Title

Quantifying Carbon Stock Variation in Batiquitos Lagoon’s Salt Marshes: Implications for Conservation and Nature-based Solutions to Reduce the Impacts of Climate Change

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Implications for Conservation and Nature-based Solutions to Reduce the Impacts of Climate Change

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Outline

Abbreviations

BCE = blue carbon ecosystems
CO_2 = carbon dioxide
Ppm = parts per million
EPA = Environmental Protection Agency
CNRA = California Natural Resource Agency
AB 45 = Assembly Bill 45
CCC = California Coastal Commission
CCIAA = Center for Climate Change Impacts and Adaptations
OPC = Ocean Protection Council
CDFW = California Department of Fish & Wildlife
%OC = percentage of organic carbon
CV = coefficient of variation
$CaCO_3$ = calcium carbonate
$MgC_{org}\ ha^{-1}$ = megagram of organic carbon per hectare
$g\ cm^{-3}$ = gram per cubic centimeter
$gC_{org}\ cm^{-3}$= gram of organic carbon per cubic centimeter

Definitions

Blue carbon = the fraction of atmospheric carbon captured and stored in the sediment of coastal wetlands such as mangroves, salt marshes, and seagrasses
Bulk density ($g\ cm^{-3}$) = the dry weight of each soil sample divided by the corresponding sample's volume
Percentage of organic carbon (%OC) = the fraction of organic carbon in each soil sample
Organic carbon density ($gC_{org}\ cm^{-3}$) = the multiplication of bulk density with the percentage of organic carbon in each soil sample
Carbon stock ($MgC_{org}\ ha^{-1}$) = the absolute quantity of carbon held in each sample pool

Executive Summary

Salt marshes and other coastal ecosystems are pivotal in the sequestration and storage of carbon, commonly known as "coastal blue carbon." However, these ecosystems face severe degradation and anthropogenic impacts. This study focuses on assessing the carbon storage potential within the salt marshes of the Batiquitos Lagoon. Our investigation reveals significant carbon stocks ranging from 2.56 to 238.70 MgC_{org} ha^{-1}, influenced by crucial factors such as maximum sediment depth and carbon density. Additionally, we compare the determined carbon stocks with regional benchmarks, yielding valuable insights to inform future conservation strategies aimed at safeguarding the carbon sinks of salt marshes. This work contributes to the expanding body of research on blue carbon ecosystems, emphasizing the vital role of ongoing research, monitoring, and conservation efforts.

I. Introduction

Since 1958, monitoring of atmospheric carbon dioxide (CO_2) concentrations has been conducted at the Mauna Loa Observatory. Notably, the findings project that global atmospheric concentrations of carbon dioxide (CO_2) will reach 450 parts per million (ppm) by the year 2040 (C. D. Keeling et al., 2005). With ongoing increases in CO_2 concentrations driven predominantly by anthropogenic fossil fuel combustion and land use changes, research efforts have intensified to curb global emissions and limit global warming to within 2°C above pre-industrial levels (Solomon et al., 2007). Beyond decarbonization, removal of carbon dioxide will be required to avoid the worst effects of climate change. There has been increasing interest in the potential for nature-based solutions as a viable approach to combat climate change by harnessing natural carbon sink capacities (Macreadie et al., 2021).

Earlier efforts focused primarily on terrestrial ecosystems, neglecting the potential of coastal and ocean ecosystems (Nellemann et al., 2009). However, a significant body of research has emerged highlighting the potential significance of blue carbon ecosystems (BCEs) within coastal and oceanic settings as potential carbon sinks (Macreadie et al., 2021).

I.1 Blue Carbon Ecosystem Services

The concept of "coastal blue carbon" pertains to the portion of atmospheric carbon that is captured and stored within the biomass and sedimentary deposits of coastal wetland environments, including mangroves, salt marshes, and seagrasses (Poppe & Rybczyk, 2021). These blue carbon ecosystems are of importance within coastal regions, offering a multitude of ecological services such as carbon sequestration, nutrient cycling, sediment stabilization, and the provision of habitats for a diverse array of organisms (Lovelock & Duarte, 2019). Blue carbon ecosystems are recognized for their capacity to store and sequester substantial quantities of organic carbon within their sedimentary environments, owing to their remarkable attributes of high primary productivity, rates of sediment accumulation, and nutrient remineralization processes (Ward et al., 2021). Furthermore, these ecosystems play a crucial role in safeguarding coastal areas against erosion and storm surges, contributing to the overall resilience and well-being of coastal ecosystems, and even serving as spaces for recreational activities (Nahlik & Fennessy, 2016).

Coastal wetland ecosystems play a crucial role in the storage of organic carbon. This capstone project primarily focuses on salt marsh ecosystems, although mangrove forests and most seagrass beds also exhibit high primary productivity. Primary productivity refers to the rate at which plants convert solar energy into organic matter through photosynthesis (Alongi, 2020). These ecosystems' plants are highly effective at capturing carbon dioxide from the atmosphere and converting it into organic matter. Within these ecosystems, tidal currents transport sediment, which gets deposited in the marshes, forming a layer of organic-rich sediment that gradually accumulates over time (Duarte et al., 2013). This sediment is highly effective at trapping and storing carbon, as well as nutrients and pollutants. The decomposition of organic matter in the ecosystems allows for the rapid recycling of nutrients while carbon continues to be sequestered (Morris et al. 2002). This decomposition releases nutrients that enable primary production, but some fraction of organic matter remains undecomposed, entering into long-term storage in sediments.

I.2 Coastal Ecosystem Loss

According to the findings of the California State Coastal Conservancy, there has been significant degradation and loss of wetlands in San Diego over the past 140 years due to habitat loss and fragmentation caused by urban development (State Coastal Conservancy, 1989). This loss is particularly concerning considering San Diego's extensive coastline and high levels of coastal development. Among the valuable ecosystems affected by these changes are salt marshes and seagrass beds, which are known for their remarkable biological productivity and support for diverse marine biodiversity, waterfowl, crustaceans, and insects (Brennan, 2021). Within San Diego, salt marshes are the prevalent coastal wetland ecosystem, where investigation of salt marsh blue carbon will be conducted in this study.

The decline and degradation of salt marshes can have severe consequences, not only in terms of biodiversity loss but also carbon sequestration. As highlighted by McMahon et al. (2023), the loss and degradation of salt marshes can diminish their capacity to sequester carbon, leading to a shift from being a carbon sink to becoming a carbon source. This implies that the ecological function of salt marshes as natural carbon sinks is compromised, with potential implications for regional and global carbon cycling dynamics (Macreadie et al., 2013; Howard et al., 2017; Lovelock et al., 2017). Efforts to mitigate wetland loss and promote conservation measures are crucial for maintaining the carbon sequestration potential of these ecosystems and avoiding the conversion of carbon sinks into carbon sources. Furthermore, safeguarding the ecological integrity of salt marshes is essential for the conservation of biodiversity and the sustained provision of ecosystem services in coastal regions.

I.3 Blue Carbon Conservation Policy

Scientific research has established the critical role of blue carbon ecosystems, including those in San Diego County, in mitigating the adverse impacts of climate change through their efficient sequestration and storage of substantial quantities of atmospheric carbon dioxide (Fourqurean et al., 2012). As an illustration, the seagrass beds located in San Diego Bay have been identified as housing a noteworthy carbon stock, currently estimated at 170,000 metric tons (Port of San Diego, 2023). However, despite their ecological significance, the sustainability of blue carbon ecosystems in San Diego County, as well as globally, is under threat from various stressors such as climate change, pollution, and coastal development. The sizable carbon stocks found in the seagrass beds of the San Diego Bay underscore the importance for a set of conservation policies that can effectively protect and conserve these blue carbon ecosystems.

A comprehensive understanding of the regulatory landscape is imperative for effectively addressing the challenges and threats confronting blue carbon ecosystems and implementing suitable measures for their conservation and protection. This necessity arises from the intricate governance structure that governs wetlands in the United States, operating across federal, state, and local levels (Spidalieri, 2020). The U.S. Army Corps of Engineers assumes primary responsibility for regulating wetlands and coastal zones, guided by legislative acts such as the Clean Water Act of 1972 and the Rivers and Harbors Act of 1899 (Clean Water Act of 1972; Rivers and Harbors Act of 1899). Additionally, states have the authority to regulate their coastal zones through participation in the federal Coastal Zone Management program, while local governments exercise primary control over land use through the implementation of zoning and floodplain ordinances (Spidalieri, 2020). Approximately 75% of the remaining wetlands in the continental United States are privately owned, prompting the Environmental Protection Agency (EPA) to establish voluntary programs aimed at supporting private landowners in wetland conservation endeavors through educational, technical, and financial assistance (EPA, 2021).

In 2020, Governor Gavin Newsom of California enacted Executive Order N-82-20, known as the Nature-Based Solutions Executive Order. Under this directive, California committed itself to implementing ecosystem management practices that advance both biodiversity conservation and climate change mitigation (CNRA, 2022). As part of this commitment, the 30x30 Initiative aims to safeguard an additional six million acres of land and half a million acres of coastal waters, organized into ten distinct Pathways. The California Natural Resource Agency (CNRA) actively seeks collaborative partnerships among land managers, community conservationists, scientists, environmental stewards, California Native American tribes, and all residents of California (CNRA, 2022).

More recently, Assembly Bill 45 (AB 45), authored by Assemblymember Boerner Horvath of Encinitas, proposes to authorize the California Coastal Commission (CCC) to require blue carbon demonstration projects in wetlands and other natural systems as a means of offsetting greenhouse gas emissions on public lands (Brennan, 2022). AB 45 builds upon the

State Wetland Conservation Policy of 1993, which established the goal of "No Net Loss" of wetlands. AB 45 is an initiative that seeks to promote and advance research on blue carbon by focusing on the protection, monitoring, and systematic collection of data in coastal ecosystems. The bill is sponsored by WILDCOAST, an environmental organization, and has garnered support from local stakeholders, including the Environmental Center of San Diego and Buena Vista Audubon.

I.4 San Diego County Assessment

Given the spatial variability of stored carbon in salt marsh ecosystems, few existing studies accurately account for this variation at the local scale (Miller et al. 2023). Within the San Diego region, land managers and policymakers within the San Diego region have yet to sufficiently capture carbon data for its coastal blue carbon ecosystems. In an attempt to narrow the gap, the Center for Climate Change Impacts and Adaptations (CCCIA) has partnered with Wildcoast, an environmental nonprofit, to conduct the first countywide blue carbon assessment. The collaborative research is funded by grants from the Ocean Protection Council (OPC), Builders Initiative, and California Coastal Conservancy. The assessment has the objective of informing future management and restoration efforts to maximize carbon storage and sequestration in coastal ecosystems (CCCIA 2019).

I.5 Goal of Capstone Report

This Capstone study incorporates data, derived from an ongoing research initiative throughout the county, specifically on the Batiquitos Lagoon. The primary objective of this Capstone project is to contribute, by collecting, processing, and analyzing the available data, to the understanding of the distinct factors influencing the variability of salt marsh carbon stocks within the Batiquitos Lagoon. The findings obtained from this research endeavor will be presented to both the Batiquitos Lagoon Foundation and the California Department of Fish & Wildlife, with the overarching intention of fostering the conservation of natural landscapes in alignment with the directives outlined in Executive Order N-82-20.

