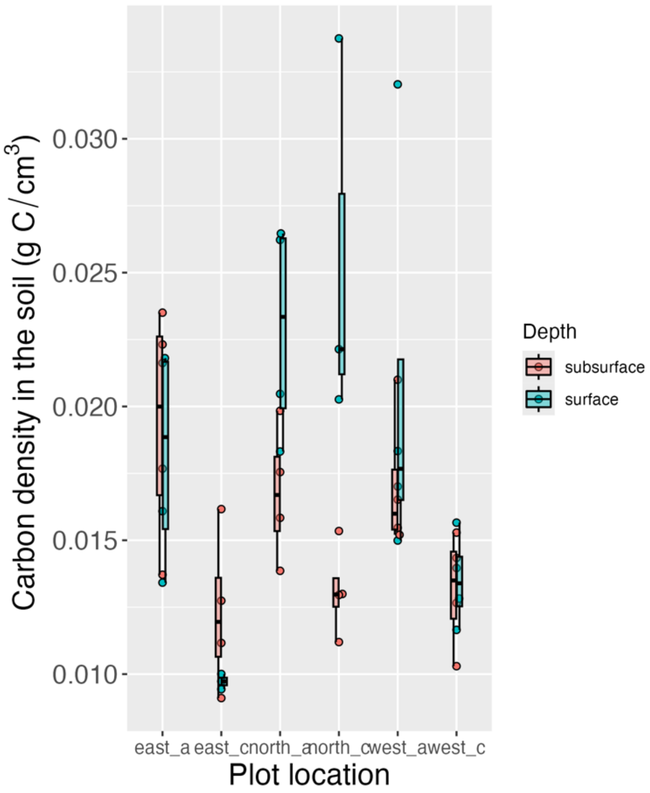


Figure 4: Carbon density (g/cm^3) in the surface and subsurface soil by NCOS plot location. There is significant variation in the surface soil carbon density (ANOVA: p-value << 0.01). There is also significant variation in the subsurface soil carbon density (ANOVA: p-value = 0.01).

Carbon accumulation:

The average soil carbon accumulation since restoration across all NCOS plots is 33.3 g C/m^2 yr, with a range from 6.8 g C/m^2 yr to 74.8 g C/m^2 yr. Carbon accumulation varies significantly by plot location (Table 4, Figure 5; ANOVA: p-value << 0.01).

Table 4: Carbon accumulation (g C/m^{2}yr) by plot location

Plot location	**Minimum**	**Maximum**	**Mean**	**Sample size**
East A	19.999192	43.31593	32.60645	4
East C	25.966690	50.98296	42.21459	3
North A	13.580352	46.29706	23.44706	4
North C	60.827134	74.77560	69.89812	3
West A	6.745385	35.74817	20.66942	4
West C	9.121117	41.54060	22.13967	4

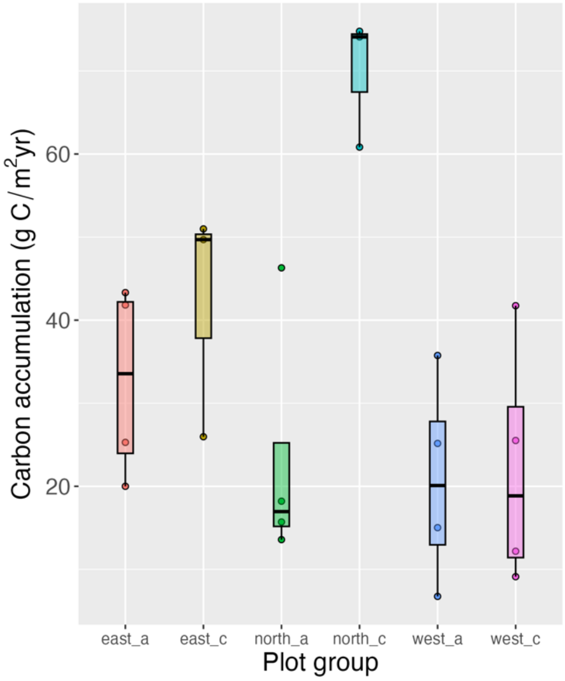


Figure 5: Carbon accumulation (in grams of C per square meter per year) by NCOS plot location. Carbon accumulation varies significantly by plot location (ANOVA: p-value << 0.01)

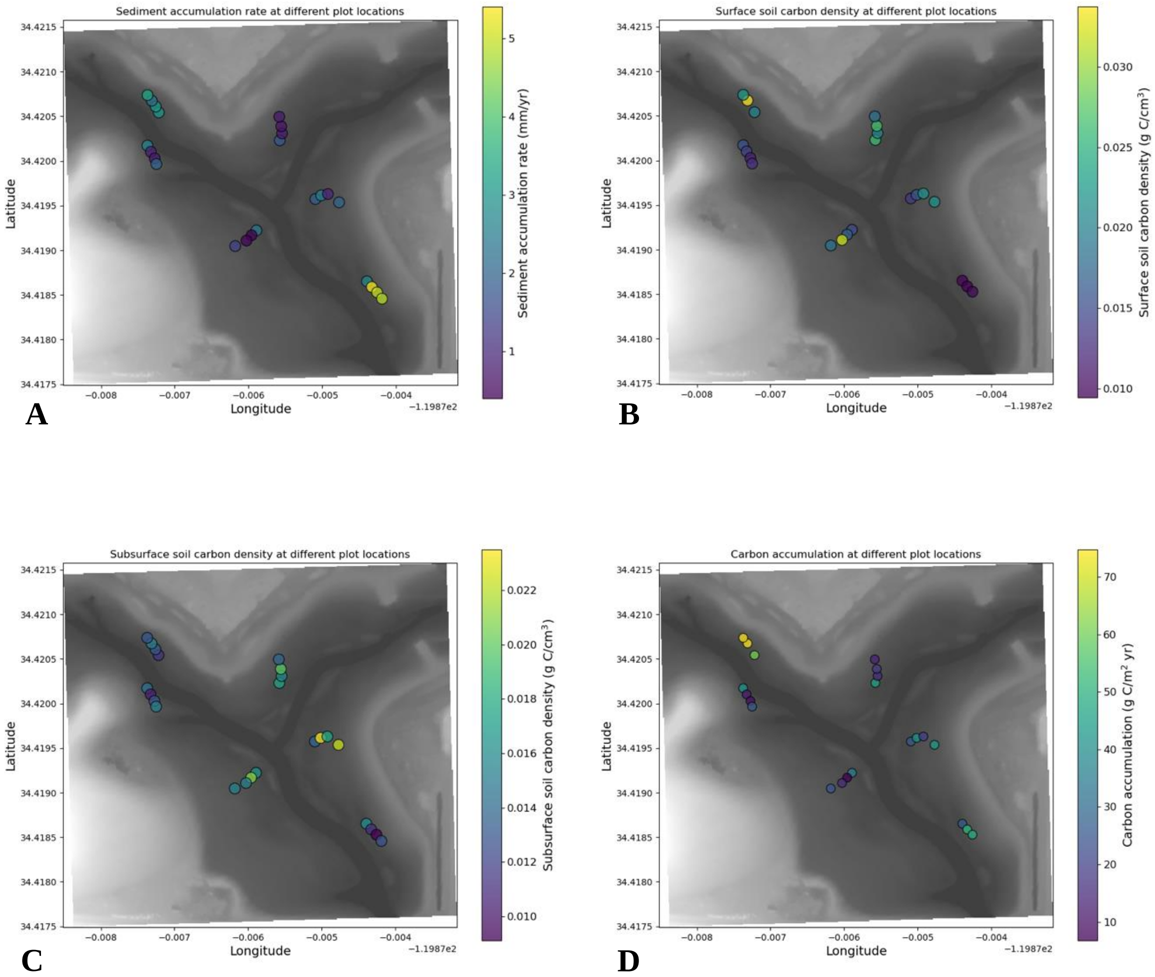


Figure 6: A) Spatial variation in sediment accumulation rate by plot location overlaid on a digital elevation model (DEM). The plots with the highest sediment accumulation are the North C and East C plots. B) Spatial variation in surface soil carbon density overlaid on a DEM. The plots with the highest surface soil carbon density are North C and North A, and the plots with the lowest amount of carbon are the East C plots. C) Spatial variation in subsurface soil carbon density overlaid on a DEM. D) Spatial variation in carbon accumulation (measured as g C/m^{2}yr) overlaid on a DEM. North C plots have the highest average carbon accumulation.

A. *Biotic factors*

Aboveground biomass:

The average total aboveground biomass was measured as 827.3 grams per m^2. The pickleweed and dead categories contributed the most to vegetation weight at each plot location (Figure 9B). There is a negative relationship between aboveground biomass and sediment accumulation rate (Figure 11; p-value = 0.049). There is a positive relationship between surface soil carbon density and aboveground biomass (Figure 12; p-value = 0.028). There is no relationship between aboveground biomass and subsurface soil carbon density (Figure 13). There are significant differences in vegetation and soil carbon density between NCOS and COPR, the lower portion of the Devereux Slough, closer to the Pacific Ocean (Figure 7; t-test: p-value << 0.01). COPR did not undergo restoration and was never a golf course. Thus, COPR is more similar to a natural wetland system and can serve as a comparison site for the restored wetland.

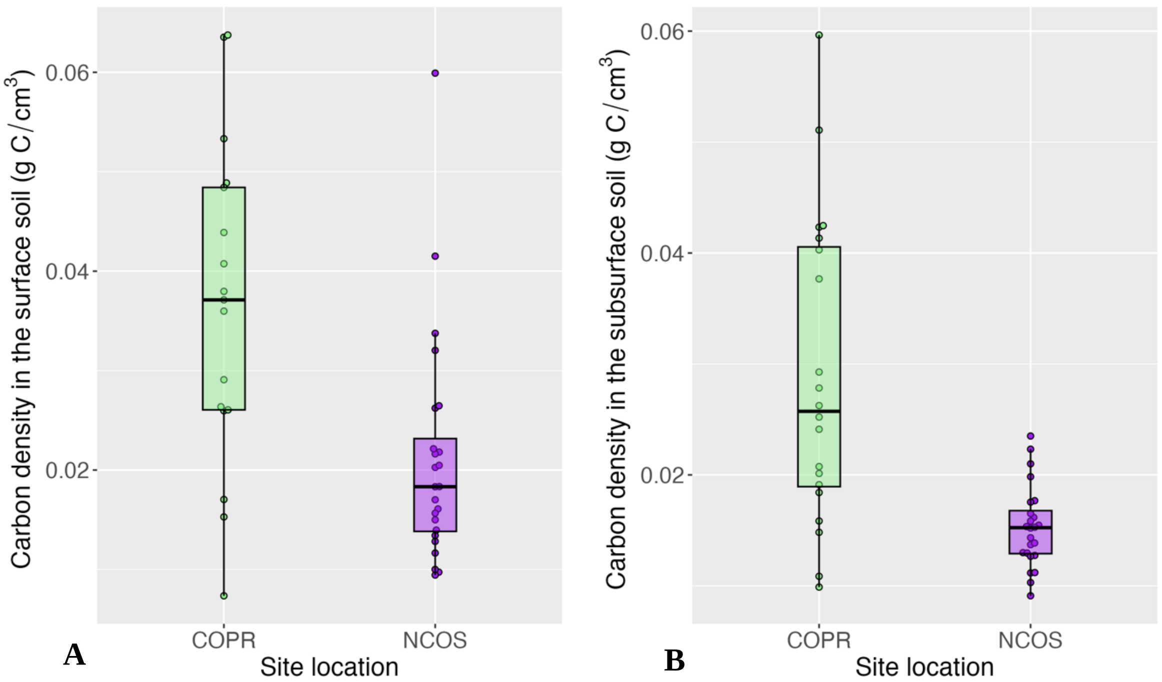


Figure 7: A) Comparison of surface soil carbon density between COPR (a natural wetland) and NCOS (a restored wetland). B) Comparison of subsurface soil carbon density between COPR and NCOS. COPR has significantly higher amounts of carbon density in both the surface and subsurface soil (t-test: p-value << 0.001).

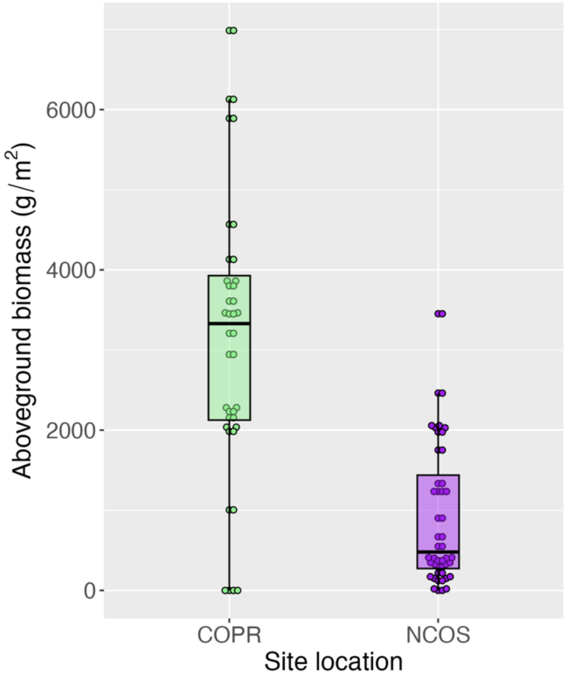


Figure 8: Comparison of total aboveground biomass, living and dead, in COPR and NCOS. There is only a slightly significant difference between the aboveground biomass at the two sites (t-test: p-value=0.06).