This capstone study specifically focuses on providing support for Executive Order N-82-20’s through addressing ways the Batiquitos Lagoon can implement pathways from the California 30x30 Initiative. The California 30x30 Initiative is a comprehensive conservation effort that seeks to protect and conserve 30% of California's land and coastal waters by the year 2030. The initiative recognizes the urgent need to safeguard and restore diverse ecosystems to address ongoing challenges such as biodiversity loss and climate change impacts. By implementing pathways outlined within the initiative, including Pathway 6: Expanding and Accelerating Environmental Restoration and Stewardship and Pathway 10: Evaluating Conservation Outcomes and Adaptive Management, the capstone study aims to align its objectives with the broader goals of the California 30x30 Initiative while contributing to the scientific discourse and educational efforts surrounding blue carbon .

Pathway 6 places priority on the restoration and continuous stewardship activities that foster functional ecosystems within urban areas where biodiversity loss has occurred (CNRA, 2022). Specifically, within the Pathways to Achieve 30x30 framework, Priority Action 6.2 aims to identify areas where environmental restoration can yield substantial climate benefits, including the preservation of carbon stores, carbon sequestration, and the buffering of communities from climate change impacts (CNRA, 2022).The capstone study explores the application of Pathway 6 within the context of Batiquitos Lagoon, identifying areas where restoration efforts can yield substantial climate benefits and protect carbon stores.

Pathway 10 concentrates on enhancing effective conservation and adaptive management strategies that integrate up-to-date scientific knowledge, consistent data collection, and long-term monitoring (CNRA, 2022). Within Pathway 10: Evaluating Conservation Outcomes and Adaptive Management, Priority Action 10.8 focuses on understanding the measurement of carbon sequestration and storage on natural and working lands. Within the capstone study, Pathway 10 is examined to develop an understanding of how to evaluate the measurement of carbon sequestration and storage within the Batiquitos Lagoon ecosystem. This contributes to the scientific discourse surrounding blue carbon, which refers to the role of coastal and marine ecosystems in capturing and storing carbon dioxide from the atmosphere. By aligning with the California 30x30 Initiative and exploring Pathways 6 and 10, the capstone study not only addresses the specific goals of preserving Batiquitos Lagoon's natural ecosystem and biodiversity but also supports broader conservation objectives at the state level.

II. Methods

II.1 Study Area

The Batiquitos Lagoon, located in Carlsbad, California, is a coastal wetland ecosystem that supports a diverse array of plant and animal species, including several endangered and threatened species. The lagoon is fed by several streams and rivers, including Batiquitos Creek, which flows into the lagoon through a narrow channel. The watershed of the lagoon covers approximately 142 km^2 and includes urban, agricultural, and undeveloped areas. The hydrology of the lagoon is influenced by tides and seasonal variations in rainfall, with freshwater inputs decreasing during the dry summer months. The water in the lagoon is typically brackish, with salinity levels varying depending on the location and the amount of freshwater inflow (CDFW, 2023). The salt marsh at Batiquitos Lagoon is dominated by several species of flowering plants, including *Spartina foliosa*, *Salicornia pacifica*, and *Jaumea carnosa*. These plants are adapted to the harsh environmental conditions of the salt marsh, including fluctuating salinity levels, high temperatures, and low sediment oxygen levels.

II.2 Field Sampling and Laboratory Analysis

The adopted methodologies for the collection, processing, and analysis of sediment samples, employed to estimate the current carbon stock (MgC/ha) within the salt marshes of the

Batiquitos Lagoon, were provided by Dr. Matthew T. Costa. Prior permission for field sampling was obtained from the California Department of Fish & Wildlife, and sampling activities were conducted on eight separate occasions spanning from December 20th, 2022, to February 21st, 2023. Throughout this two-month period, a total of 85 sediment samples were collected along five transect lines (with a core at east end of the transect) and at three additional individual locations, as illustrated in Fig. 1.

Figure 1: 85 sediment cores were collected from 13 site locations within the Batiquitos Lagoon in Carlsbad, California.

During the low tide, a transect tape was extended from the low intertidal edge of salt marsh vegetation to the high intertidal edge. The low intertidal sampling point was designated as 5 m upslope from the low end of the transect, and the high intertidal sampling point 5 m downslope from the high end. In locations in which the intertidal was narrow, a single coring location in the middle of this narrow swath was used. Following the protocols established by Dr. Matthew T. Costa (Costa et al., 2019), a Russian peat corer was utilized to extract vertical, semi-cylindrical samples at 50 cm intervals. The coring process was repeated in 50 cm increments within each hole using extension rods until refusal, resulting in core depths ranging from 14 cm to 266 cm. Subsequently, subsamples measuring 5 cm vertically were systematically extracted at 20 cm intervals, with additional samples being collected at sediment transition zones, using a knife and measuring tape.

After collection, the samples were subjected to a drying process in an oven set at 60°C for a minimum of 24 hours or until the change in mass from the previous day was less than 0.1g.

Once completely dried, the samples were ground into a fine powder using a mortar and pestle, followed by passing them through a 500-micron sieve. To ensure the removal of calcium carbonate ($CaCO_3$) to obtain solely organic carbon, the homogenized samples underwent HCl-fumigation according to the methods employed by Ramnarine et al. (2011) and Costa et al. (2019). Subsequently, approximately 10±2 mg of each sample was precisely weighed into tin capsules and analyzed using an ECS 4010 CHNSO Elemental Analyzer at Scripps Institution of Oceanography. This analysis provided the mass percentage of organic carbon present in the samples.

II.3 Analysis

In accordance with Costa et al. (2022), a comprehensive assessment of the carbon stock in the Batiquitos Lagoon's salt marshes was conducted using a standardized methodology. The analysis involved the determination of bulk density (g cm^{-3}), percent organic carbon (%OC), organic carbon density (gC_{org} cm^{-3}), and carbon stock (MgC_{org} ha^{-1}). The calculation of bulk density involved dividing the dry weight of each soil sample by the corresponding sample's volume. By multiplying the bulk density with the percentage of organic carbon (%OC) in each soil sample, the carbon density of each subsample was obtained. The carbon density values for individual subsamples were then averaged within each sediment layer, based on sediment type, and integrated with depth to ascertain the carbon stock of each core.

III. Results

Fig. 2 presents comprehensive depth information pertaining to thirteen plot profiles, encompassing a depth range of 14 cm to 266 cm, with an average depth of 116 cm. The

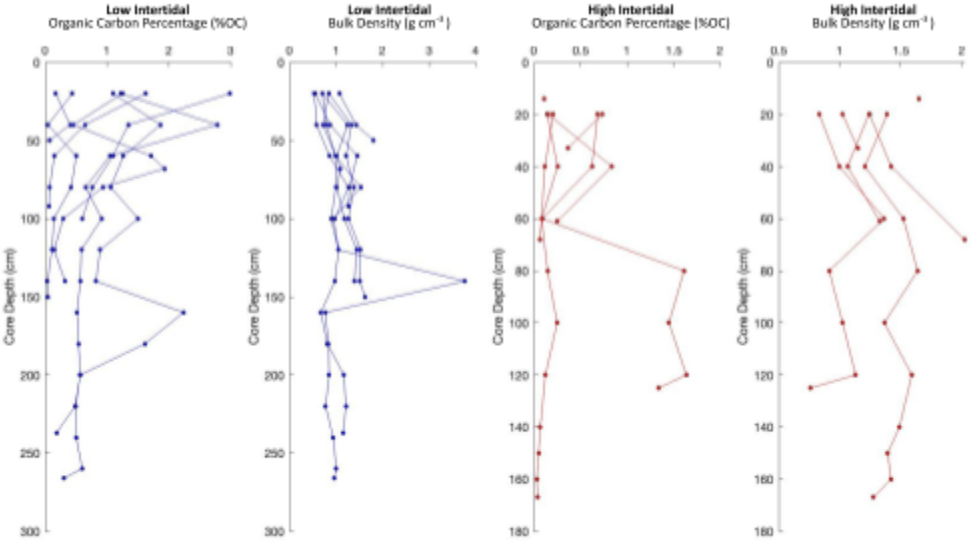


Figure 2: Down-core trends (surface = 0 cm) comparing the bulk density (g cm^{-3}) and % organic carbon (%OC) between the low intertidal (blue) and high intertidal (red) cores.

relationship between bulk density and the percentage of organic carbon (%OC) in the low and high intertidal zones was examined by means of graphical representation. The consistency of this relationship was observed across all 85 subsamples. See appendix 1 for the depth profile of %OC and bulk density in each of the 13 cores included in this study. Through profile analysis, notable depths were identified wherein the highest %OC values were observed. Specifically, within the low intertidal locations, enhanced carbon content was concentrated within the initial 60 cm of the depth profile. Conversely, the high intertidal location exhibited greater variability in %OC and bulk density as a function of depth, likely attributed to the presence of diverse sediment layers characterized by higher %OC content within the uppermost 30 cm of the profile.

The relationship between sediment carbon stock and the two contributing factors of weighted average carbon density and maximum depth of each core was examined through data visualization and analysis of coefficients of variation of the two factors. The analysis of thirteen cores revealed the significant influence of both weighted average carbon density and maximum depth on shaping variation in the carbon stock within the Batiquitos Lagoon (Fig. 3). To better comprehend the association between these variables, the coefficient of variation (CV) was employed as a measure of relative variability. The CV was computed for two parameters, namely the weighted average carbon density and maximum sediment depth, for each core. This involved dividing the standard deviation by the mean values, resulting in CV estimates of 0.62 for the weighted average carbon density and 0.66 for the maximum sediment depth.

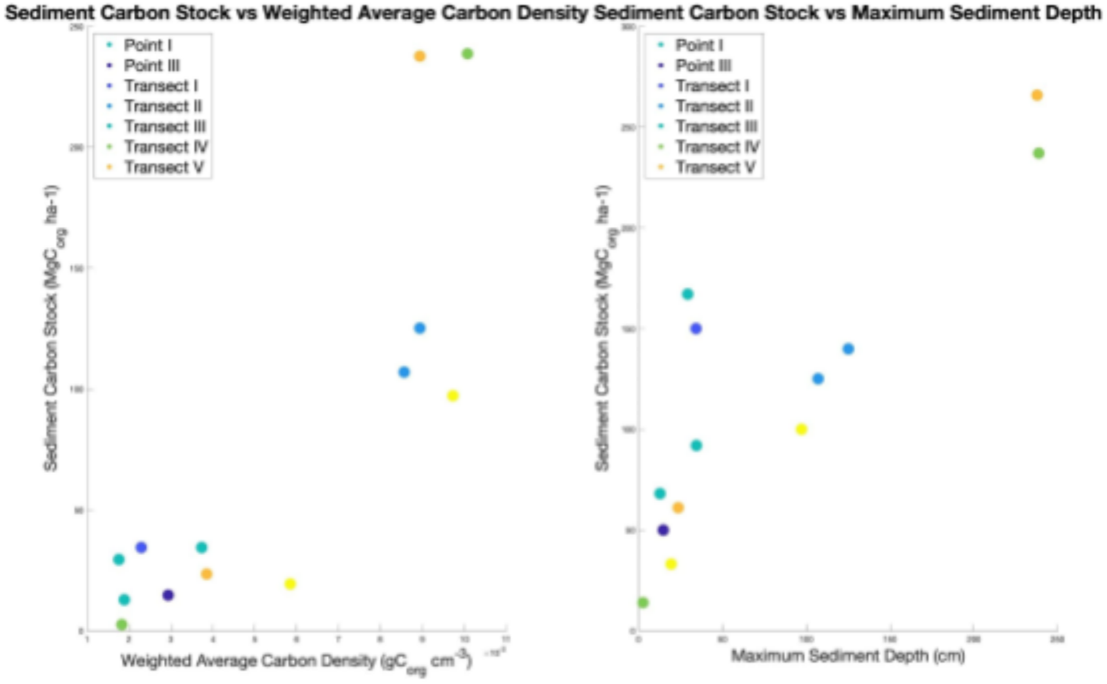


Figure 3: Side-by-side plots illustrating the relationship between weighted average carbon density and maximum depth in influencing the carbon stock of the thirteen core sites within Batiquitos Lagoon.

To Investigate the potential influence of intertidal location on the carbon stock of the Batiquitos Lagoon's salt marshes. Specifically, we aimed to explore whether the low intertidal and high intertidal zones exhibited differential carbon stock characteristics. To address this, we analyzed a dataset consisting of six cores from the low intertidal zone and seven cores from the high intertidal zone (Fig. 4). The carbon stock of each core was plotted to visually compare the differences between the two zones.

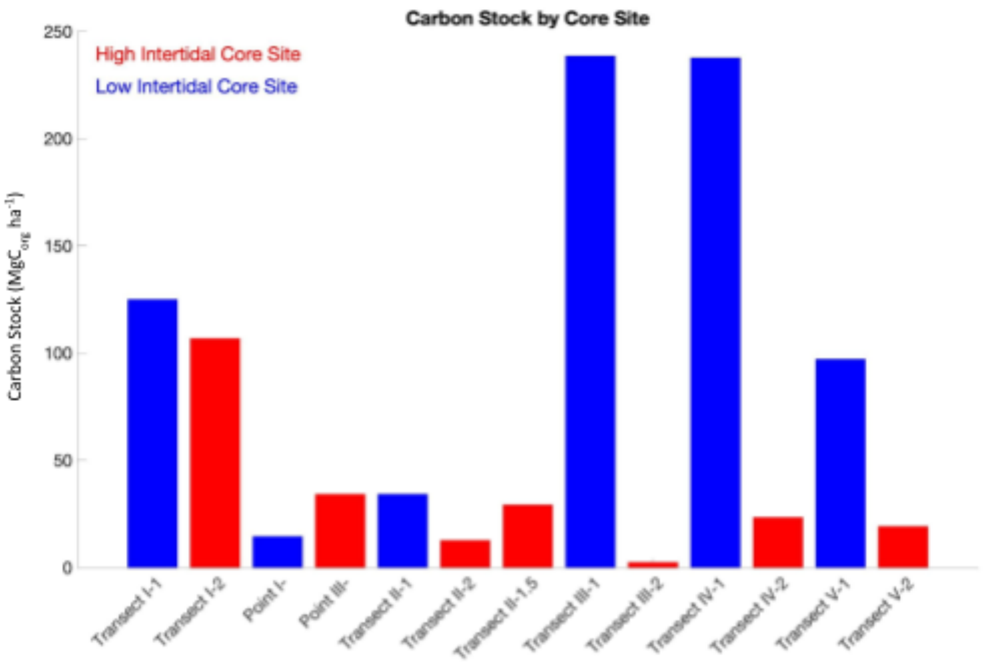


Figure 4: Mean total organic carbon (OC) stocks in thirteen cores obtained from Batiquitos Lagoon, ordered from west to east as depicted in Figure 1. Cores labeled with a "1" indicate low intertidal locations, whereas cores labeled with a "2" represent high intertidal sites. Individual points on the figure correspond to specific locations, where Point I- signifies a low intertidal site, and Point III- and Transect II-1.5 represent high intertidal locations.

The graphical representation reveals that the highest carbon stocks are all found in the low intertidal, though there is large variation within both the low and the high intertidal that makes a simple generalization impossible (Fig. 5). To assess the hypothesis that the distribution of carbon stocks in the low intertidal zone differs from that of the high intertidal zone, a Mann-Whitney U test was conducted ($U = 46$, $df = 11$, $p > 0.1$), and no significant difference was found. These findings and the corresponding statistical analysis will be discussed in more detail in the subsequent discussion section, wherein we will explore the implications of these results and the underlying factors influencing the observed carbon stock patterns in the Batiquitos Lagoon's salt marshes.

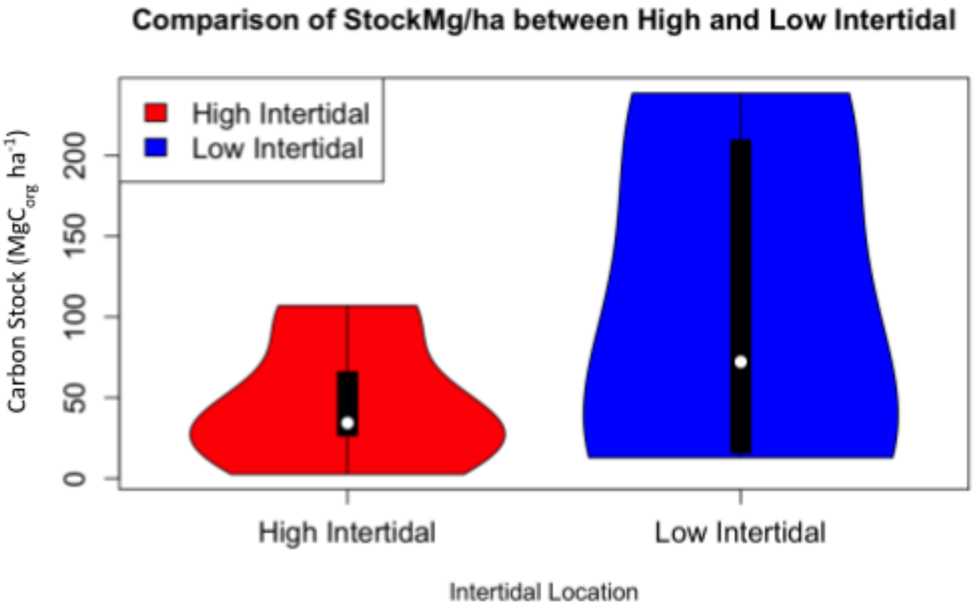


Figure 5: Violin plot depicting the comparison of carbon stock between low and high intertidal salt marshes in Batiquitos Lagoon (Whitney-Mann U Test, P value: 0.7308, No significant difference observed).

IV. Discussion

IV.1 Overview

The discussion section provides insights into the variation in depth and sediment composition of thirteen cores examined in the study. It highlights the relationship between bulk density and organic carbon content, indicating an inverse association between the two. The discussion further explores the importance of carbon density and maximum sediment depth in determining carbon stock in coastal wetland ecosystems. It emphasizes the significance of safeguarding vegetation, facilitating organic matter inputs, and preserving deeper sediment layers to enhance long-term carbon storage. The section also compares carbon stocks between high and low intertidal zones, highlighting the greater carbon stocks typically found in the low intertidal. Regional comparisons are made, indicating the variability in carbon stocks across different studies and locations. This section also acknowledges the limitations of the study, such as the small sample size and the need for larger datasets to draw more conclusive results. Finally, it highlights the implications of the findings for conservation strategies and the need for further research to enhance our understanding of carbon dynamics in coastal ecosystems.

IV.2 Bulk Density vs. % Organic Carbon

In the present study, thirteen cores were examined to gain insights into the variation in depth and sediment composition. Core location IV-1 displayed the greatest depth, reaching 266 cm. This particular location was characterized by a compact fine brown sand composition, indicative of its proximity to the shoreline and potential wave action. On the other hand, Core III-2, situated 5 m from the high tide line on Transect III, exhibited the shallowest depth recorded, measuring 14 cm. The sediment composition at this location was predominantly a solid gray clay mixture, suggesting a low-energy decomposition environment, in contrast to the sandy core discussed previously.

Furthermore, there is a significant relationship between bulk density and the percentage of organic carbon (%OC) across the entire dataset. The plots clearly demonstrated that subsamples with higher bulk density readings corresponded to lower %OC values, and vice versa (Craft, 2007; Kauffman et al. 2020). This finding indicates an inverse association between bulk density and organic carbon content, suggesting that denser sediment layers tend to have lower organic carbon concentrations, as seen in other studies of tidal wetland sediments (Morris et al. 2016; Keller et al. 2015; Craft 2007; Kauffman et al. 2020). This relationship holds true when considering all 85 subsamples analyzed in this study, providing robust evidence of the observed pattern.

IV.3 Carbon Density & Maximum Depth

The findings of this study provide empirical support that there is significant spatial variation in the carbon stock of the Batiquitos Lagoon, related both to variation in carbon density and in maximum sediment depth, aligning with prior investigations conducted in analogous coastal wetland ecosystems. Carbon density, which represents the amount of carbon stored per unit volume, is a crucial factor influencing the overall carbon stock in coastal wetland ecosystems (Smith et al., 2018). Higher values of carbon density are indicative of a greater quantity of carbon sequestered within the sediments of the lagoon, a phenomenon attributable to a multitude of factors including the productivity of vegetation, inputs of organic matter, and depositional processes. Moreover, other research has highlighted the importance of considering maximum sediment depth as a determinant of carbon storage capacity (Costa et al., 2022; Kauffman et al., 2018; Johnson & Brown, 2019). The relationship between sediment depth and carbon stock is influenced by various mechanisms, including protracted sediment residence times, diminished exposure to oxygen, and augmented preservation of organic matter (Johnson & Brown, 2019).

This study provides insight into the factors that shape the carbon stock of the Batiquitos Lagoon's salt marshes. Our findings underscore the importance of safeguarding vegetation, facilitating organic matter inputs, and preserving deeper sediment layers to engender long-term storage. Integration of these objectives into conservation strategies enables stakeholders to effectively conserve the valuable carbon stocks present within the Batiquitos Lagoon and comparable ecosystems. These insights not only advance our comprehension of carbon dynamics within coastal ecosystems but also bear significant implications for the design and implementation of conservation strategies aimed at preserving carbon stocks and mitigating the impacts of climate change, discussed in more detail in section 4.5.

IV.4 Intertidal Comparisons

There was significant variation in carbon stock in both the high and low intertidal, but all of the greatest carbon stocks were found in the low intertidal. This pattern may be due to the low intertidal's high vegetation density, low decomposition rates, anoxic conditions, and minimal level of disturbance. Vegetation biomass and productivity play a crucial role in carbon sequestration within salt marsh ecosystems, as the highly productive vegetation typically accumulates substantial amounts of biomass (Macreadie et al., 2019). Secondly, sediment deposition and organic matter accumulation are also important mechanisms contributing to the greater carbon stock observed in low intertidal zones. The regular tidal inundation experienced by these zones results in sediment deposition of organic matter derived from both plant material and associated microbes. Over time, this organic matter accumulates and becomes buried, leading to a high carbon stock (Kelleway et al., 2017). Additionally, anoxic conditions prevailing in the sediments of low intertidal zones have a significant impact on carbon preservation. Limited oxygen availability in these zones slows the decomposition rates of organic matter. As a result, the organic matter remains relatively intact and preserved, allowing for its long-term storage and contributing to the relatively high carbon stocks (Chmura et al., 2003).