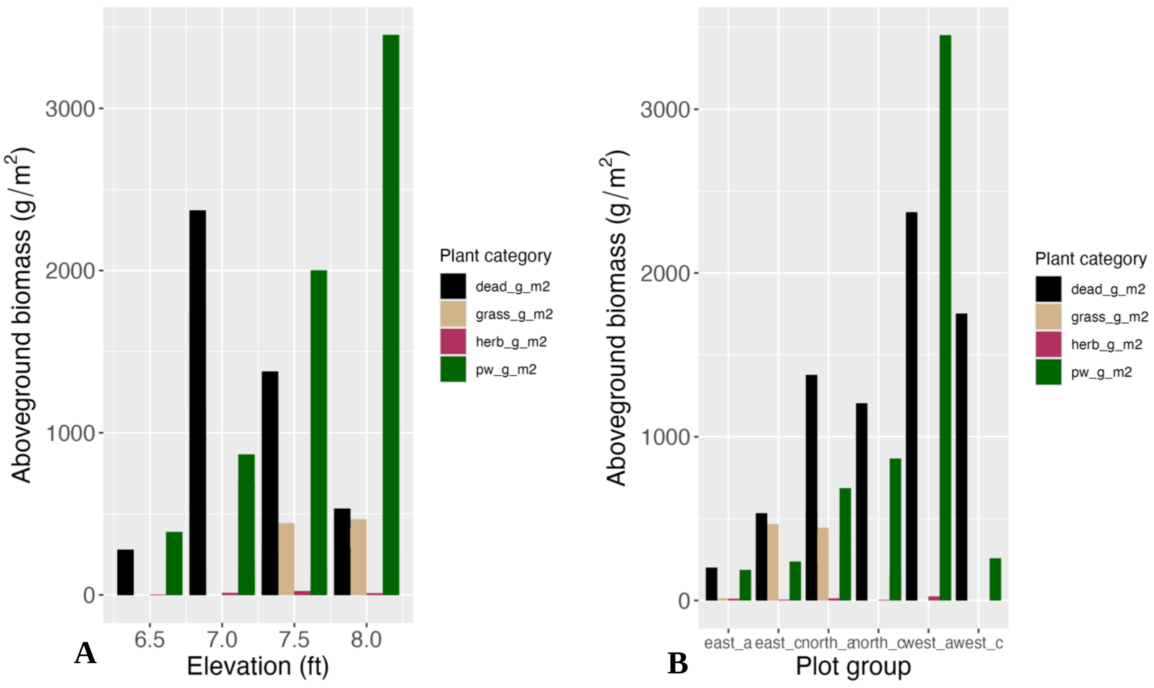


Figure 9: A) Categorization of aboveground biomass material by elevation. The amount of pickleweed and grass increases at higher elevations. B) Categorization of aboveground biomass by plot location. West A plots have high amounts of pickleweed.

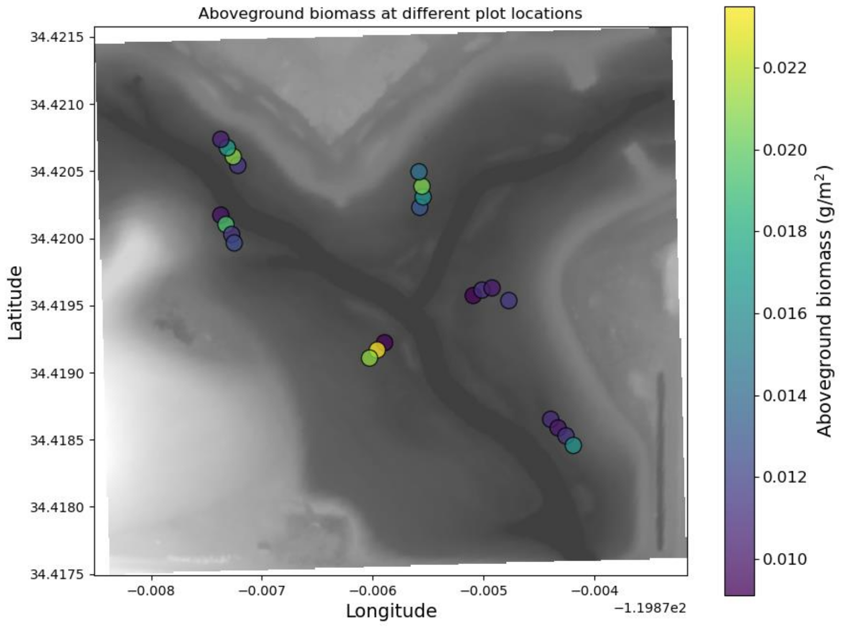


Figure 10: Spatial variation in aboveground biomass overlaid on a DEM. East plots have lower amounts of biomass, whereas West and North plots have more.

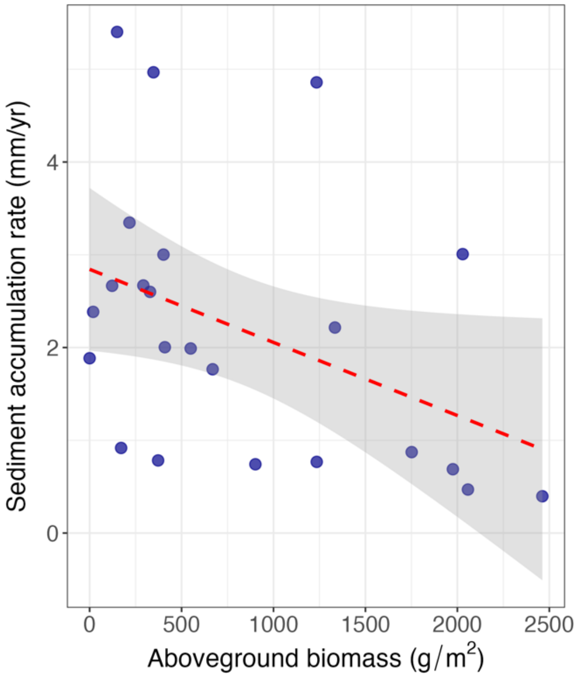


Figure 11: Relationship between aboveground biomass and sediment accumulation rate. There is a slightly significant negative correlation between these two variables (slope = -0.00079, p-value = 0.049, R^2=0.1718).

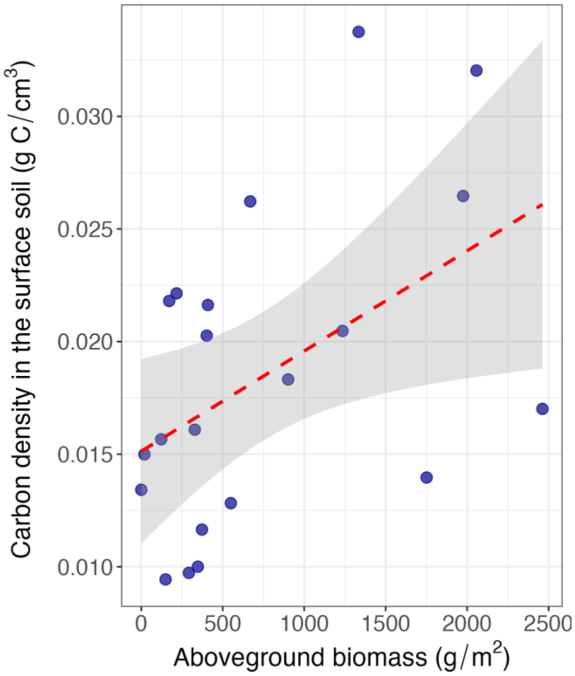


Figure 12: Relationship between aboveground biomass and surface soil carbon density. There is a slightly significant positive correlation between these two variables (slope = 0.015, p-value = 0.028, R^2=0.2298).

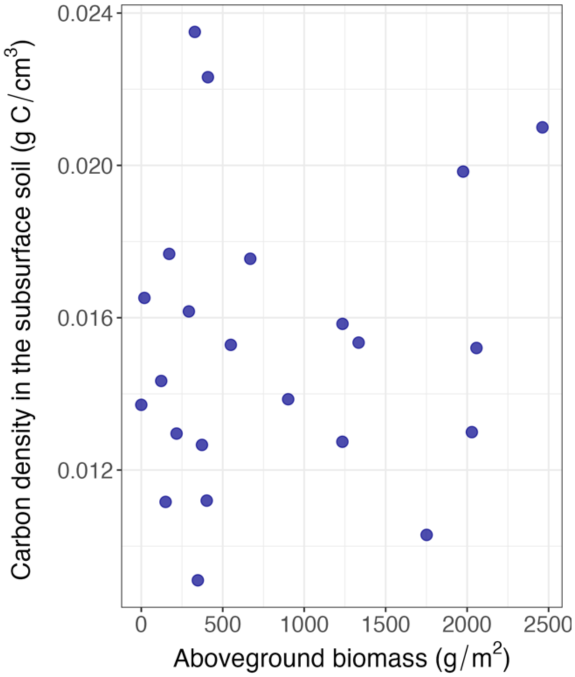


Figure 13: Relationship between aboveground biomass and soil carbon density. There is no significant relationship between these two variables.

B. Hydrologic factors

Flooding frequency:

The average number of times a plot in NCOS has been flooded is 9.7 times. There is a clear trend showing that lower elevation plots were flooded more frequently than higher elevation plots (Table 6, Figure 15). There is no significant difference in flooding frequencies at different plot locations (Table 5, Figure 14). There is a positive correlation between flooding frequency and surface and subsurface soil salinity, measured by electrical conductivity (Figure 17; p-value << 0.01). There is no clear relationship between flooding frequency and sediment accumulation rate or surface or subsurface soil carbon density (Figures 19, 20). In our analysis, we did not determine what caused plot flooding, but freshwater stream inputs or saline water tidal influence are two possible explanations for plot inundation.

There was significantly less flooding at COPR than NCOS (t-test: p-value << 0.01). NCOS plots also had greater surface soil salinity, measured as electrical conductivity (mS/cm) (Figure 18).

Table 5: Flooding frequencies by plot location

Plot location	**Minimum**	**Maximum**	**Mean**	**Sample size**
East A	3	21	13.25	4
East C	4	22	11.50	4
North A	5	12	7.75	4
North C	6	15	10.50	4
West A	3	15	8.75	4
West C	4	9	6.50	4

Table 6: Flooding frequencies by plot elevation (feet)

Elevation (ft)	**Minimum**	**Maximum**	**Mean**	**Sample size**
6.5	9	22	15.666667	6
7.0	7	17	11.333333	6
7.5	5	12	7.666667	6
8.0	3	6	4.166667	6

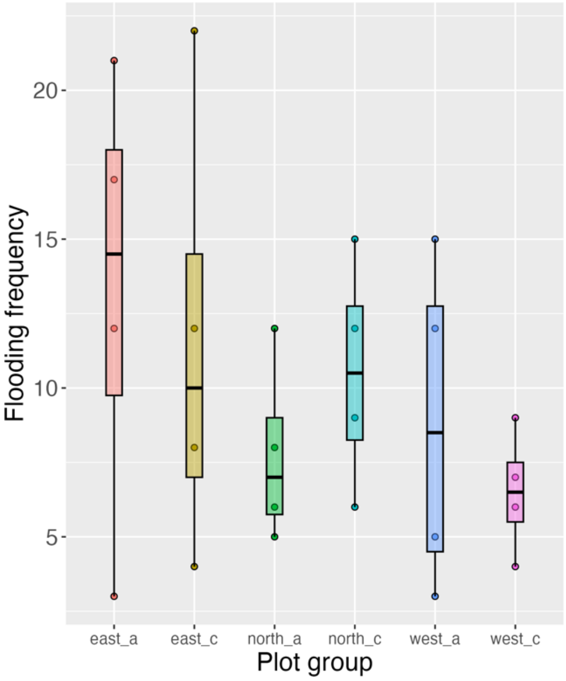


Figure 14: Flooding frequencies across different plot locations in NCOS. There is no significant difference between the amount of flooding between plot locations.

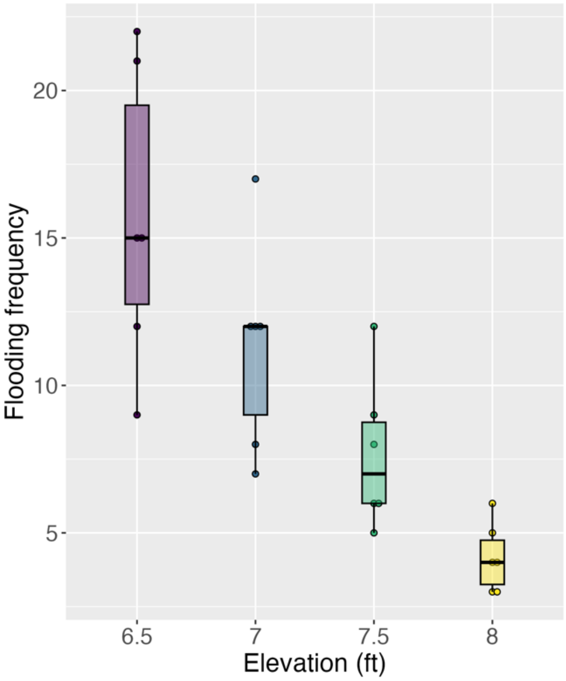


Figure 15: Flooding frequencies across different plot elevations. There is a significant difference in flooding frequencies by plot elevation (ANOVA: p-value << 0.001). Plots at lower elevations were flooded more frequently.

Stream inputs:

The water surface level measurements that are collected every 15 minutes are an important temporal measurement but contribute little to our understanding of the spatial dynamics affecting sediment accumulation and soil carbon content. Stream inputs are related to differences in suspended sediment concentrations which will be discussed in the physiochemical environment section. Differences in how stream inputs affect the plot locations should also be revealed by flooding frequency data.