Our study's findings reinforce existing research highlighting the importance of low intertidal zones in shaping carbon dynamics within salt marsh ecosystems (Callaway et al. 2012). Understanding these processes is crucial for the successful management and conservation of wetlands, as these areas serve as invaluable natural carbon sinks. However, it is important to acknowledge that further research is necessary to fully comprehend the intricate interactions and feedback mechanisms among these factors and to evaluate their resilience in the face of changing environmental conditions. Future investigations should focus on assessing the long-term stability and vulnerability of carbon stocks in response to climate change, as well as examining how intertidal restoration efforts and marsh creation initiatives will impact future carbon sequestration potential. Through more research, we can gain deeper insights into the dynamics of carbon storage in salt marshes and inform strategies for sustainable wetland management and carbon mitigation.

IV.5 Statistical Analysis

The results of the statistical analysis reveal variability in both the weighted average carbon density and maximum sediment depth, surpassing their respective means. This indicates a wide distribution of values within the dataset, suggesting a significant driving relationship between maximum sediment depth and carbon stock, as well as between weighted average carbon density and carbon stock. These findings contribute to a comprehensive understanding of the factors that influence carbon storage capacity within the studied ecosystem.

The carbon stocks of the high and low intertidal cores were compared (using a non-parametric test because of unequal variance) to determine whether the two means were equal. The test did not yield statistically significant results (U = 38, p = 0.7308); this outcome may be due to the high variance observed within our relatively small dataset. Despite the lack of statistical significance, a visual examination of the data supports the observation that low intertidal zones in salt marshes tend to exhibit higher carbon stocks. These findings align with previous research findings indicating that the most substantial carbon stocks are often found in the low intertidal zones (Macreadie et al., 2019; Lovelock et al., 2017).

However, it is important to acknowledge the limitations of our study, particularly the small sample size consisting of only six low intertidal and seven high intertidal cores. Given the wide range of depths observed in our dataset (ranging from 14 cm to 266 cm) and the considerable variation in carbon stock values (ranging from 2.56 to 238.70 $MgC_{org}\ ha^{-1}$) (Fig. 6), we propose that a larger sample size would yield more conclusive results on the question of the variation of carbon stock between low and high intertidal zones in this region. The inclusion of a larger dataset would enable a more robust statistical analysis and enhance the statistical power to detect significant differences between the low and high intertidal zones in terms of carbon stock.

Figure 6: Geographical map showcasing the thirteen core locations with their respective carbon stock values (ranging from 2.56 to 238.70 MgC(org)/ha).

IV.6 Regional Comparisons

A growing body of research has been devoted to estimating the total carbon stocks in coastal wetlands across North America and the United States (Kauffman et al., 2020; Holmquist et al., 2018; Nahlik & Fennessy, 2016). However, despite this increased attention, the wetlands of California, including San Diego County, remain underrepresented in the scientific literature (Kauffman et al., 2020). Limited academic studies have been published regarding the carbon stock of San Diego County, although contributions by Weiss et al. (2001) and Ward et al. (2021) have enhanced our understanding of carbon stocks in the region. Additionally, an assessment of salt marsh carbon stocks across San Diego County (Costa et al., in prep) is currently being prepared, which will further contribute to our knowledge in this area.

Specifically, in Batiquitos Lagoon's salt marshes, the mean carbon stock was 75 MgC^{org}/ha, with a range of 2.56-238.70 MgC_{org} ha^{-1}. This suggests that the salt marsh exhibits a relatively moderate carbon stock compared to other salt marsh locations for which data are available (see table 1). In contrast, Weiss et al. (2001) conducted a study in the Tijuana River Estuary in 1998 and reported a considerably higher carbon stock of 239 ± 17.42 MgC_{org} ha^{-1}, surpassing the levels found in Batiquitos Lagoon. Ward et al. (2021), focusing on various locations in California such as Newport Bay, Elkhorn Slough, and Tomales Bay, reported a carbon stock of 235 ± 17.74 MgC_{org} ha^{-1}. This value is similar to that reported in the Tijuana River Estuary and exceeds the carbon stock observed in Batiquitos Lagoon's salt marshes.

Furthermore, Kauffman et al. (2020) investigated multiple salt marsh locations along the US West Coast, including Gray's Harbor, Lower Columbia Estuary, Nehalem Estuary, Yaquina Estuary, Coos Estuary/South Slough NERR, and Humboldt Estuary. Their study reported a carbon stock of 190 ± 167 MgC_{org} ha^{-1}. Kauffman et al. also found a large variability range in carbon stock for California salt marshes on a larger scale than this study.This variability suggests that large variations may be a characteristic of carbon stock ecosystems, supporting the argument that the data from Batiquitos Lagoon are not necessarily a shortcoming but rather a reflection of reality. While specific values for each location were not provided, this mean carbon stock is lower than the values reported in the Tijuana River Estuary and the previously discussed California locations but greater than that observed in our study of Batiquitos Lagoon.

In summary, regional carbon stocks exhibit variability across different studies and locations. The Tijuana River Estuary and the California locations included in Weiss et al. 2001 and Ward et al. 2021 tend to exhibit higher carbon stocks when compared to Batiquitos Lagoon and the US West Coast locations studied by Kauffman et al. However, it is important to consider that variations in habitat types, species composition, and sampling dates may contribute to the observed differences in carbon stocks. Additionally, given the limited sample size and substantial variation in Batiquitos Lagoon's salt marshes, a larger dataset would provide a more precise and comparable range of carbon stocks. Further analysis of the Batiquitos Lagoon is necessary to establish a more comprehensive understanding in order to compare to regional carbon stocks.

Table 1: Summary of previously reported carbon stocks across salt marsh locations, ranging in scale from Batiquitos Lagoon to the US West Coast. Values are reported as mean ± SD, unless otherwise noted.

Location(s)	**Latitude(s)**	**Longitude(s)**	**Habitat Type/Species**	**Sample Date**	**Carbon Stock ($\mathrm{MgC_{org}\ ha^{-1}}$)**	**Study**
Batiquitos Lagoon	33.0926255	-1.173025123	Salt Marsh dominated by *Spartina foliosa*, *Salicornia pacifica*, and *Jaumea carnosa*	2023	75 (2.56-238.70)[1]	This study
Tijuana River Estuary	32.56948	-117.13034	Salt Marsh dominated by *Spartina foliosa*, *Salicornia virginica*, *Jaumea carnosa*, and *Batis maritima*	1998	239 ± 17.4[2]	Weiss et al. (2001)
California[3]	33.2807, 36.4915, 38.1017	-117.5317, -121.4506, -122.5446	Salt marsh dominated by *Sarcocornia pacifica*, *Distichlis spicata*, and *Jaumea carnosa*	2021	235 ± 17.7[4]	Ward et al. (2021)[5]
US West Coast[6]	46.8912, 46.3055, 45.7441, 44.5898, 43.2932, 40.7042,	-123.9872, -123.6951, -123.8572, -123.9470, -124.3235, -124. 2161	Variable	2020[7]	190 ± 16[8]	Kauffman et al. (2020)

1: Reported mean of C stock in Batiquitos Lagoon with ranges of C stock between 2.56 and 238.70 $\mathrm{MgC_{org}\ ha^{-1}}$.
2: All locations listed are from Ward et al. 2021.
3: Coordinates match the samples collected at sites in order of: Newport Bay, Elkhorn Slough, and Tomales Bay.
4: These C stocks were measured down to a depth of 20 cm, not until the bottom of the sediment column.
5:This study included non-salt marsh values (eelgrass and mudlfats). The stock values listed above are solely from the salt marsh sites studied by Ward et al. 2021.
6: Coordinates match the samples collected at sites in order of: Gray's Harbor, Lower Columbia Estuary, Nehalem Estuary, Yaquina Estuary, Coos Estuary/ South Slough NERR, Humboldt Estuary.
7: When sampling dates are not reported, the date of publication of data is given.

V. Recommendations

V.1 Managing Marsh Migration

The hydrological, ecological, and geomorphological processes of salt marsh ecosystems will be significantly affected by sea-level rise and storms, as highlighted in the study by Fagherazzi et al. (2019). These impacts will lead to the migration of salt marshes towards higher elevations, encroaching upon existing upland boundaries in some areas and in others coming up against hard limits to expansion created by coastal development. Additionally, seagrass will be forced to shift into marshlands due to the changing conditions. As sea levels continue to rise, the encroachment of salt marshes will predominantly occur in low-lying areas, resulting in a decline of upland habitat due to insufficient regeneration and increased salinity levels (Fagherazzi et al., 2019).

Given the ongoing consequences of sea-level rise and the critical need to conserve carbon stocks within salt marshes, the implementation of eelgrass bed restoration is recommended as an effective conservation strategy. Eelgrass beds offer a multitude of ecological benefits, such as carbon sequestration, sediment stabilization, and habitat provision for diverse species. Restoring eelgrass beds adjacent to salt marsh ecosystems can enhance the capacity for carbon storage and promote long-term habitat resilience against rising sea levels. As sea levels rise, eelgrass beds situated downslope from salt marshes may migrate upslope, colonizing former marsh areas, thereby maintaining a certain level of carbon sequestration and potentially safeguarding existing carbon stocks (see Figure 7). Recent efforts have been made to simulate sediment stabilization using vegetative root mats incorporating different seagrass species in Sweden and the United States (Temmink et al., 2020). These above- and below-ground structures provide positive support for seagrass growth by mitigating physical stressors during the growth process. In theory, the addition of such structures in specific salt marsh transition zones could enhance seagrass growth.

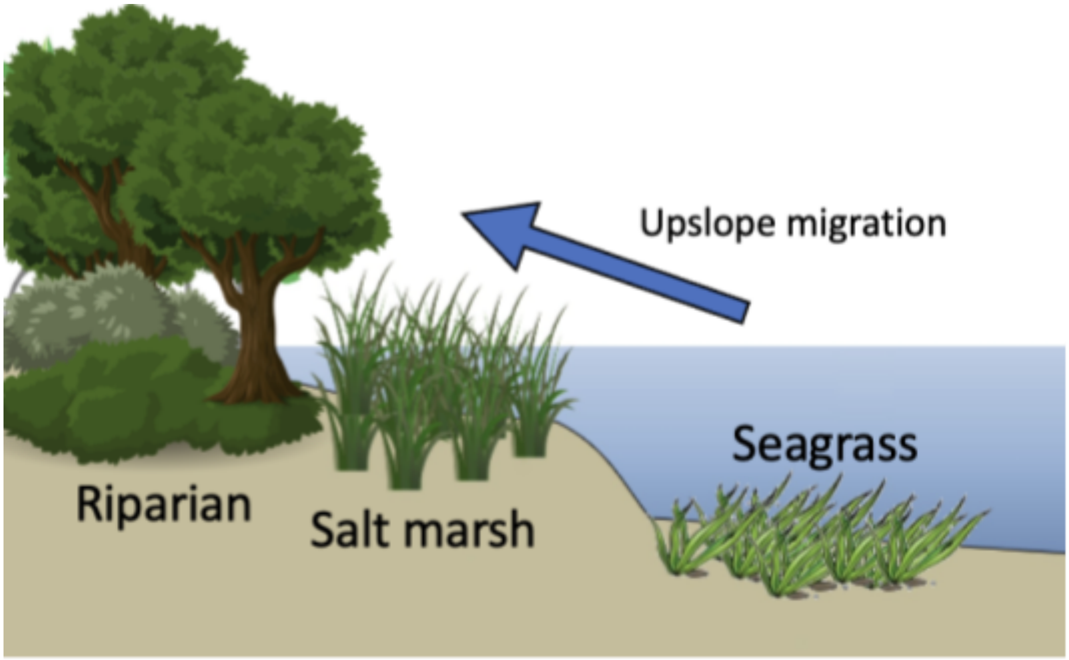


Figure 7: Visualization of seagrass migration into salt marsh zones with sea level rise.

When undertaking restoration efforts, it is imperative to prioritize the identification of suitable locations based on factors such as water depth, sediment composition, and hydrodynamic conditions. Collaborative partnerships among scientists, conservation organizations, and local communities play a vital role in ensuring the success of eelgrass restoration projects. Furthermore, it is crucial to employ rigorous scientific assessments, including regular surveys of carbon stocks, eelgrass biomass, and associated ecological parameters, to monitor the progress and effectiveness of restoration efforts.

V.2 Understanding Spatial Variability of Intertidal Zones

To ensure the effective conservation of carbon stocks in salt marshes and mitigate the consequences of sea-level rise, it is imperative to acquire a comprehensive understanding of the spatial variability of intertidal zones. These zones, influenced by tidal inundation, play a critical role in the sequestration and storage of carbon. Therefore, conducting spatial analyses and mapping exercises becomes crucial in identifying areas with significant carbon stocks and prioritizing conservation efforts accordingly. The integration of advanced remote sensing techniques, such as aerial imagery and LiDAR (Light Detection and Ranging), with field surveys and geospatial analysis tools can provide accurate and up-to-date maps of intertidal zones and their associated carbon stocks. By incorporating these technologies, decision-makers can make informed decisions regarding coastal land-use planning, restoration prioritization, and conservation strategies.

For instance, a study conducted by Byrd et al. (2018) successfully developed an aboveground dataset utilizing remote sensing techniques to measure biomass, species composition, and aboveground plant carbon content within six tidal marshes in the United States. This research exemplifies the potential of mapping techniques to measure carbon stocks at a larger scale. As seen in the findings of Batiqutos Lagoon, there is significant spatial variation in the amount of carbon stored per unit area that can only be observed through sediment core analysis, which measures carbon density and sediment depth. By utilizing the approach by Byrd et al. (2018) in conjunction with belowground coring measurements, comprehensive maps can be generated, enabling better decision-making processes and enhancing our ability to safeguard carbon stocks in salt marshes. Through a combination of measurement techniques and aboveground mapping, we can improve our ability to eventually model belowground variation based on easier-to-measure observations. By identifying areas with high carbon stocks, such mapping exercises facilitate strategic coastal land-use planning, restoration prioritization, and the formulation of effective conservation strategies. Therefore, the utilization of spatial analyses and mapping techniques serves as a crucial tool in the scientific pursuit of carbon stock conservation and the mitigation of sea-level rise impacts in salt marsh ecosystems.

V.3 Adaptive Management in the Face of Sea Level Rise

Given the ongoing impacts of sea-level rise, implementing adaptive management strategies is necessary to effectively conserve carbon stocks in salt marshes. Adaptive management entails continuous monitoring and assessment of ecological processes, allowing for flexible adjustment of management practices in response to changing environmental conditions. Establishing long-term monitoring programs to track changes in carbon stocks, vegetation dynamics, sedimentation rates, and other relevant parameters within salt marsh ecosystems is crucial. These monitoring efforts should be accompanied by regular data analysis and scientific evaluations to inform adaptive management decisions. By integrating knowledge gained from monitoring into management practices, stakeholders can proactively address challenges posed by sea-level rise and ensure the long-term preservation of carbon stocks. Moreover, adaptive management should prioritize the restoration and protection of coastal habitats acting as natural buffers against sea-level rise, such as salt marshes and eelgrass beds. These habitats provide critical carbon storage functions and contribute to shoreline stabilization. Enhancing and protecting these habitats through land-use planning, habitat restoration, and conservation measures will enhance the overall resilience of coastal ecosystems and their carbon storage capacity.

VI. Conclusion

This study highlights the importance of salt marshes for mitigating climate change by sequestering and storing carbon. These ecosystems provide numerous ecological services, including carbon sequestration, nutrient cycling, sediment stabilization, and habitat provision. However, coastal ecosystems, including salt marshes, are facing significant degradation, fragmentation, and loss due to urban development, resulting in the reduction of their carbon sequestration capacity. This emphasizes the urgent need for conservation and restoration efforts to protect and enhance the carbon storage potential of these ecosystems.

This research conducted in the salt marshes of Batiquitos Lagoon, in San Diego County, demonstrates the significance of local-scale assessments in understanding the variability of carbon stocks within specific coastal wetland ecosystems. The findings contribute to the scientific discourse surrounding blue carbon and provide valuable insights for land managers and policymakers in formulating effective conservation and restoration strategies. Furthermore, the study aligns with the goals outlined in Executive Order N-82-20 and the 30x30 Initiative, which emphasize the preservation of carbon stores and the evaluation of conservation outcomes. By implementing effective management and restoration measures, it is possible to enhance the conservation of natural landscapes and mitigate the adverse impacts of climate change in coastal regions.

VII. References

Alongi, D.M. Carbon Balance in Salt Marsh and Mangrove Ecosystems: A Global Synthesis. J. Mar. Sci. Eng. 2020, 8, 767. https://doi.org/10.3390/jmse810076

Barr, J. G., Engel, V., Smith, T. J., & Fuentes, J. D. (2013). Hurricane disturbance and recovery of energy balance, CO2 fluxes and canopy structure in a mangrove forest of the Florida Everglades. Agricultural and Forest Meteorology, 178, 127-140.

Batiquitos Lagoon Foundation. (n.d.). Salt Marsh. Retrieved from https://www.batiquitosfoundation.org/education/salt-marsh/

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J. R., Simard, M., & Windham-Myers, L. (2018). A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing, 139, 255–271. https://doi.org/10.1016/j.isprsjprs.2018.03.019

Callaway, J. C., Borgnis, E. L., Turner, R. E., & Milan, C. S. (2012). Carbon Sequestration and Sediment Accretion in San Francisco Bay Tidal Wetlands. Estuaries and Coasts, 35(5), 1163–1181. https://doi.org/10.1007/s12237-012-9508-9

CDFW. (2023). Batiquitos Lagoon Ecological Reserve. CDFW. https://wildlife.ca.gov/Lands/Places-to-Visit/Batiquitos-Lagoon-ER

C. D. Keeling, S. C. Piper, R. B. Bacastow, M. Wahlen, T. P. Whorf, M. Heimann, and H. A. Meijer, Atmospheric CO2 and 13CO2 exchange with the terrestrial biosphere and oceans from 1978 to 2000: observations and carbon cycle implications, pages 83-113, in "A History of Atmospheric CO2 and its effects on Plants, Animals, and Ecosystems", editors, Ehleringer, J.R., T. E. Cerling, M. D. Dearing, Springer Verlag, New York, 2005.

Chastain, S. G., Kohfeld, K. E., Pellatt, M. G., Olid, C., & Gailis, M. (2021). Quantification of Blue Carbon in Salt Marshes of the Pacific Coast of Canada [Preprint]. Biogeochemistry: Wetlands. https://doi.org/10.5194/bg-2021-157

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. Global biogeochemical cycles, 17(4), 1111.

CNRA. (2021). *30X30*. California Nature. https://www.californianature.ca.gov/pages/30x30

Costa, M. T., Salinas-de-León, P., & Aburto-Oropeza, O. (2019). Storage of blue carbon in isolated mangrove forests of the Galapagos' rocky coast. *Wetlands Ecology and Management*, *27*(4), 455–463. https://doi.org/10.1007/s11273-019-09653-8

Costa, M. T., Ezcurra, E., Ezcurra, P., Salinas‐de‐León, P., Turner, B., Kumagai, J., Leichter, J., & Aburto‐Oropeza, O. (2022). Sediment depth and accretion shape belowground mangrove carbon stocks across a range of climatic and geologic settings. Limnology and Oceanography, 67(S2). https://doi.org/10.1002/lno.12241

Costa, M., Ezcurra, E., Aburto-Oropeza, O., Maltz, M., Arogyaswamy, K., Botthoff, J., & Aronson, E. (2022). Baja California Sur mangrove deep peat microbial communities cycle nitrogen but do not affect old carbon pool. Marine Ecology Progress Series, 695, 15–31. https://doi.org/10.3354/meps14117

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change, 3(11), 961-968.

Fagherazzi, S., Anisfeld, S. C., Blum, L. K., Long, E. V., Feagin, R. A., Fernandes, A., Kearney, W. S., & Williams, K. (2019). Sea Level Rise and the Dynamics of the Marsh-Upland Boundary. Frontiers in Environmental Science, 7, 25. https://doi.org/10.3389/fenvs.2019.00025

Fourqurean, J. W., Kendrick, G. A., Collins, L. S., Chambers, R. M., Vanderklift, M. A., & Walker, D. I. (2012). Carbon, nitrogen, and phosphorus storage in seagrass meadows in relation to habitat health status and wave energy regimes. Biogeosciences, 9(10), 3993-4005.

Gallagher, J. B., Chew, S.-T., Madin, J., & Thorhaug, A. (2020). Valuing Carbon Stocks across a Tropical Lagoon after Accounting for Black and Inorganic Carbon: Bulk Density Proxies for Monitoring. Journal of Coastal Research, 36(5), 1029. https://doi.org/10.2112/JCOASTRES-D-19-00127.1

Holmquist, J. R., Windham-Myers, L., Bernal, B., Byrd, K. B., Crooks, S., Gonneea, M. E., Herold, N., Knox, S. H., Kroeger, K. D., McCombs, J., Megonigal, J. P., Lu, M., Morris, J. T., Sutton-Grier, A. E., Troxler, T. G., & Weller, D. E. (2018). Uncertainty in United States coastal wetland greenhouse gas inventorying. Environmental Research Letters, 13(11), 115005. https://doi.org/10.1088/1748-9326/aae157

Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M., & Orbach, M. (Eds.). (2017). Coastal Blue Carbon: Methods for Assessing Carbon Stocks and Emissions Factors in Mangroves, Tidal Salt Marshes, and Seagrasses. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature.

Johnson, A. B., & Brown, M. T. (2019). Influence of sediment depth on carbon storage in coastal wetland soils. Wetlands, 39(3), 623-631.

Kauffman, J. B., Giovanonni, L., Kelly, J., Dunstan, N., Borde, A., Diefenderfer, H., Cornu, C., Janousek, C., Apple, J., & Brophy, L. (2020). Total ecosystem carbon stocks at the marine‐terrestrial interface: Blue carbon of the Pacific Northwest Coast, United States. Global Change Biology, 26(10), 5679–5692. https://doi.org/10.1111/gcb.15248

Kauffman, J. B., A. F. Bernardino, T. O. Ferreira, N. W. Bolton, L. E. d. O. Gomes, and G. N. Nobrega. 2018. Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in northeastern Brazilian mangroves. Ecol. Evol. 8:5530–5540. doi:10.1002/ece3.4079

Keller, J. K., Anthony, T., Clark, D., Gabriel, K., Gamalath, D., Kabala, R., King, J., Medina, L., & Nguyen, M. (2015). Soil Organic Carbon and Nitrogen Storage in Two Southern California Salt Marshes: The Role of Pre-Restoration Vegetation. Bulletin, Southern California Academy of Sciences, 114(1), 22–32. https://doi.org/10.3160/0038-3872-114.1.22

Kelleway, J. J., Saintilan, N., Macreadie, P. I., Skilbeck, C. G., Zawadzki, A., & Ralph, P. J. (2017). Sediment and carbon deposition vary among vegetation assemblages in coastal salt marshes. Biogeosciences, 14(9), 2309-2320.