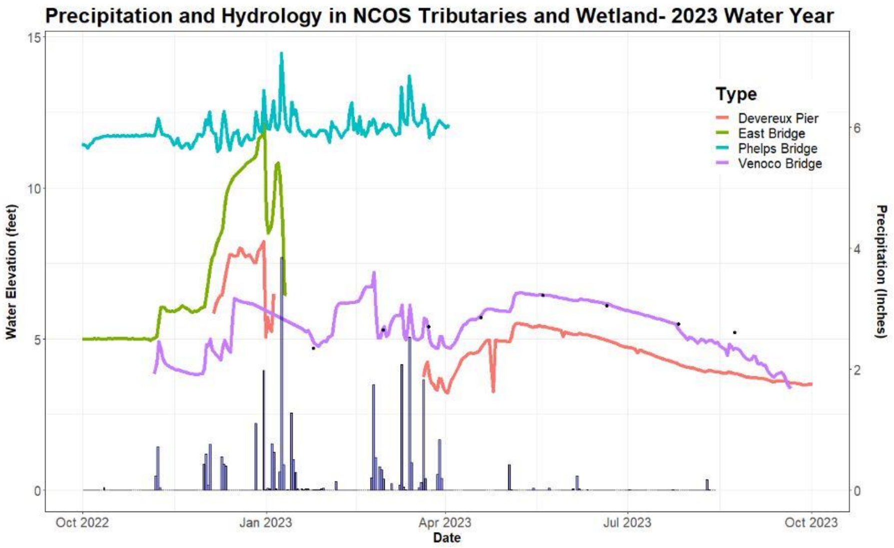


Figure 16: Stream inputs quantified by water elevation (feet) for Phelps Bridge, Devereux Pier, East Bridge, and Venoco Bridge for the 2023 water year. The highest water level is shown at Phelps Bridge, which matches high suspended sediment concentration at this stream (figure taken from CCBER Monitoring Report Year 6; Rickard, 2024).

Tidal influence:

Here we report the number of days per water year since NCOS was restored that it experienced tidal influence. Since this measurement is at a finer temporal resolution than the sediment accumulation values measured here, we cannot draw relationships on a year-by-year scale. However, flooding frequency differs by plot location, as does salinity, as listed in the physiochemical environment factors. These two variables combined can allow us to make some inferences about how tidal influence might differ spatially within the wetland and thus how tides might affect sediment accumulation rates and soil carbon density.

Table 7: Number of days per water year that experience tidal influence (taken from CCBER Monitoring Report Year 6; Rickard, 2024)

Water Year	Start date	End date	days tidal	Days not tidal
2019	Jan 7, 2019	March 21, 2019	47	26
2020	March 16, 2020	April 5, 2020	9	11
2021	Jan 28, 2021	Feb 15, 2021	18	0
2022	Dec 23, 2021	Jan 16, 2022	22	2
2023	Dec 31, 2022	Feb 4, 2023	28	7
2023	Feb 25, 2023	March 4, 2023	7	1
2023	March 10, 2023	March 30, 2023	20	1

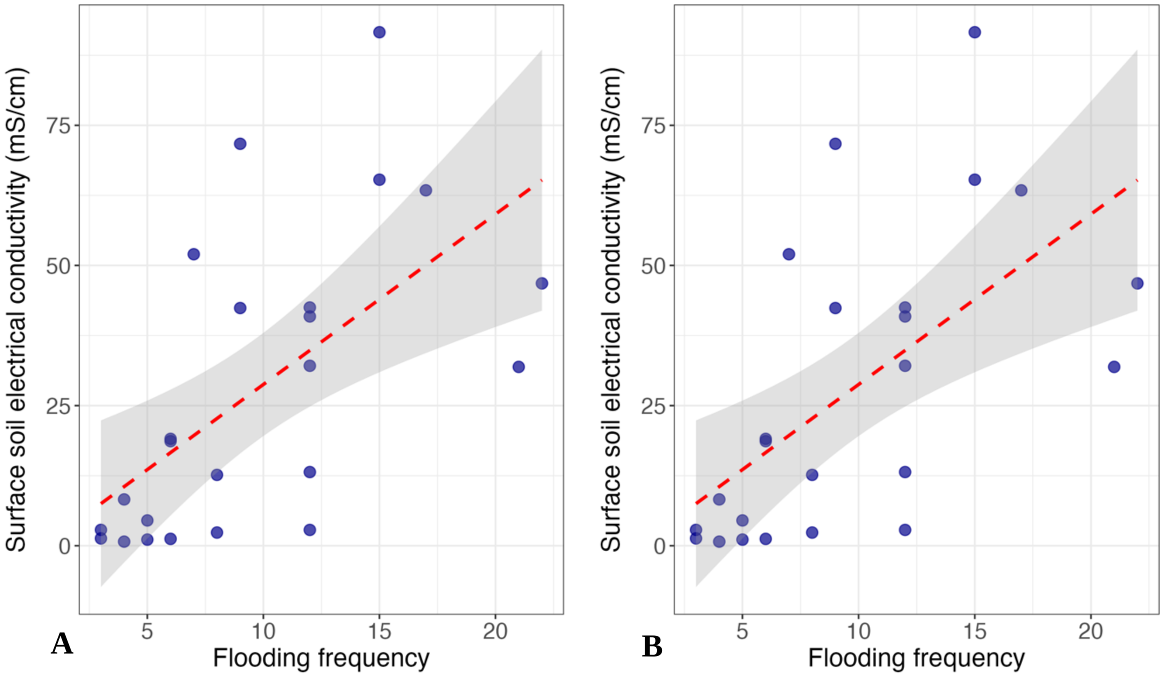


Figure 17: A) Relationship between flooding frequency and surface soil salinity, measured as electrical conductivity in mS/cm. There is a significantly positive correlation between surface soil salinity and flooding frequency (slope = 3.03, p-value = 0.0015, R^2=0.373). B) Relationship between flooding frequency and subsurface soil salinity. There is a significantly positive relationship between subsurface soil salinity and flooding frequency (slope = 0.48, p-value = 0.0087, R^2=0.274).

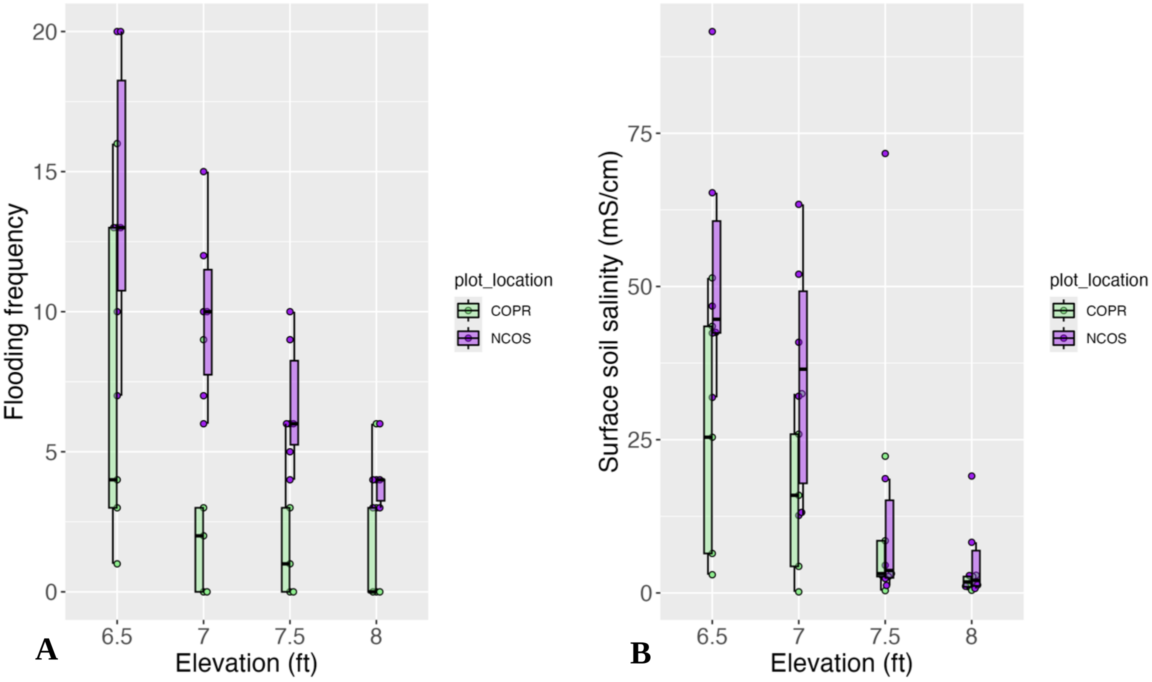


Figure 18: A) Flooding frequencies at COPR and NCOS. NCOS plots were flooded more frequently than COPR (t-test: p-value << 0.001). B) Surface soil salinity at COPR and NCOS. NCOS plots had higher surface soil salinity (t-test: p-value = 0.02).

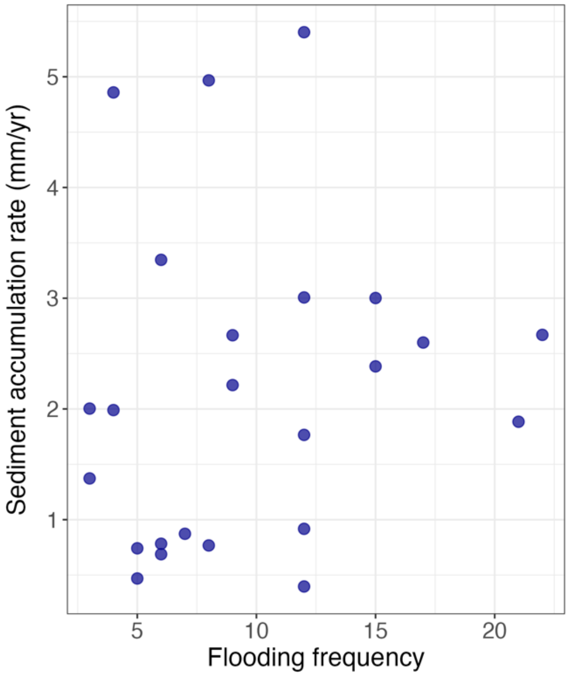


Figure 19: Relationship between flooding frequency and sediment accumulation rate (mm/yr). There is no significant relationship between these variables (p-value = 0.48).

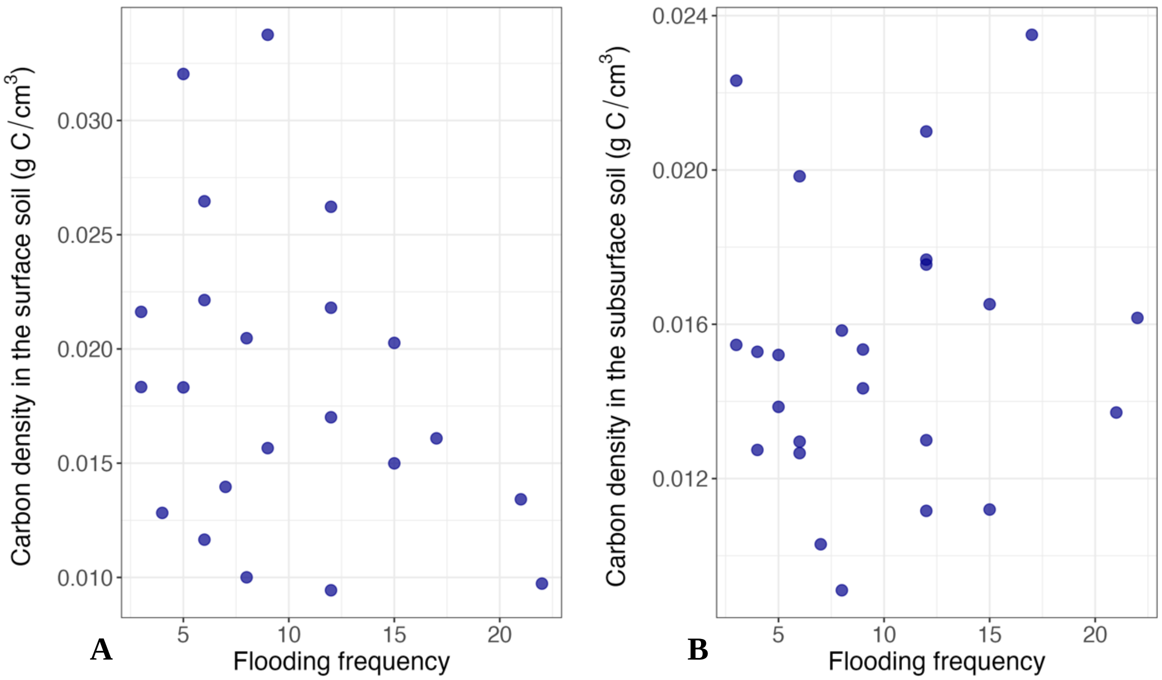


Figure 20: A) Relationship between surface soil carbon density and flooding frequency. There is no significant relationship (p-value = 0.16). B) Relationship between subsurface soil carbon density and flooding frequency. There is no significant relationship (p-value = 0.64).

C. Physiochemical environment factors

Elevation:

There is no significant difference between sediment accumulation rate and surface or subsurface soil carbon content between plots at the four chosen elevations. There is a clear relationship between increased flooding frequency and lower elevations, as well as salinity, measured by electrical conductivity (Figure 21).

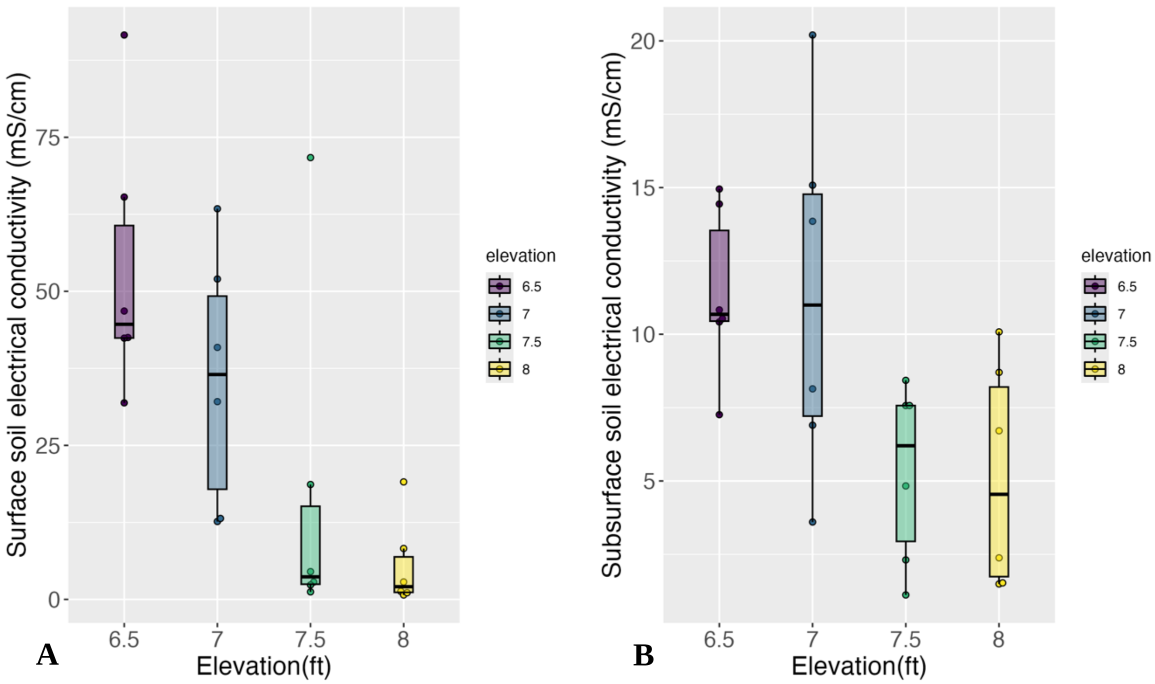


Figure 21: A) Surface soil salinity at different elevations. Surface soil salinity at lower elevations is significantly higher than surface salinity at higher elevations (ANOVA: p-value << 0.01). B) Subsurface soil salinity at different elevations. Subsurface soil salinity is still significantly higher at lower elevations, though there is less of a difference in subsurface salinity between elevations (ANOVA: p-value = 0.017).

Bulk density:

The average bulk density of the surface soil was 1.34 g/cm^3. The average bulk density of the subsurface soil was 1.46 g/cm^3 (Figure 22). Subsurface bulk density was higher than surface bulk density (Figure 23). Surface and subsurface bulk density were used to calculate carbon density. The surface bulk density was also used to calculate carbon accumulation in this study. Surface bulk density has no relationship with sediment accumulation rate or surface soil carbon content. However, there is a negative relationship between subsurface bulk density and subsurface soil carbon content (Figure 24; p-value << 0.001). Surprisingly, there is no relationship between aboveground biomass and bulk density (Figure 25). There is a negative correlation between surface bulk density and percent fine texture particles, which is calculated by adding clay and silt percentages together (Figure 26;

slope=-0.0055, R^2=0.187, p-value=0.039). There is also a significant negative relationship between subsurface bulk density and percent fine texture particles (Figure 26; slope=-0.0082, R^2=0.49, p-value=0.00022). We would expect a larger proportion of fine texture particles would correspond to a lower bulk density, as clay and silt particles aggregate and create a larger volume of pore space. Soil bulk density measurements are difficult to capture, as hammering the copper core into the earth could cause compaction and thus some errors in capturing the bulk density.

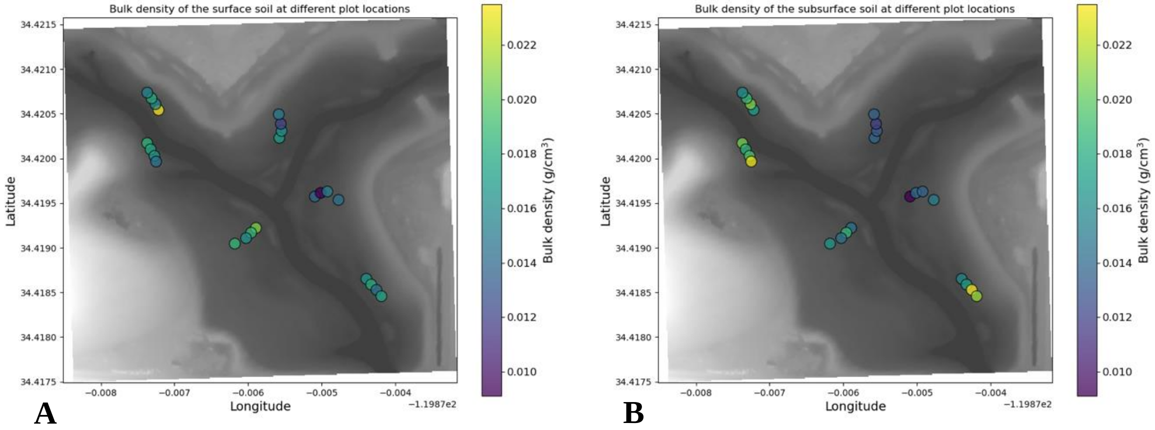


Figure 22: A) Surface bulk density measurements for each plot in NCOS. B) Subsurface bulk density measurements for each plot in NCOS.

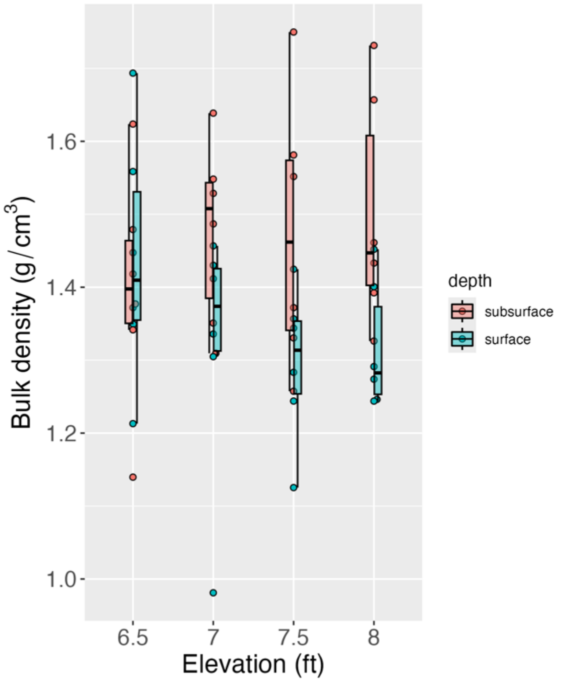


Figure 23: Surface and subsurface bulk densities at different plot elevations. Subsurface bulk density is significantly higher than surface bulk density (t-test: p-value << 0.01).

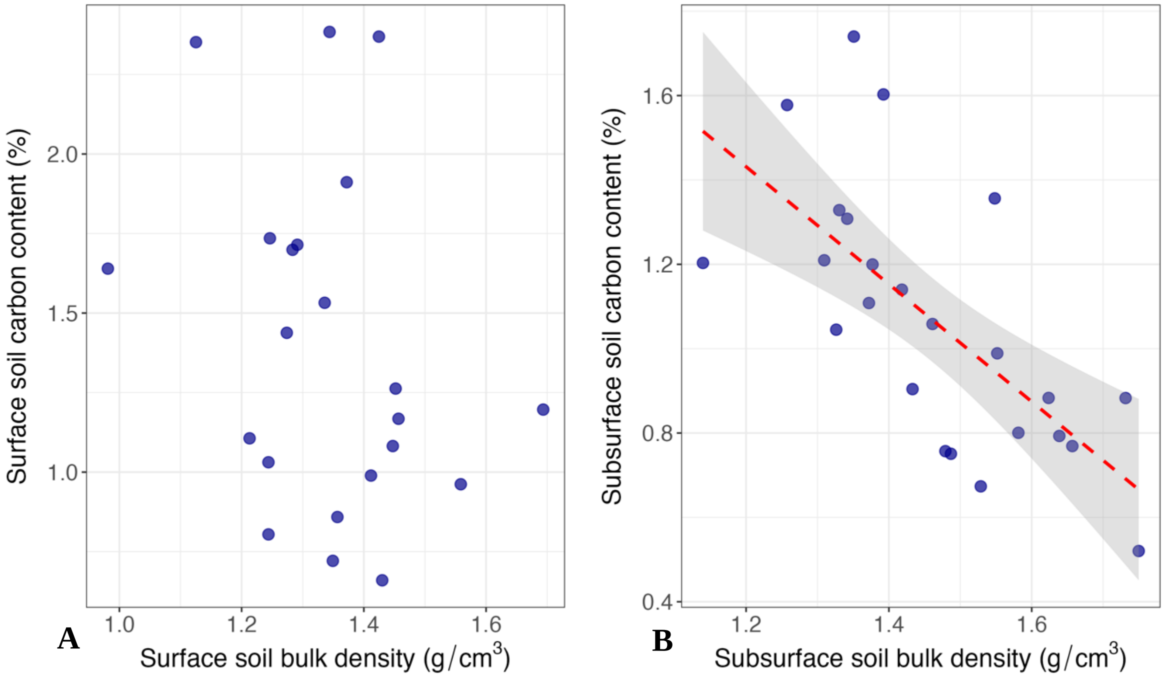


Figure 24: A) There is no significant relationship between surface soil carbon content (%) and surface soil bulk density (p-value = 0.19). B) Relationship between subsurface soil bulk density and subsurface soil carbon content as a percent. There is a significant negative correlation between subsurface bulk density and subsurface carbon content (slope=-1.39, p-value << 0.001, R^2=0.464).

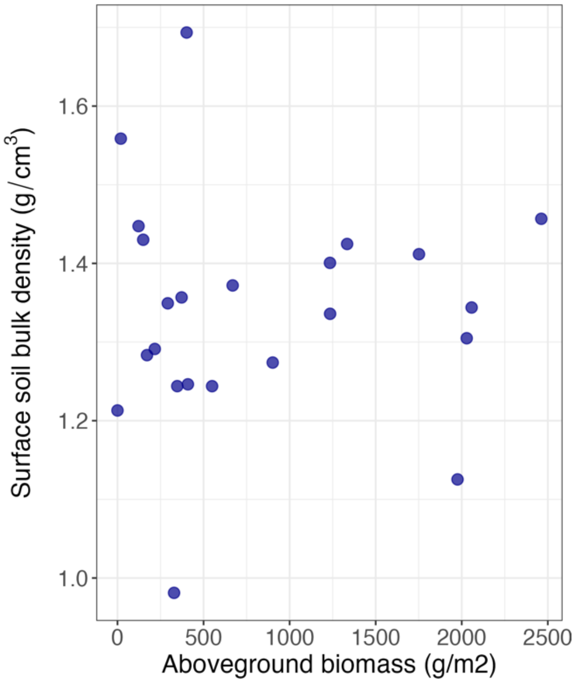


Figure 25: There is no significant relationship between aboveground biomass and surface bulk density (p-value = 0.977).

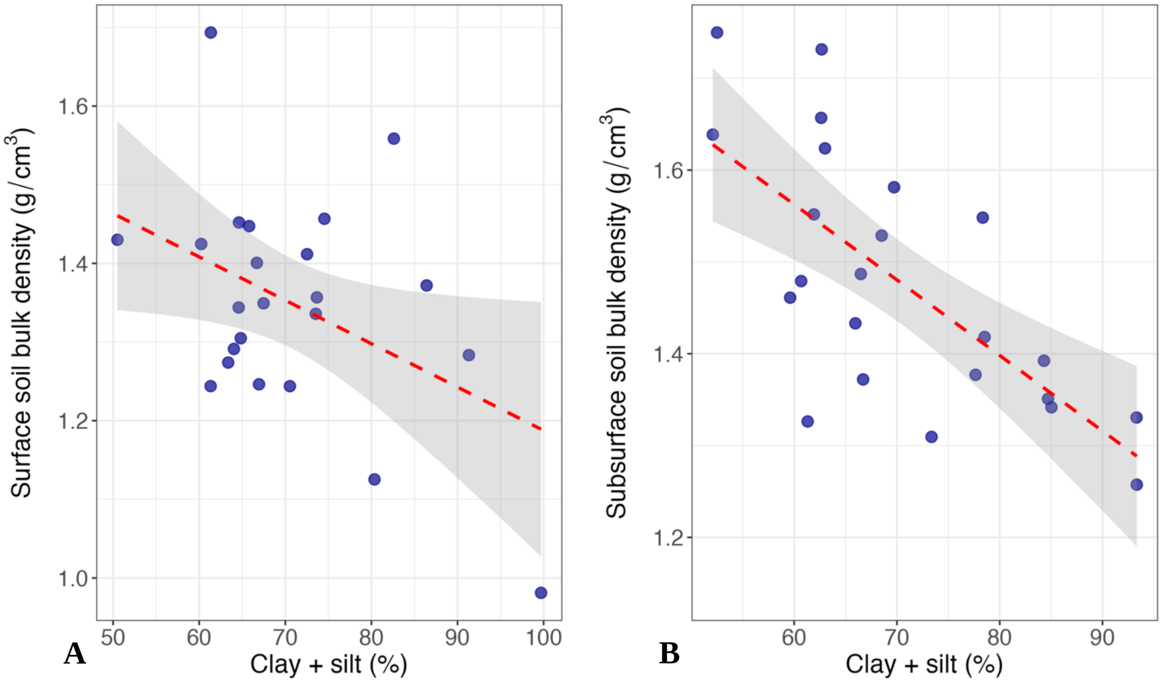


Figure 26: A) There is a slightly negative relationship between percent fine texture particles in the surface soil and surface bulk density (p-value = 0.03). B) There is a strong negative relationship between subsurface percent fine texture particles and subsurface bulk density (slope=-0.0082, R^2=0.49, p-value << 0.001).