Macreadie, P. I., Costa, M. D. P., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. Nature Reviews Earth & Environment, 2(12), 826–839. https://doi.org/10.1038/s43017-021-00224-1

Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A., ... & Serrano, O. (2019). The future of Blue Carbon science. Nature Communications, 10(1), 1-11.

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO 2. Frontiers in Ecology and the Environment, 9(10), 552–560. https://doi.org/10.1890/110004

McMahon, K. W., Bok, M. J., Castorani, M. C., Geraldi, N. R., & Foster, M. S. (2023). Blue Carbon Stocks and Accumulation Rates in Salt Marshes Across Climate Zones and Sea-Level Rise Scenarios. Frontiers in Marine Science, 10, 1011.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Miller, L. C., Smeaton, C., Yang, H., & Austin, W. E. N. (2023). Carbon accumulation and storage across contrasting saltmarshes of Scotland. Estuarine, Coastal and Shelf Science, 282, 108223. https://doi.org/10.1016/j.ecss.2023.108223

Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., & Cahoon, D. R. (2002). Responses of coastal wetlands to rising sea level. Ecology, 83 (10), 2869-2877.

Morris, J. T., Barber, D. C., Callaway, J. C., Chambers, R., Hagen, S. C., Hopkinson, C. S., Johnson, B. J., Megonigal, P., Neubauer, S. C., Troxler, T., & Wigand, C. (2016). Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earth's Future, 4(4), 110–121. https://doi.org/10.1002/2015EF000334

Nellemann, C. et al. Blue Carbon — The Role of Healthy Oceans in Binding Carbon (UN Environment, 2009).

Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of Blue Carbon and emerging perspectives. Biology Letters, 15(3), 20180781. https://doi.org/10.1098/rsbl.2018.0781

Lovelock, C. E., Adame, M. F., Bennion, V., Hayes, M., O'Mara, J., Reef, R., ... & Baldock, J. (2017). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature, 526(7574), 559-563.

Poppe, K. L., & Rybczyk, J. M. (2021). Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PLOS ONE, 16(9), e0257244. https://doi.org/10.1371/journal.pone.0257244

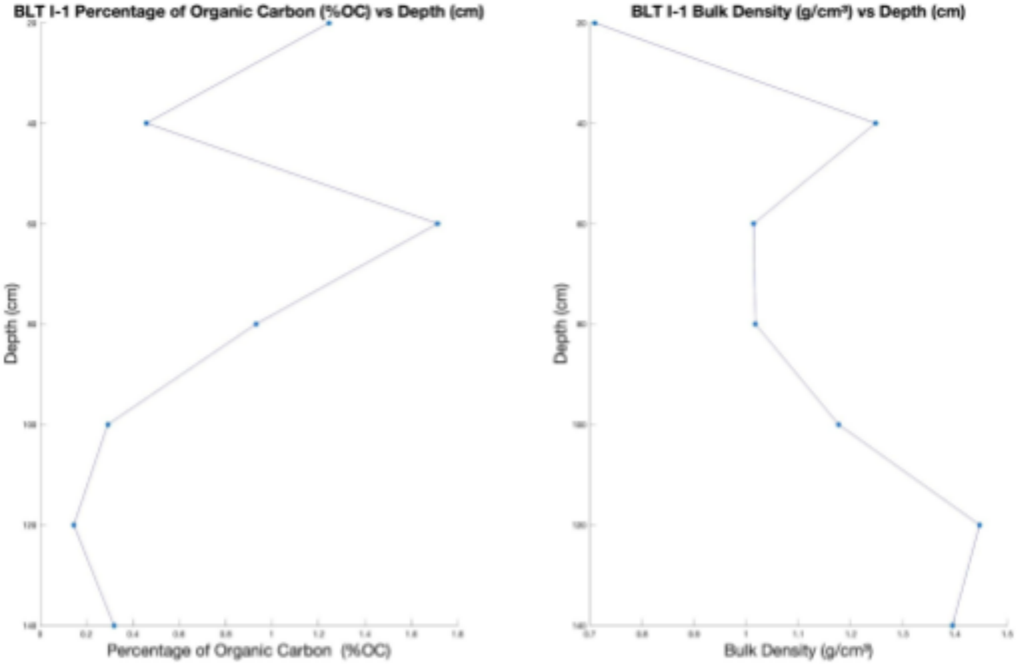
State Coastal Conservancy. (1989). Proceedings of the San Diego Bay Planning Workshop, San Diego, CA, May 26, 1989. California State Coastal Conservancy.

Smith, C. D., et al. (2018). Carbon stocks and accumulation rates in a southern California coastal lagoon. Estuaries and Coasts, 41(2), 460-472.

Temmink, R. J. M., Christianen, M. J. A., Fivash, G. S., Angelini, C., Boström, C., Didderen, K., Engel, S. M., Esteban, N., Gaeckle, J. L., Gagnon, K., Govers, L. L., Infantes, E., Van Katwijk, M. M., Kipson, S., Lamers, L. P. M., Lengkeek, W., Silliman, B. R., Van Tussenbroek, B. I., Unsworth, R. K. F., … Van Der Heide, T. (2020). Mimicry of emergent traits amplifies coastal restoration success. Nature Communications, 11(1), 3668. https://doi.org/10.1038/s41467-020-17438-4

Ward, M. A., Hill, T. M., Souza, C., Filipczyk, T., Ricart, A. M., Merolla, S., Capece, L. R., O'Donnell, B. C., Elsmore, K., Oechel, W. C., & Beheshti, K. M. (2021). Blue carbon stocks and exchanges along the California coast. Biogeosciences, 18(16), 4717–4732. https://doi.org/10.5194/bg-18-4717-2021

Appendix 1: The following appendix shows the variation with depth in %OC and bulk density for each core separately. The left panel shows %OC and the right panel bulk density.



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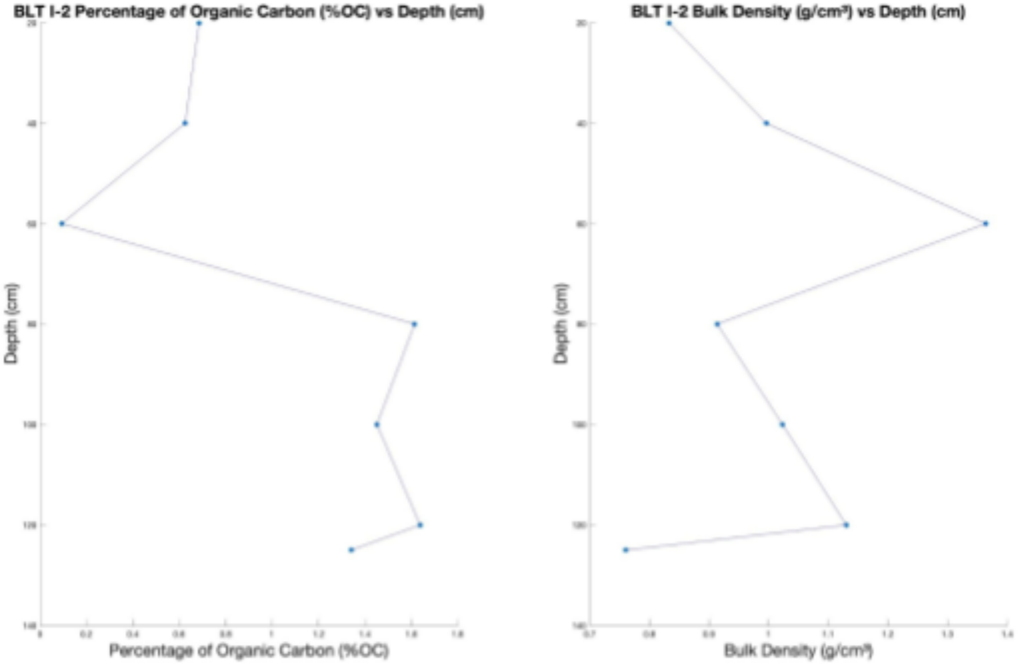