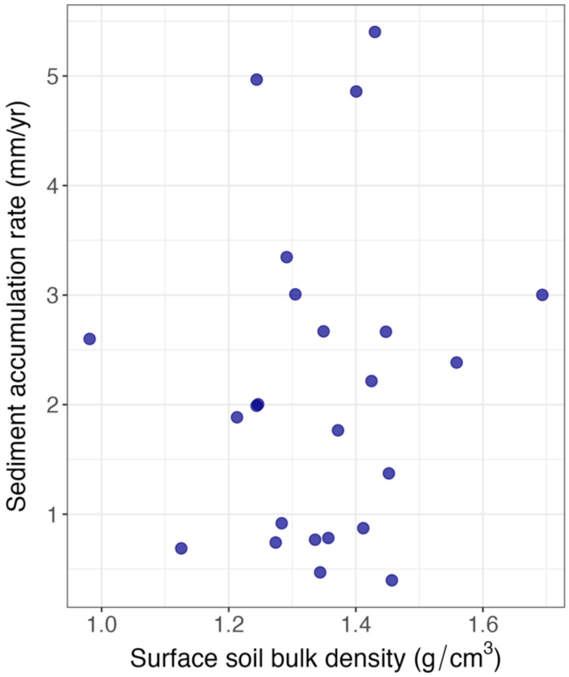


Figure 27: There is no significant relationship between surface bulk density and sediment accumulation rate (p-value = 0.64).

Soil texture:

The average surface soil texture across all NCOS plots was 29.26% sand, 44.62% silt, and 26.12% clay. This would be in the soil textural class of "loam." The average subsurface soil texture was 29.46% sand, 33.56% silt, and 36.98% clay. This would be in the soil textural class of "clay loam". There is a slightly negative relationship between the fine percentage (clay +silt) and sediment accumulation rates (Figure 28; slope=-0.054, R^2=0.1725, p-value=0.049). There is no relationship between the surface soil fine fraction and surface soil carbon density (Figure 29). However, there is a strong positive relationship between subsurface fine fraction and subsurface soil carbon density (Figure 30; slope=0.022, R^2=0.69, p-value << 0.001).

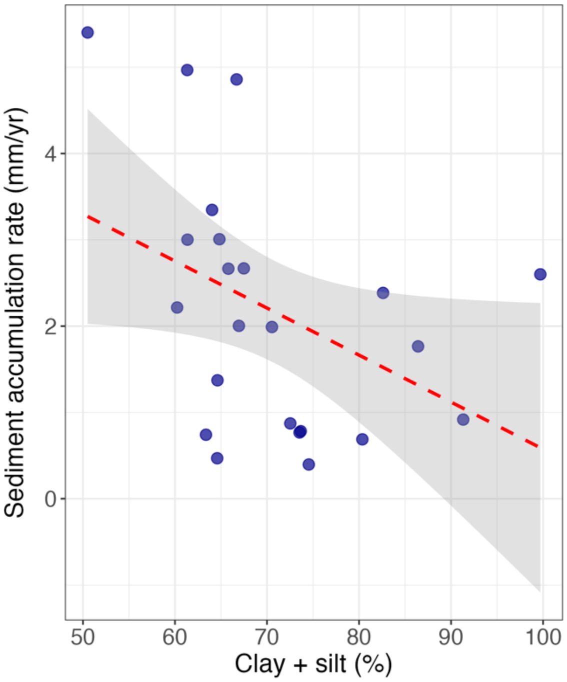


Figure 28: Relationship between surface clay and silt percent and sediment accumulation rate. There is a slightly negative relationship between percent surface fine texture particles and sediment accumulation rate (slope=-0.054, R^2=0.1725, p-value=0.049).

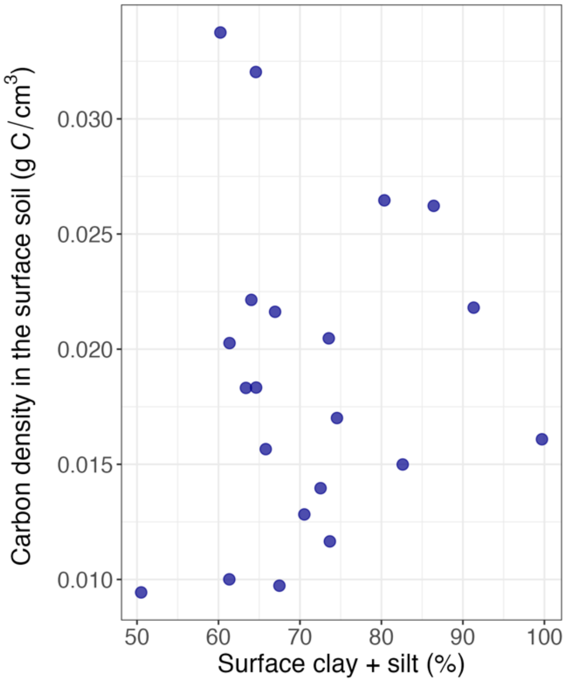


Figure 29: There is no relationship between surface clay and silt percentage and carbon density in the surface soil (p-value = 0.71).

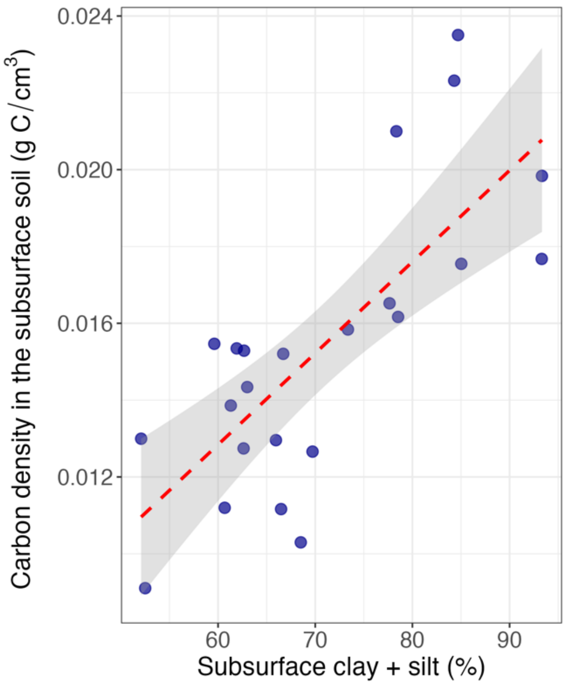


Figure 30: Relationship between subsurface clay and silt percentage and subsurface carbon density. There is a strong positive correlation between these variables (slope = 0.00024, R^2=0.57, p-value << 0.0001).

Soil pH/EC:

The average pH across all NCOS plots was 7.78 in the surface soil and 8.07 in the subsurface soil. There is no significant difference in pH across different elevations or plot locations. The average salinity, measured by electrical conductivity, was 27.88 mS/cm in the surface soil and 8.29 mS/cm in the subsurface soil (Figure 21). There is significantly higher salinity at the lower elevation plots. This trend is most obvious in the surface soil. There is no significant variation in surface or subsurface electrical conductivity by plot location. There is no significant relationship between surface soil salinity and aboveground biomass (Figure 31A; p-value = 0.229). There is a weak negative association between subsurface soil salinity and aboveground biomass (Figure 31B; p-value=0.0729).

Neither electrical conductivity nor pH show a significant relationship with sediment accumulation, surface soil carbon content, or subsurface soil carbon content.

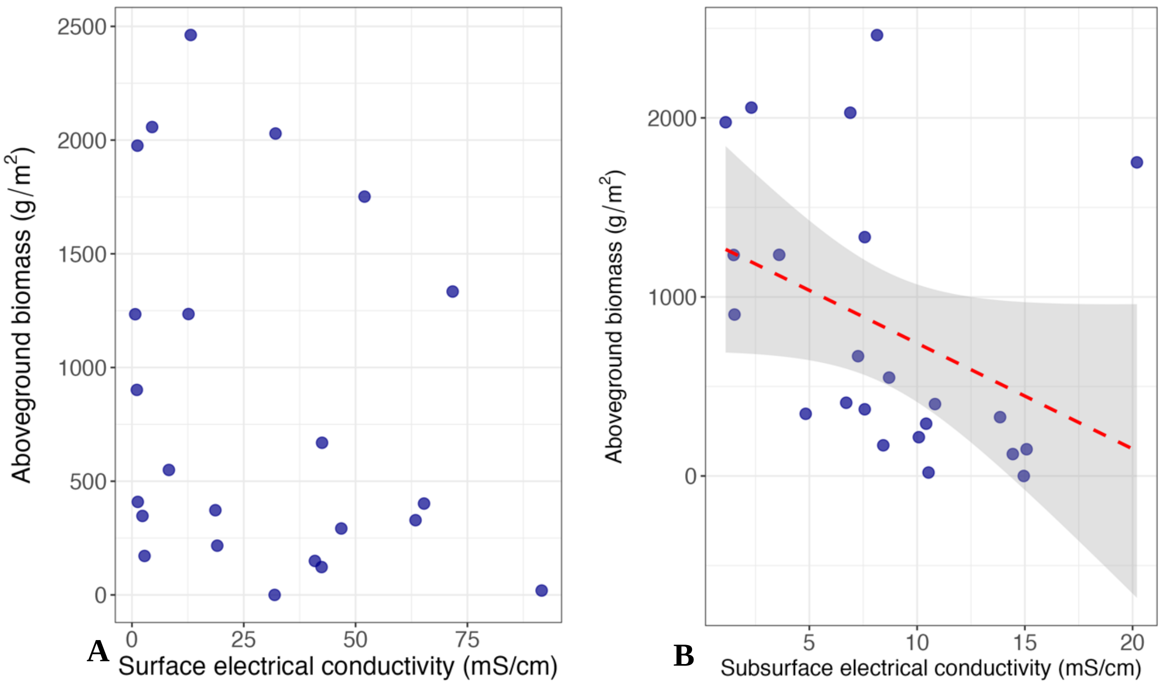
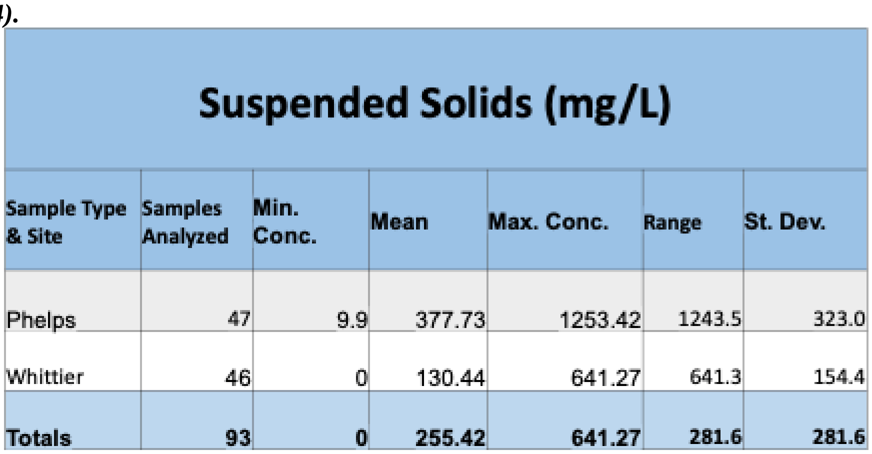


Figure 31: A) Surface soil salinity and aboveground biomass have no significant relationship (p-value = 0.23). B) There is a slightly negative relationship between subsurface soil salinity and aboveground biomass (slope=-59.01, R^2=0.145, p-value=0.0729).

Sediment inputs:

The results from the 47 samples from Phelps Creek and 46 samples from Whittier Channel from the 2023 water year measured an average sediment concentration of 377.73 mg/L in Phelps Creek and 130.44 mg/L in Whittier Channel (Table 8).

Table 8: Suspended sediment concentrations in Phelps Creek and Whittier Channel for the 2023 water year. (Rolland, 2024).



Suspended Solids (mg/L)

Sample Type & Site	Samples Analyzed	Min. Conc.	Mean	Max. Conc.	Range	St. Dev.
Phelps	47	9.9	377.73	1253.42	1243.5	323.0
Whittier	46	0	130.44	641.27	641.3	154.4
Totals	**93**	**0**	**255.42**	**641.27**	**281.6**	**281.6**

Distance from sediment source:

Each sampling location has a different measured downstream distance, though those in the same plot quad are more similar to other plot locations. There is a negative relationship between downstream distance and sediment accumulation rate (Figure 32; slope = -0.003, R^2=0.187, p-value = 0.035). There is a very slight positive relationship between surface soil carbon density and downstream distance (Figure 33A; slope = 0.002, R^2=0.144, p-value=0.082). There is no correlation between subsurface soil carbon density and downstream distance (Figure 33B; p-value=0.837).

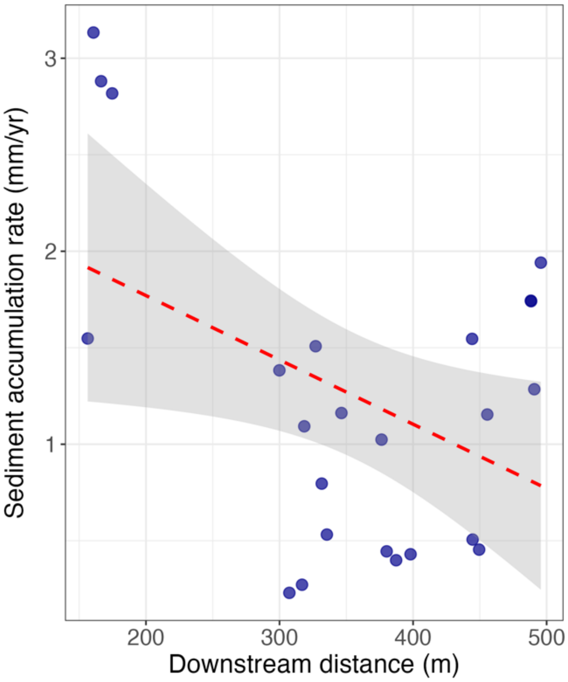


Figure 32: Relationship between downstream distance (in meters) and sediment accumulation rate. There is a significant negative relationship between these variables (slope = -0.003, R^2=0.187, p-value = 0.035).