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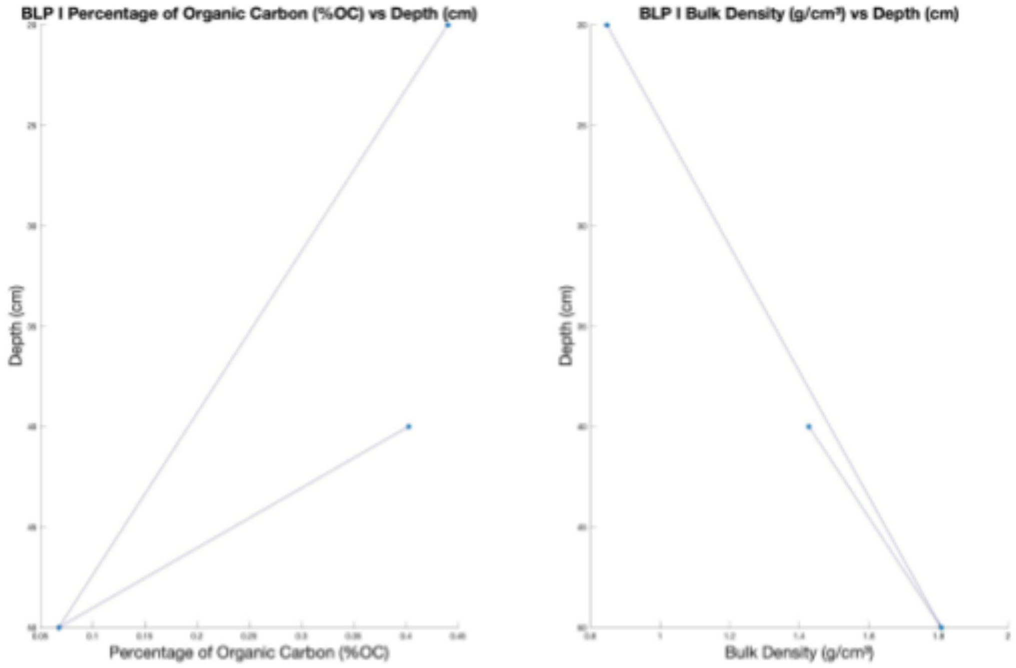
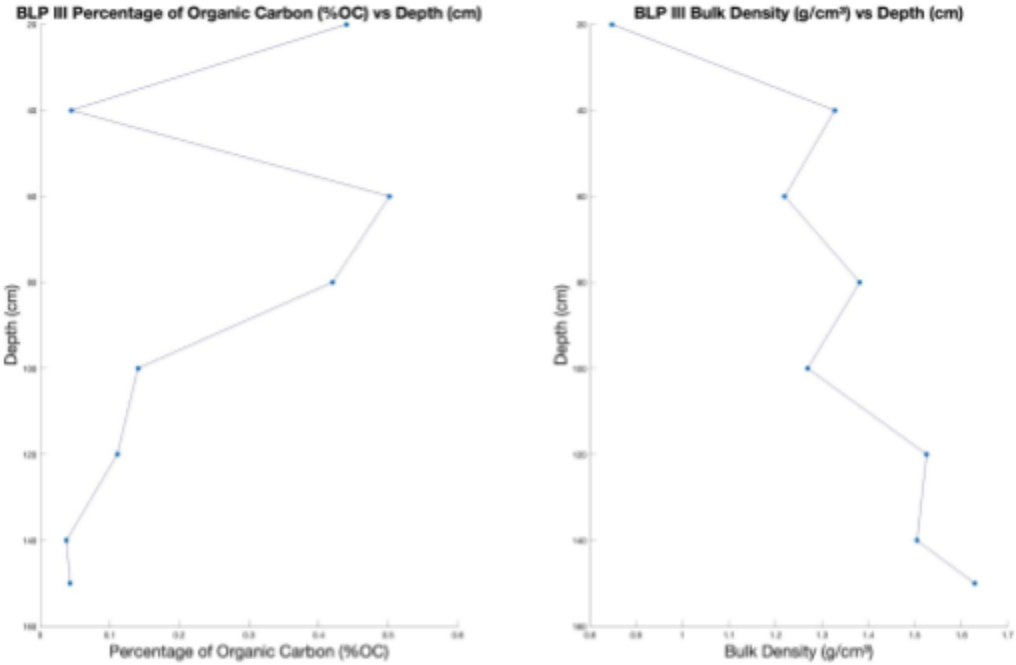
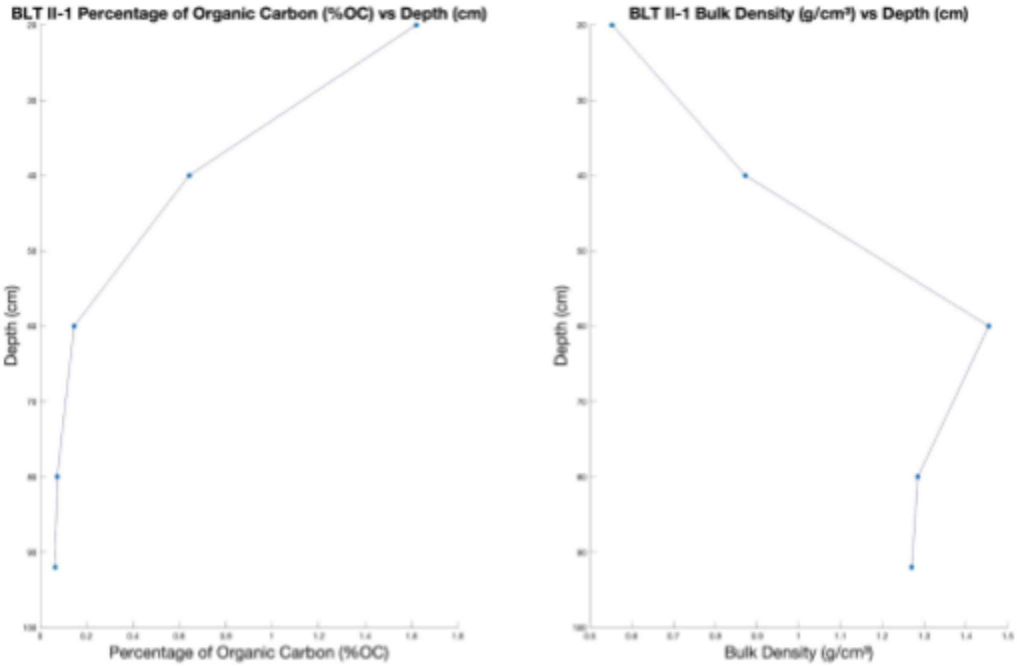

BLP I Percentage of Organic Carbon (%OC) vs Depth (cm)
Depth (cm)
Percentage of Organic Carbon (%OC)
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
20
25
30
35
40
45
50
BLP I Bulk Density (g/cm³) vs Depth (cm)
Depth (cm)
Bulk Density (g/cm³)
0.8
1
1.2
1.4
1.6
1.8
2

BLP 1

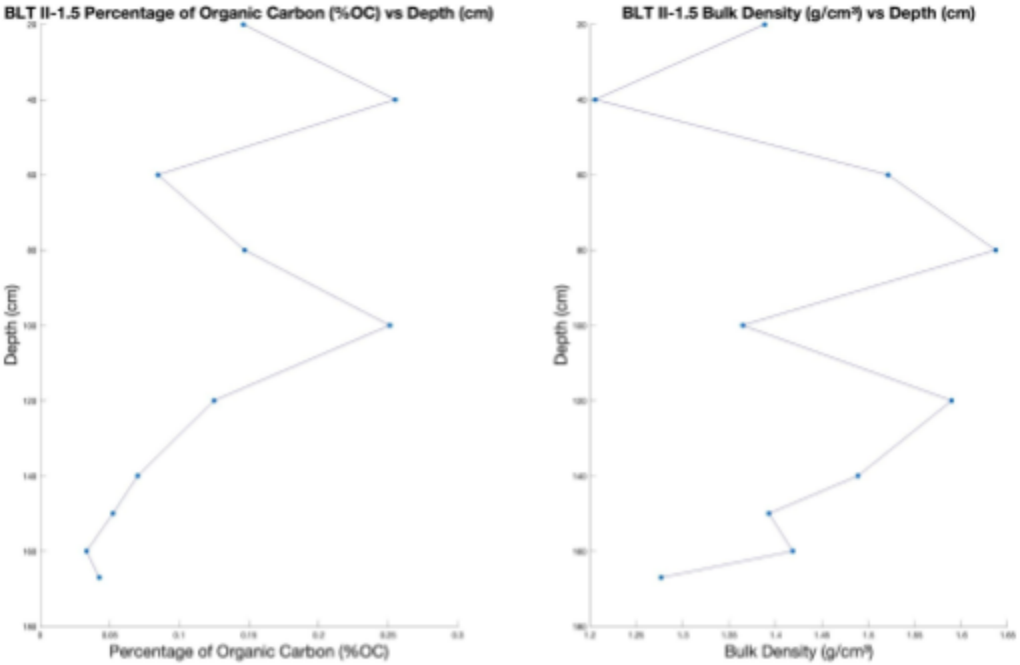

BLP III Percentage of Organic Carbon (%OC) vs Depth (cm)
Depth (cm)
Percentage of Organic Carbon (%OC)
0
0.1
0.2
0.3
0.4
0.5
0.6
20
40
60
80
100
120
140
160
BLP III Bulk Density (g/cm³) vs Depth (cm)
Depth (cm)
Bulk Density (g/cm³)
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7

BLP III


BLT II-1 Percentage of Organic Carbon (%OC) vs Depth (cm)

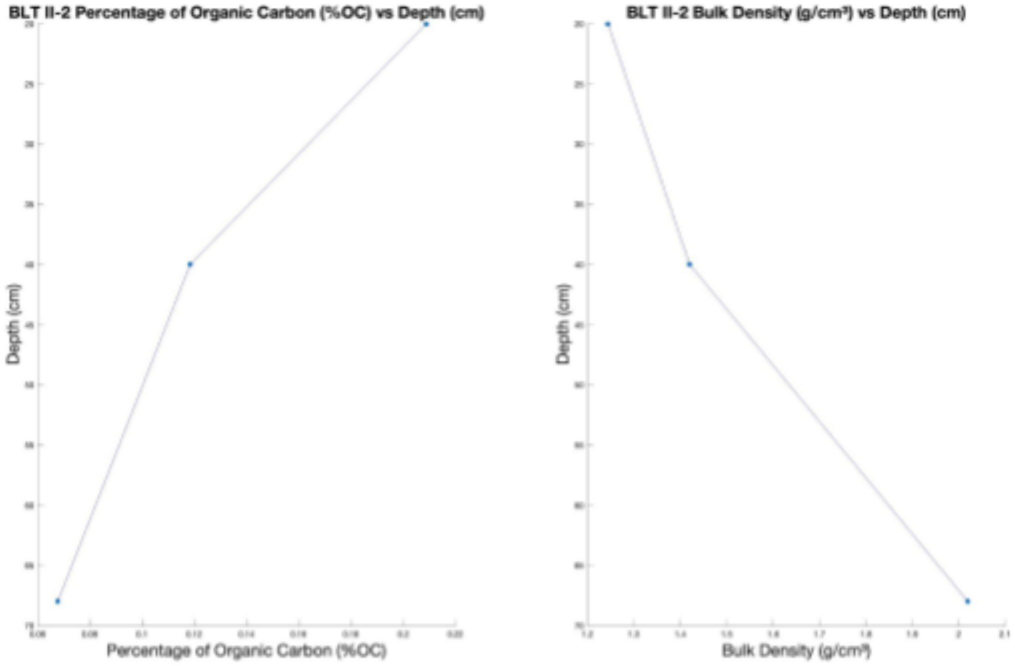
BLT II-1 Bulk Density (g/cm³) vs Depth (cm)

BLT II-1


BLT II-1.5 Percentage of Organic Carbon (%OC) vs Depth (cm)

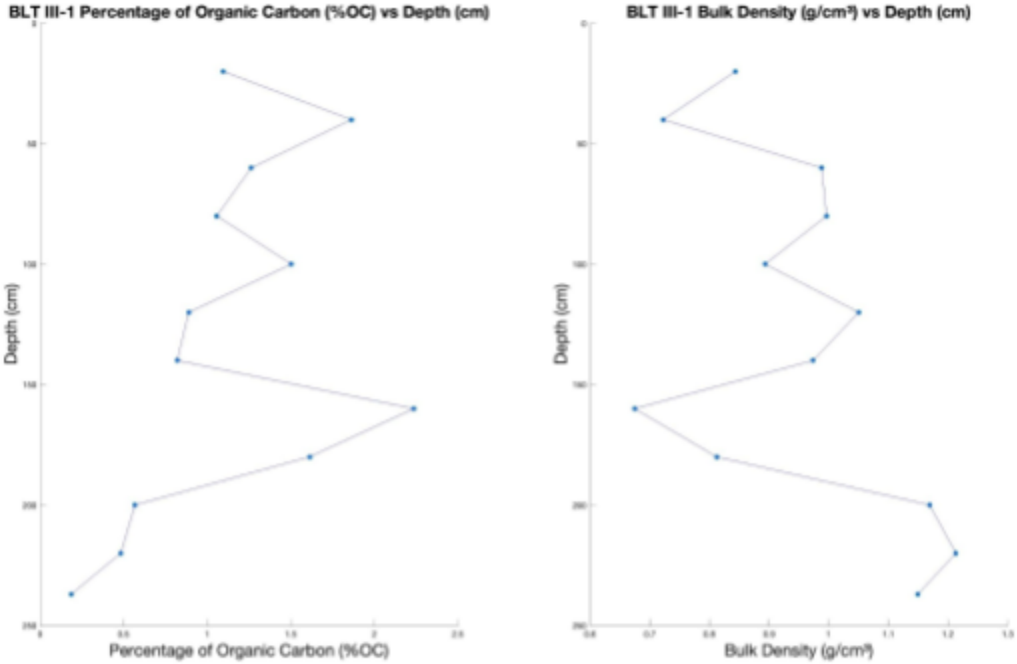
BLT II-1.5 Bulk Density (g/cm³) vs Depth (cm)

BLT II-1.5


BLT II-2 Percentage of Organic Carbon (%OC) vs Depth (cm)