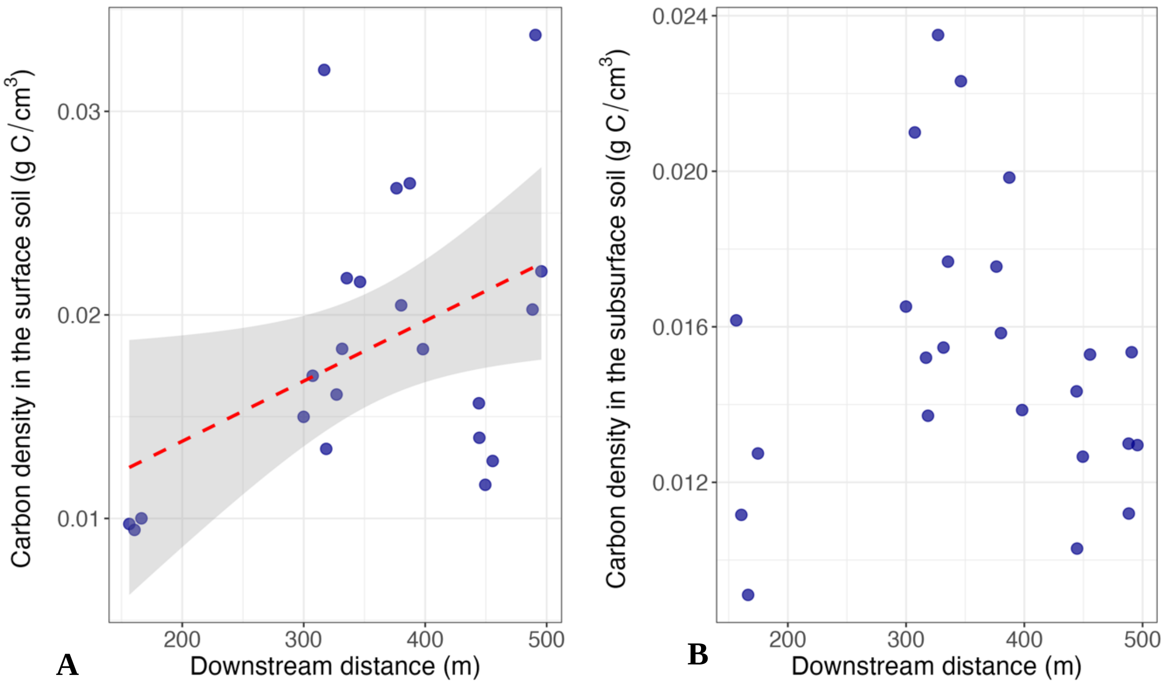


Figure 33: A) There is a positive relationship between downstream distance and surface soil carbon density (slope = 0.00003, R^2=0.197, p-value=0.039). B) There is no significant relationship between downstream distance and subsurface soil carbon density (p-value = 0.931).

Model outputs:

Using biotic, hydrologic, and physiochemical environment variables, I created multiple linear regression models to see which variables best predict sediment accumulation and surface and subsurface soil carbon density. The variables that best predict sediment accumulation were plot location and vegetation (Table 9). This model has a R^2 of 0.71. The variable that best predicts surface soil carbon density was plot location (Table 10). This model has a R^2 of 0.59. The variable that best predicts subsurface soil carbon density was percentage sand (Table 11). This model has a R^2 of 0.57.

Table 9: Models to predict sediment accumulation.

Model	**Variables**	**BIC**	**Δ BIC**
0	~1	90.78	19.81
1	Plot location	74.79	3.82

2	elevation	99.25	28.28
3	Plot location + vegetation	70.97	Best
4	Plot location + vegetation + salinity	73.91	2.94
5	Plot location + flooding frequency	77.74	6.77
6	Plot location + vegetation + flooding frequency	72.54	1.57
7	Plot location + vegetation + percent silt	72.54	1.57
8	Plot location + vegetation + elevation	76.30	5.33
9	Flooding frequency	93.40	22.43
10	Percent sand	86.90	15.93
11	Plot location + percent sand	76.41	5.44
12	Plot location + vegetation + downstream distance	74.11	3.14
13	Plot location + downstream distance	77.91	6.94
14	Bulk density	93.71	22.74
15	Plot location + vegetation + bulk density	73.70	2.73

Table 10: Models to predict surface soil carbon density

Model	**Variables**	**BIC**	**Δ BIC**
0	~1	-152.14	4.0
1	Plot location	-156.14	Best
2	elevation	-147.11	9.03
3	Plot location + vegetation	-149.45	6.69
4	Plot location + vegetation + salinity	-146.54	9.60
5	Plot location + flooding frequency	-156.11	0.04
6	Plot location + vegetation + flooding frequency	-149.13	7.01

7	Plot location + vegetation + percent silt	-139.38	16.76
8	Plot location + vegetation + elevation	-149.65	6.49
9	Flooding frequency	-151.32	4.82
10	Percent sand	-141.76	14.38
11	Plot location + percent sand	-146.79	9.35
12	Plot location + vegetation + downstream distance	-147.65	8.49
13	Plot location + downstream distance	-153.87	2.27

Table 11: Models to predict subsurface soil carbon density

Model	**Variables**	**BIC**	**Δ BIC**
0	~1	-195.70	7.22
1	Plot location	-197.0	5.91
2	elevation	-186.41	16.51
3	Plot location + vegetation	-185.46	17.46
4	Plot location + vegetation + salinity	-182.51	20.41
5	Plot location + flooding frequency	-193.84	9.08
6	Plot location + vegetation + flooding frequency	-182.37	20.54
7	Plot location + vegetation + percent silt	-181.77	21.14
8	Plot location + vegetation + elevation	-176.63	26.28
9	Flooding frequency	-192.76	10.15
10	Percent sand	-202.91	Best
11	Plot location + percent sand	-198.48	4.44
12	Plot location + vegetation + downstream distance	-182.38	20.53
13	Plot location + downstream distance	-193.82	9.09

IV. Discussion

Sediment accumulation:

It is likely that restoring this wetland system increased the sediment accumulation rate from when the system was a golf course. In a disturbed and an undisturbed wetland in Australia, the disturbed wetland had an average accretion rate of 3.37 mm/yr, whereas the undisturbed wetland saltmarsh had an average accretion rate of 0.98 mm/yr, demonstrating that the disturbed wetland had a higher accretion rate than the undisturbed (Howe et al., 2009). Comparing sediment accumulation rates from natural salt marshes in nearby southern California Mediterranean-climate zone, the calculated potential accretion rates ranged from 0.05 mm/yr to 0.32 mm/yr (Rosencranz et al., 2016). NCOS has an average accretion rate of 2.16 mm/yr, which is much higher than the natural coastal marshes nearby in Los Angeles County and thus we can assume that restoration of this system caused sediment accumulation to increase.

We also have the data available to conduct a temporal comparison of these sediment accumulation rates. In 2016, sediment accumulation rates were measured by ^{137}Cs cores taken in COPR, the natural wetland system in the lower part of Devereux Slough. These rates ranged from 2.8 mm/yr to 4.7 mm/yr, though there were only two cores to collect measurements (Stratton & King, 2021). The average sediment accumulation rate in NCOS is lower than this range of measurements, however this study provides greater spatial resolution, as a larger number of samples were measured.

Following a moderate mitigation climate change scenario, referred to as Representative Concentration Pathway (RCP) 4.5, the average global mean change is predicted to be 53.5 cm by the year 2100 (Carson et al., 2016). However, relative sea level (RSL) rise on the US

Pacific coast is predicted to be lower than the average global mean, at around 43 cm in Goleta, where NCOS is located (Carson et al., 2016). The average sediment accumulation rate observed in this study of 2.16 mm/yr would take almost 200 years to keep pace with 43 cm of RSL rise, which would likely be too late to provide important adaptation services like flood mitigation. The two most important processes for wetland elevation accretion to keep pace with SLR are suspended sediment settlement and plant productivity (Parker & Boyer, 2019). Vertical elevation building in wetlands is made up of both mineral sediments delivered and organic matter contributions (Buffington et al., 2020). In its early years post-restoration, it appears that wetland elevation accretion in NCOS is mostly due to suspended sediment settlement instead of organic matter contributions or plant productivity. This is similar to findings comparing disturbed and undisturbed wetlands in Australia in which the disturbed system had lower biomass and root development, and thus accretion rate accounted for most surface elevation change (Howe et al., 2009).

What spatial dynamics best predict variation in sediment accumulation rates? The model that best predicts sediment accumulation rate includes plot location and aboveground biomass. However, models with a ΔBIC of 5 or lower only have moderate or marginal evidence that these models are worse than the “best” model (Jerde et al., 2019). Accordingly, the models that also include flooding frequency, percent silt, downstream distance, and salinity also may predict a similar amount of sediment accumulation rate. There are significantly higher amounts of sediment accumulation at plots located near the mouth of the channel, indicated by Venoco Bridge, and closer to stream inputs with higher suspended sediment concentrations, indicated by Phelps Creek. There is a weak negative association between sediment accumulation and aboveground biomass (Figure 11). There is no significant relationship between flooding frequency or surface or subsurface soil salinity with sediment accretion rate (Figure 19). There is a significantly negative relationship between the percent silt and clay in the surface soil and sediment accumulation (Figure 28). There is a weak negative association between sediment accumulation and downstream distance (Figure 32).

Plot location is an important predicting variable as both a hydrologic and physiochemical environment factor. The plots with the highest rates of sediment accumulation are associated with increased flooding frequency, causing higher soil salinity and decreasing the amount of vegetation. They also tend to be further downstream or nearer to Venoco Bridge and the slowing down of water that occurs here. These hydrologic factors would have no significant effect on sediment accumulation rate if there were not substantial sediment inputs in the water that floods and slows down around different plot locations. It has been shown that the success of restoration projects in increasing rates of accretion and elevation change is primarily driven by sediment availability (Liu et al., 2021; Butzeck et al., 2014). It is shown that sediment supply decreases with distance from the river mouth (Liu et al., 2021).

The role of aboveground biomass in predicting sediment accumulation shows the importance of biotic factors. The relationship between aboveground biomass and sediment accumulation is surprising. We would expect higher aboveground biomass would correspond to higher rates of sediment accumulation, based on the concept of ‘biomass trapping’ – increased biomass density increases sediment trapping and thus sediment accumulation (Morris et al., 2002). However, the trend we observed was that increased aboveground biomass correlated to decreased sediment accumulation. It is difficult to assess which of these variables establishes itself first: do plants need more sediment accumulation to establish themselves or do wetlands need more plants to trap and increase sediment accumulation? In a study conducted in the Bay of Fundy at the northeastern end of the Gulf of Maine, researchers found that rapid sediment accumulation rates created a ‘clean slate’ for vegetation to colonize the restored wetland (van Proosdij et al., 2023). However, they measured an average sediment accumulation rate of between 5.99 to 7.17 cm/year, which is greater than the sediment accumulation rates measured in NCOS (van Proosdij et al., 2023). It is possible that the sediment accumulation rates in NCOS are not rapid enough to create the ‘clean slate’ for wetland vegetation to establish itself and thrive. It is also believed that if a restored wetland system is not able to keep up its equilibrium elevation to establish optimal primary productivity, then the system will not be able to accelerate sediment accumulation to keep pace with SLR (Morris et al., 2016). This is likely what we are witnessing in the first six years after restoration in NCOS, as elevation has not significantly increased to optimize primary productivity, and thus sediment accretion rates are not keeping pace with local rates of predicted SLR.

Another factor that could explain the difficulty of establishing a strong vegetation community is the variable soil salinity. The semi-arid Mediterranean climate where NCOS is located leads to unpredictable variation in soil salinity throughout the wetland (Parker & Boyer, 2019). Though soil salinity was greater in the surface soil, there was a significant negative relationship between subsurface soil salinity and aboveground biomass (Figure 31b). This is likely because the subsurface soil (5-15 cm) is where the majority of plant roots are and where salinity might affect their ability to extract nutrients.

However, when we compare the amount of vegetation in NCOS to COPR, we see that COPR has more aboveground biomass than NCOS, likely because COPR has had more time to establish vegetation and accumulate sediment. With more time, NCOS will likely be able to reach similar levels of productivity as COPR. With increased plant productivity, there will likely be greater amounts of elevation accretion, as suspended sediment settlement and plant productivity will work together to trap sediment and increase sediment accretion.

Downstream distance is a similar measure to plot location, since downstream distances tend to be similar for plots in the same location. The smaller the downstream distance, the closer the plot is to Venoco Bridge, a physical obstacle that causes reduction in tidal current speeds and increases the amount of sediment that gets trapped. For an early-stage post-restoration wetland that has not established an expansive vegetation community, more of the sediment trapping that might be done by biomass when a system is at equilibrium is done by other physical obstacles, like Venoco Bridge.

Suspended sediment concentrations for these creeks have been collected by CCBER since 2018, but since we only measured sediment accumulation at one time point, the increased temporal resolution is not useful for this study. The main takeaway is that Phelps Creek contributes more sediment to the restored wetland than Whittier Channel and that this will affect the spatial variation in sediment accretion across the site, with greater sediment availability near Phelps Creek.

In this study, wetland sediment accumulation six years after restoration is primarily driven by mineral sediments accumulated, rather than organic matter contributions. Important drivers of sediment accumulation are drivers that will increase the probability of delivering mineral sediments to the plot locations, like increased flooding frequency and shorter downstream distances. Other variables are affected by increased flooding; for example, salinity increases and aboveground biomass decreases. As time progresses, aboveground biomass will likely increase in the restored wetland and eventually sediment accumulation will increase with the contributions of both mineral sediments and organic matter.

Surface soil carbon content:

Current estimates of the carbon burial rate in intertidal marshes are between 57-218 g C/m^{2}yr (Hopkinson et al., 2012). The average carbon burial in NCOS since restoration was 33.3 g C/m^{2}yr. This is slightly lower than predictions of carbon burial for intertidal marshes in the literature, but these estimations are for natural wetland systems that are at steady state, whereas NCOS is a recently restored wetland that is not at steady state. Also, previous studies have found that higher carbon storage happens in wetlands at lower temperatures, whereas NCOS is located in a warm, Mediterranean climate (Lee et al., 2018). Comparing these measurements to the undisturbed and disturbed saltmarshes in Australia that we compared sediment accretion rate to, the undisturbed salt marsh had an average carbon sequestration rate of 64 g C/m^{2}yr and the disturbed system had an average rate of 137 g C/m^{2}yr (Howe et al., 2009). This is surprising because it shows that the disturbed wetland has a greater rate of carbon sequestration. However, this Australian system follows the pattern of a low energy tidal environment where carbon sequestration is proportional to marsh elevation or sediment accumulation, whereas NCOS seems to follow the pattern of high energy environments, where carbon sequestration is inversely proportional to marsh elevation (Howe et al., 2009).

The average amount of carbon in the surface soil of COPR was 9.01%, and the average carbon density in the surface soil was 0.02 g C/cm^3. Though both NCOS and COPR soil carbon percentages fall within the categorization of ‘mineral’ accumulation since their soils are less than 12 to 20% carbon content, differences in carbon content and organic matter are important to the question about what is contributing to vertical elevation change in this wetland system: mineral sediments or organic matter. For the first six years after restoration, NCOS is strongly accumulating mineral sediments, as it takes time for vegetation to establish and organic matter to accumulate, whereas COPR has higher carbon content and greater amounts of biomass.

One major factor that likely influenced the differences in aboveground biomass and surface soil carbon content between NCOS and COPR is frequency of inundation of these areas. The COPR plots had a significantly lower flooding frequency than the NCOS plots (t-test: p-value $< 10^{-3}$). Increased inundation, from tidal flooding or stream inputs, can slow down vegetation recovery and establishment in tidal marshes (Steinigeweg et al., 2023). This can also cause increases in salinity, especially in the surface soil (Figure 18). In general, plant tolerance of flooding is age dependent: younger plants show a lower tolerance to these types of disturbances caused by increased flooding and salinity (Steinigeweg et al., 2023). NCOS plants are younger, as they were planted when the wetland was restored six years ago, and thus they may have a more difficult time establishing themselves in variable conditions of inundation and salinities.

The model that best predicts surface soil carbon density in NCOS includes just plot location. However, models with a ΔBIC of 5 or lower only have moderate or marginal evidence that these models are worse than the “best” model (Jerde et al., 2019). In this case, the models with just plot location and plot location and flooding frequency have about the same evidence to explain the variation in surface soil carbon density. The model with just plot location has an R^2 of 0.59, whereas the model with plot location and flooding frequency has an R^2 of 0.5. The fact that the null model (m.0) has a ΔBIC of 4 shows that none of these models fully captured the mechanisms behind surface soil carbon density variation. Many of the variables used in these models are interrelated and co-varying, which likely makes it difficult to find a "true" model. Plot location is also included in the best model to predict sediment accumulation rate and there are many factors that vary with plot location.

The plot locations that had the greatest amount of surface soil carbon density were the northernmost plots. These were located closest to the stream inputs of Phelps Creek and Whittier Channel. The plot location with the smallest amount of surface soil carbon was the plot closest to the obstruction at Venoco Bridge, which happened to have the highest sediment accumulation rates. The negative correlation between sediment accumulation and surface carbon content suggests that this system is a high energy system that has not yet reached steady state.

Geomorphology has largely been listed as the main constraint on carbon sequestration in coastal ecosystems, but it is important to consider physiochemical, hydrologic, and biotic factors in predicting surface soil carbon sequestration in wetland systems (Kirwan et al., 2023). The fact that COPR shows much higher amounts of vegetation and higher carbon densities in the surface suggests that aboveground biomass is a strong predictor of surface soil carbon content. Previous studies show that vegetation can increase soil organic carbon (SOC) and light fraction (LF) organic carbon in the surface soil (Wang et al., 2023). There is a significant relationship between aboveground biomass and carbon density in the surface soil, however aboveground biomass is not a factor in the model that best predicts surface soil carbon density. Vegetation varies by plot location, so vegetation may still be a driver in the model since we saw significantly different surface soil carbon densities at different plot locations. What other characteristics can we deduce about the surface soil carbon? It is likely that the surface soil carbon is LF or particulate organic carbon (POC), derived from plant residues and has a much higher turnover rate than the heavy fraction (HF) or mineral-associated organic carbon (MAOC) (Janzen et al., 1992). One indication that the surface soil carbon consists of labile POC is from the relationship between the proportion of fine texture soil particles, consisting of the sum of clay and silt fractions, and surface soil carbon content (Figure 29). There is no linear relationship between these two factors, providing evidence that this carbon is not mineral associated, but mostly composed of decomposing plant residues and organic matter. This carbon is likely what has accumulated in the last couple years since restoration and as it continues to be broken down, it will be rapidly mineralized back into the atmosphere, with a small portion becoming stabilized in the soil, which we see more of in the subsurface soil.

Though we would expect higher elevation plots to have more surface carbon density as they should have higher plant biomass, we do not see any significant difference between surface soil carbon density at different elevations. However, there is significant variation in the categorization of vegetation type at different elevations (Figure 9). Grass is only present at the two highest elevations, and pickleweed is highest at these two elevations as well (Figure 9). Different vegetation types have differing effects on soil carbon content, mainly due to differences in overall biomass (Wan et al., 2019). Besides biomass or litter quantity, litter quality is also an important metric that influences carbon storage in the surface soil

(Xia et al., 2022). Elevation is also important as it controls variation in flooding frequency or inundation (Figure 15).

In this study, surface soil carbon density is quite variable and difficult to predict. There is a clear trend of differences in surface carbon density at different plot locations. However, the underlying mechanisms that are causing these spatial differences are difficult to quantify. Since surface soil carbon density is higher than subsurface carbon density and there is no relationship between the proportion of fine texture particles and carbon density, we can assume much of the carbon is POC, derived from plant residues. Thus, differences in vegetation by plot location likely drive differences by plot location. This is confirmed by the positive relationship between aboveground biomass and surface carbon density.

Subsurface soil carbon content

The average density of carbon in the subsurface soil (5-15 cm) below the layer of feldspar was 0.015 g C/cm^3. This is slightly lower than the amount of soil carbon in the surface and is consistent across different plot elevations and locations (t-test: p-value=0.059; Figure 34). This is consistent with Xia et al. (2022) who describe that soil carbon decreases with depth in the first 40 cm of soil. However, there is a clear difference in the characteristics and stability of soil carbon between the surface and the subsurface.

The high correlation between subsurface fine fraction and subsurface soil carbon density suggests that the subsurface soil carbon is composed of more mineral-associated carbon that tends to be more stable, as opposed to the more dynamic carbon that exists in the surface soil (Figure 28). The carbon in the subsurface soil has likely sorbed onto clay minerals, thus protecting it from microbial access more than the LF carbon that is associated with the surface soil.

Another argument for the increased stability of the subsurface soil carbon is the lower salinity of subsurface soil compared to surface soil (Figure 35). In a study conducted using ramped pyrolysis, Williams and Rosenheim found that freshwater marsh soil carbon was more stable than salt marsh soil carbon (2015). These differences in carbon stability are likely due to a combination of biotic, hydrologic, and physicochemical factors, rather than the previous assumption that all soil carbon stability differences were based on its molecular structure (Schmidt et al., 2011).

A major limitation for mapping soil carbon in wetland systems is the uncertainty around subsurface soil carbon content (Sharma et al., 2022). It is hypothesized that surface and subsurface soil carbon content are correlated. The surface and subsurface soil carbon content data (measured as percentages) collected in NCOS indeed show a strong correlation between surface and subsurface soil carbon content (Appendix 5). The surface and subsurface carbon densities do not show as strong of a relationship (Figure 36). The models that best predict surface and subsurface soil carbon content are very different.

In this study, the model that best predicts subsurface soil carbon content includes percent sand. The variable of percent sand is the same measurement of fine fraction, since sand is the textural fraction of the soil that is leftover after you subtract the fine fraction of silt and clay. This factor in the model demonstrates the differences in stability between surface and subsurface soil carbon, as subsurface carbon is highly correlated with percent silt and clay. This demonstrates that the subsurface soil is likely MAOC, as opposed to the surface soil that is predominated by POC.

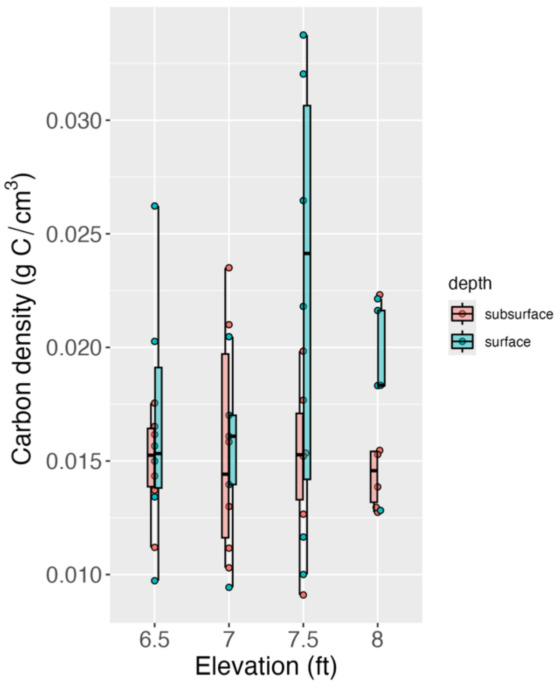


Figure 34: Soil carbon densities in the surface and subsurface soils across different elevation plots. The largest difference in carbon density between the surface and subsurface is in the highest elevation plots.

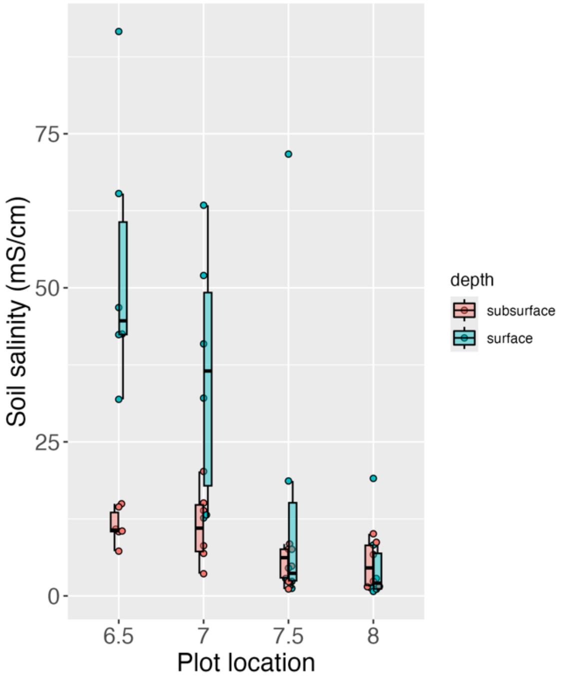


Figure 35: Soil salinity at the surface and subsurface. Soil salinity is consistently higher in the surface soil.

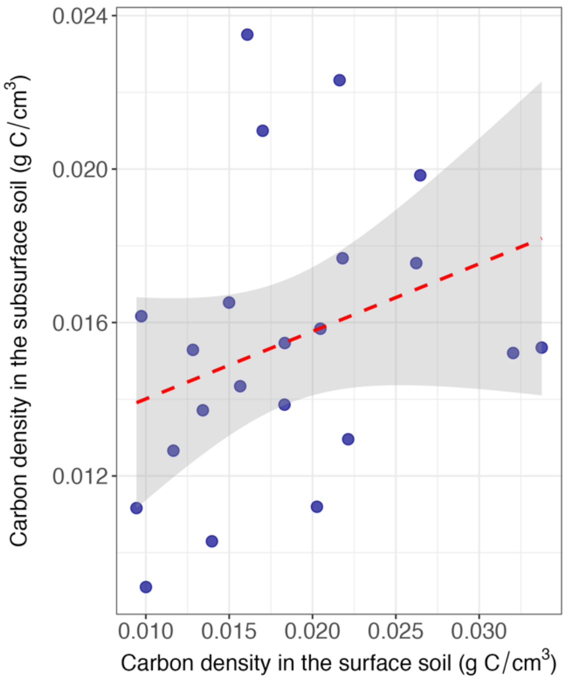


Figure 36: Relationship between surface soil carbon density and subsurface soil carbon density (slope=0.176, R^2=0.10, p-value=0.15)

Comparison of similarities and differences between what predicts sediment accumulation and surface soil carbon content:

Previous research has shown that soil carbon accumulation rates are highest in wetlands with higher rates of SLR, as this leads to greater deposition of sediments and organic matter (Kirwan et al., 2023). However, this relationship may not hold true *within* a system, as various spatial dynamics can have different effects on sediment accumulation and surface soil carbon content. In this study, we see a complicated relationship between sediment accumulation and surface soil carbon density that shows some areas with a low sediment accumulation rate had high surface soil carbon density, and some areas with high sediment accumulation had low surface soil carbon density (Figure 37).

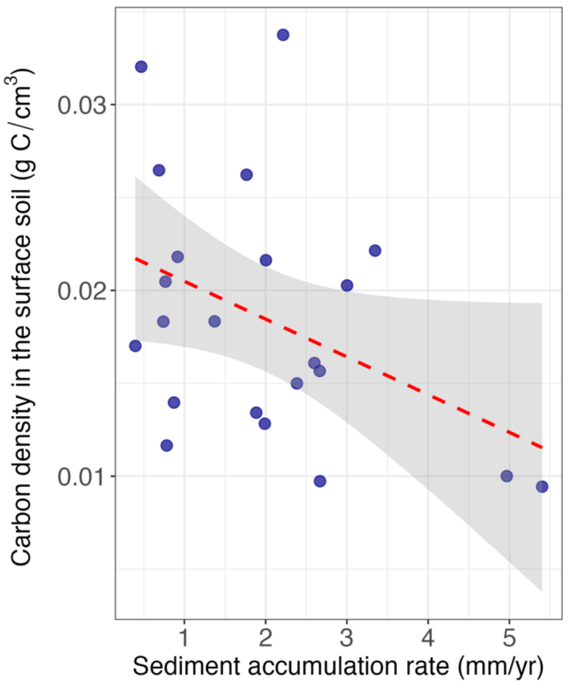


Figure 37: Relationship between sediment accumulation rate and surface soil carbon density. This negative relationship is slightly significant (slope = -0.002, R^2=0.17, p-value=0.059).