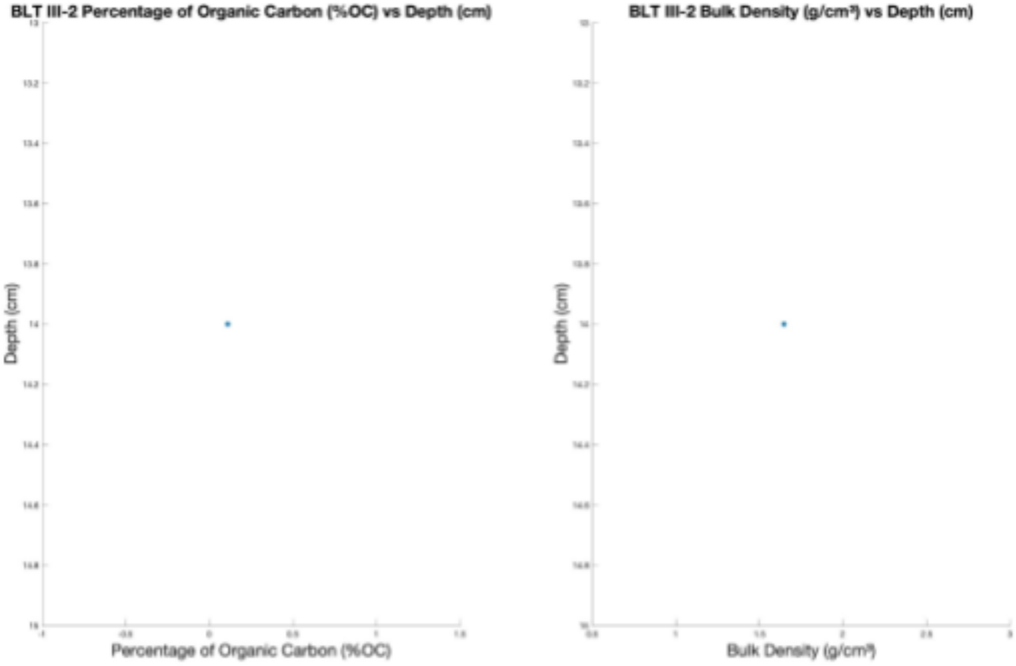
BLT II-2 Bulk Density (g/cm³) vs Depth (cm)

BLT II-2

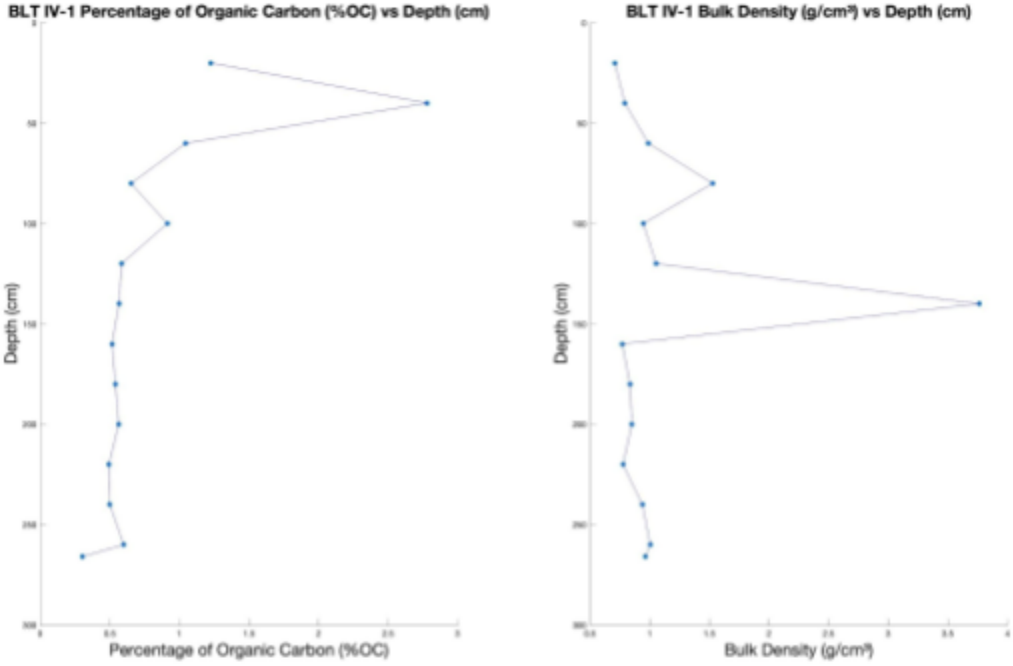

BLT III-1 Percentage of Organic Carbon (%OC) vs Depth (cm)

BLT III-1 Bulk Density (g/cm³) vs Depth (cm)

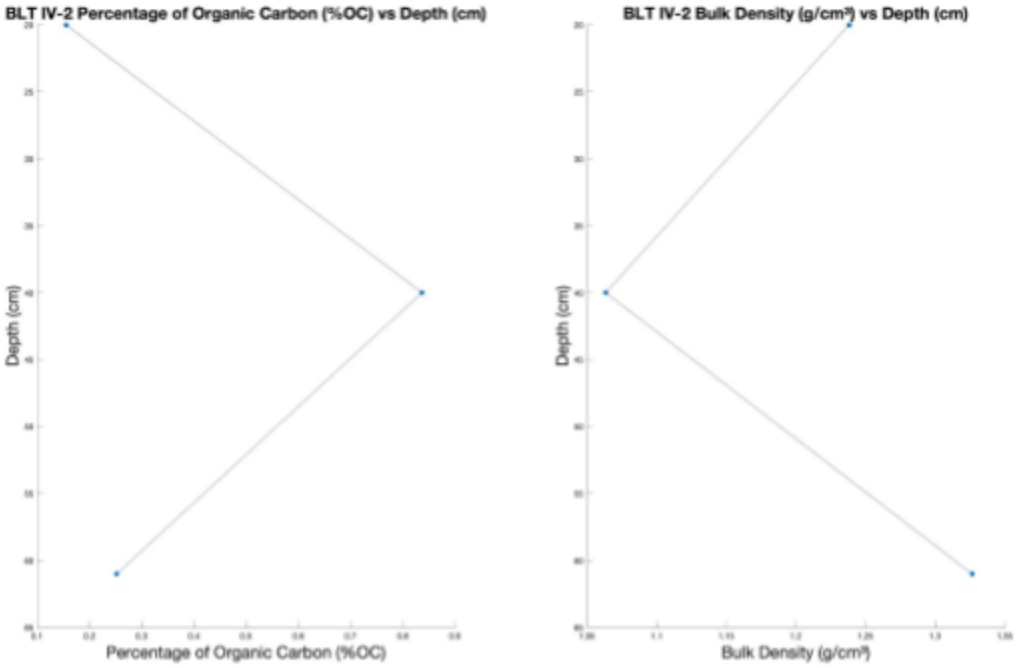
BLT III-1



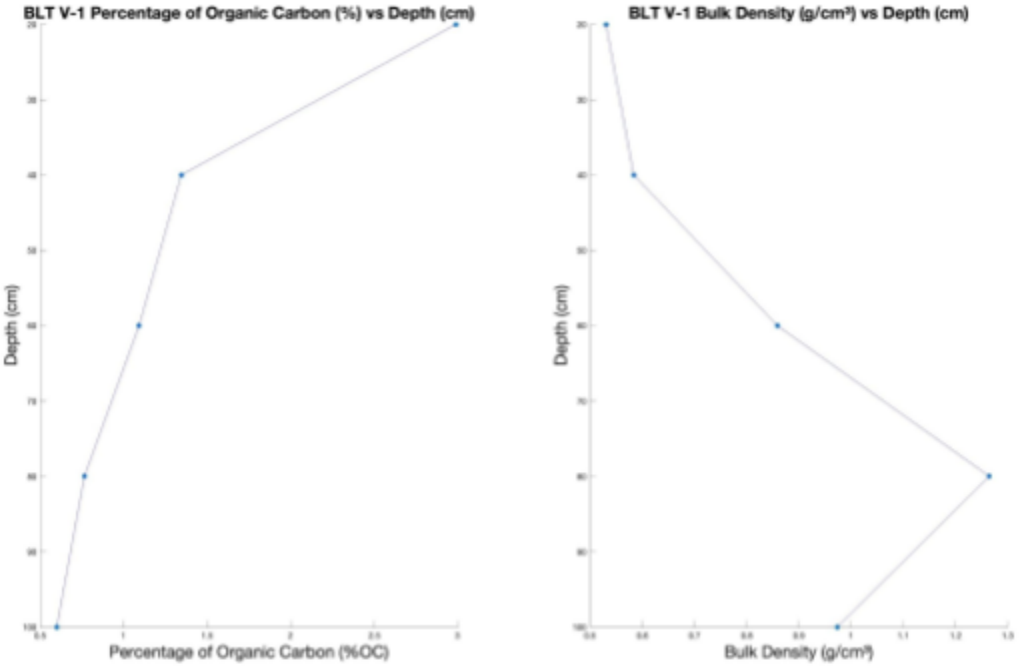
BLT III-2



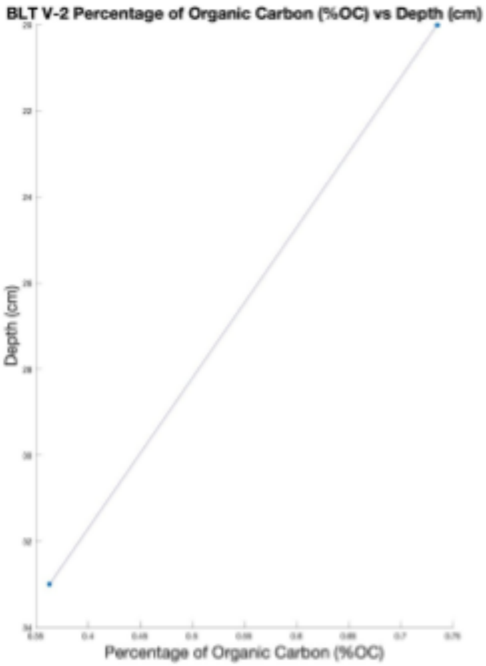
BLT IV-1

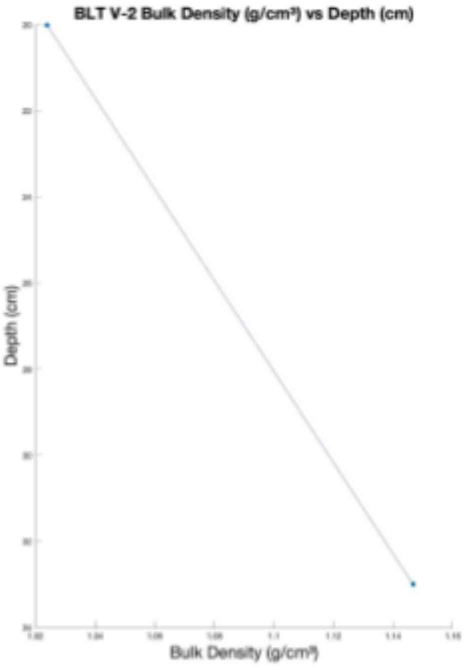


BLT IV-2



BLT V-1


BLT V-2 Percentage of Organic Carbon (%OC) vs Depth (cm)
Depth (cm)
20
22
24
26
28
30
32
34
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
Percentage of Organic Carbon (%OC)


BLT V-2 Bulk Density (g/cm³) vs Depth (cm)
Depth (cm)
20
22
24
26
28
30
32
34
1.02
1.04
1.06
1.08
1.1
1.12
1.14
1.16
Bulk Density (g/cm³)

BLT V-2