Downstream distance and aboveground biomass have opposite effects on sediment accumulation and surface soil carbon content. For aboveground biomass, this is likely due to the early stages post restoration and the difficulties that NCOS has with establishing new vegetation. Though vegetation does contribute to increasing surface soil carbon stocks, it is correlated to decreased sediment accumulation rates. Decreased downstream distance corresponds to higher rates of sediment accumulation but lower rates of surface soil carbon storage. Most previous studies state that increasing sediment accumulation corresponds to increased soil carbon storage (Kirwan et al., 2023; Howe et al., 2009). In a study conducted in Delaware Bay, Boyd and Sommerfield (2016) found that accretion rates were significantly correlated with organic matter accumulation but not with mineral sediment accumulation. This is likely a similar mechanism to what we see in NCOS because mineral sediment accumulation is the main driver of wetland elevation change in the six years after restoration.

It is important to understand the relationship between sediment accumulation and soil carbon storage because these processes guide the two most important ecosystem services that wetlands provide in order to adapt and mitigate the impact of climate change. Understanding the spatial dynamics that influence these two measurements is important for designing restoration projects that can maximize community resilience to climate change.

V. Conclusion

Biotic, hydrologic, and physiochemical factors are important in predicting sediment accumulation and surface soil carbon content within a restored wetland system. Between the model predictions for sediment accumulation, surface carbon density, and subsurface soil carbon density, the strongest model was the sediment accumulation rate prediction. In the best model, 71% of variation in sediment accumulation can be attributed to plot location and vegetation. The models predicting surface and subsurface soil carbon density are more variable. In the surface soil, 59% of variation in carbon density can be attributed to plot location, though 50% can be attributed to plot location and flooding frequency, and other variables have similarly functioning models. This shows that surface soil carbon is highly variable and relies on a complicated mix of factors. In the subsurface soil, 57% of variation in carbon density can be attributed to percent sand in the subsurface soil. The subsurface soil carbon is characterized by a strong mineral association, as shown by the strong correlation between carbon and fine texture (clay and silt fractions).

When wetland sediment accumulation studies primarily focus on differences between sites and areas with differing rates of sea-level rise, they make an unhelpful assumption that an entire wetland accumulates sediment and carbon at the same rate. Understanding spatial variability within a wetland system is important because it can be used to design restoration projects to maximize the ecosystem services of sediment accumulation and carbon storage. It also helps us to understand the mechanisms that drive these measurements.

Though surface soil carbon density is highly variable and difficult to predict, there is an interesting relationship that we found between surface carbon density and sediment accumulation rate. We found that as sediment accumulation rate increased, surface soil carbon density decreased. This is an important relationship to investigate as it questions the preconceived notion in wetland carbon sequestration models that increasing sedimentation increases soil carbon density.

Since sediment accumulation and carbon sequestration are two of the most important ways that coastal wetlands act as nature-based solutions to climate change, it is important to understand the spatial dynamics that control these processes and the relationship between them. We cannot continue to rely on sediment accumulation to predict carbon sequestration. Carbon storage needs to be measured separately from sediment accumulation, or further studies should be conducted to identify the primary mechanisms that drive the relationship between sediment accumulation and carbon sequestration.

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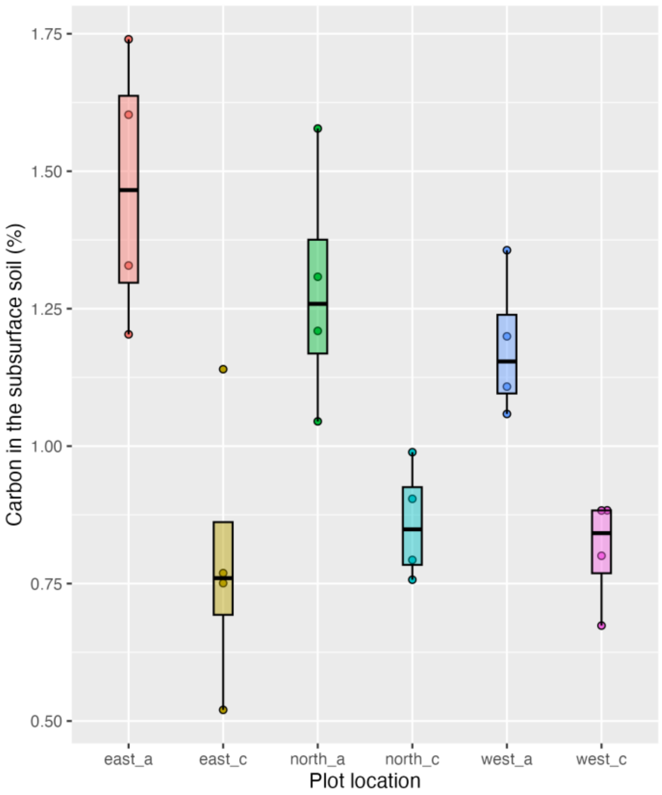
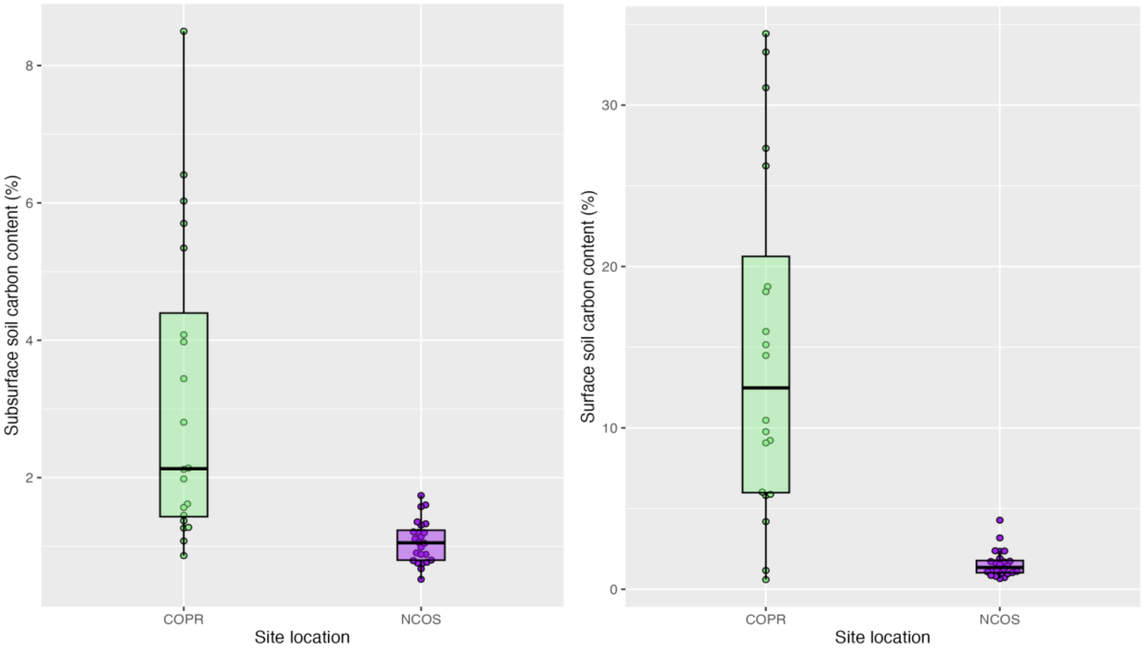
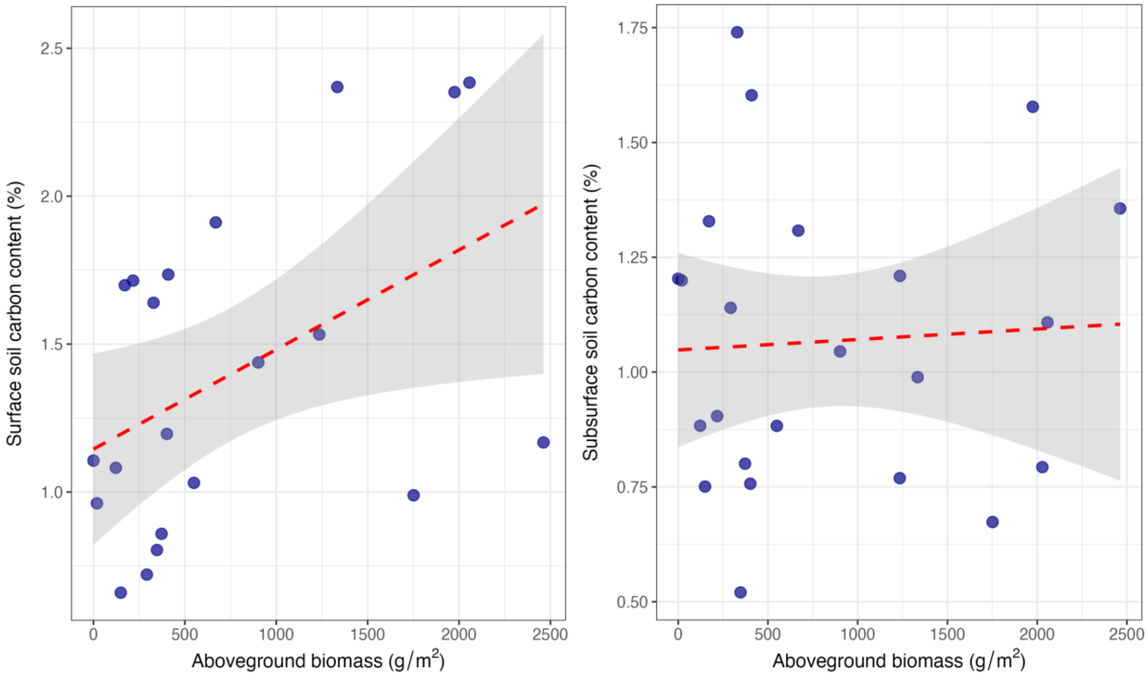
Appendix



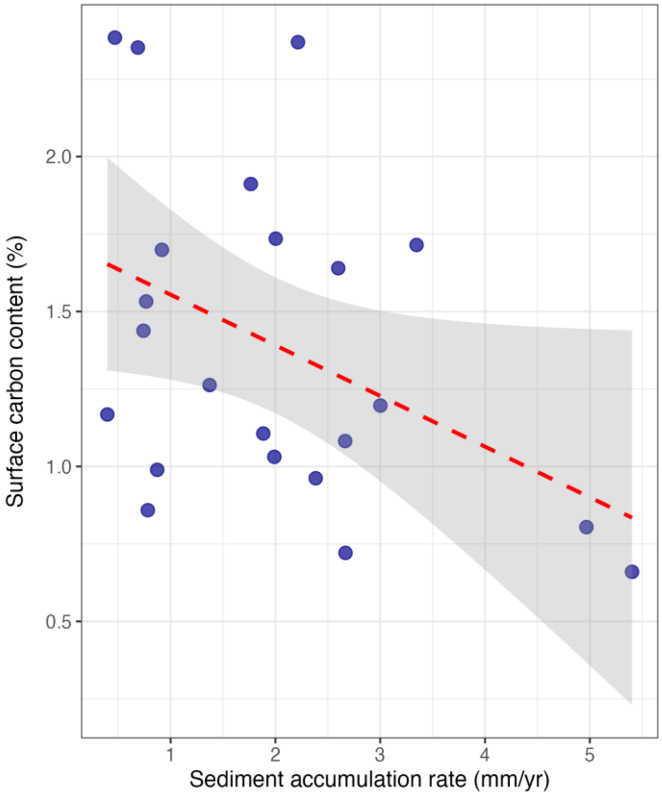
Appendix 1: Surface soil carbon content (%) measured by plot location.



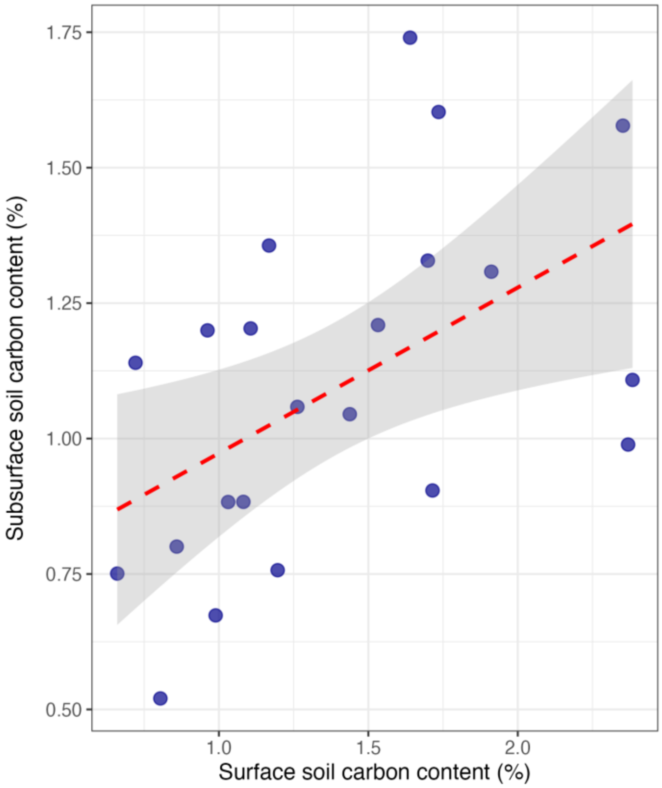
Appendix 2: Differences in surface and subsurface soil carbon content (%) between NCOS and COPR.



Appendix 3: Relationship between aboveground biomass and surface and subsurface soil carbon content (%).



Appendix 4: Relationship between sediment accumulation rate and surface soil carbon content (%).



Appendix 5: Surface soil carbon content is positively correlated with subsurface soil carbon content when analyzed by fractional content but not when soil bulk density is taken into account. This relationship is significant with carbon percentages, but not with carbon densities (slope=0.306, R^2=0.265, p-value=0.014).