Title
Soil Organic Matter of Natural and Restored Coastal Wetland Soils in Southern California

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Publication Date
2012

UNIVERSITY OF CALIFORNIA

Los Angeles

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A thesis submitted in partial satisfaction
of the requirements for the degree Master of Science in
Environmental Health Sciences

by

Barbara K Elgin

2012

ABSTRACT OF THE THESIS

Soil Organic Matter of Natural and Restored Coastal Wetland Soils in Southern California

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Master of Science in Environmental Health Sciences
University of California, Los Angeles, 2012
Professor Richard F. Ambrose, Chair

Tidal wetlands are able to sequester large amounts of organic carbon due to their high primary productivity, slow decomposition and sediment accretion. We measured soil organic matter in high resolution soil cores from three *Salicornia*-dominated coastal salt marshes in a Mediterranean-type climate. Our data for all three natural wetlands show high organic matter in the top 10 cm, averaging 14.8 ± 0.9%, with the top 2 cm of soil having the highest organic matter content at all sites. High organic matter in the surface soil decreased and then stabilized with depth. Restored habitats within each of these three wetlands were also sampled. Average percent organic matter in the top 10 cm across restored sites was 8.6 ± 1.1 %. Percent organic matter was negatively correlated with bulk density and grain size across all samples. We estimated soil organic carbon using our soil organic matter data and compared natural and restored sites. Soil organic carbon densities were statistically different between natural and restored sampling sites in all but one wetland

The thesis of Barbara K Elgin is approved.

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2012

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Acknowledgements

I would like to thank Brendan Sullivan, Jordan Rosencranz, Randy Reyes, Brady Elgin and Samantha Macks for donating their time and hard work to this project. I would also like to thank the staff of the Environmental Division at Naval Base Ventura County (NVBC) including Martin Ruane. I greatly appreciate Brian Collins, Jeff Crooks and Chris Peregrin for their help at Tijuana River National Estuarine Research Reserve. Thanks also to Andrew Brooks at UCSB for his help at Carpinteria Salt Marsh Reserve. I would also like to thank Carla Navarro Woods from Upper Newport Bay Ecological Reserve. This project would not have been possible without the generous support of Sea Grant.

Special thanks to Monique Myers for her help from start to finish on this project. Thanks to Jason Keller of Chapman University for his attention to detail and constructive comments. A big thanks to Dr. Suffet and Dr. Fong for finding the time and energy to review this work and provide constructive comments.

I could not have asked for a more dedicated advisor. I would like to extend my deepest gratitude to Dr. Ambrose for his enduring support, time and patience.

I would also like to thank my family, Barbara Fleming, Lee Elgin, Ross Garrett, Kristin Garrett, Miles Garrett and Brady Elgin, for their love and support throughout my education. A big thanks to Josh Mosberg for his patience, humor and support.

Introduction

A growing concern about the unprecedented atmospheric concentration of greenhouse gases, particularly carbon dioxide (CO_2), has catalyzed a discussion regarding possible methods of remediation. There are two approaches to mitigate increasing atmospheric CO_2: reducing emissions, and removing CO_2 from the atmosphere, for example by enhancing CO_2 sinks. Enhancing CO_2 sinks may be accomplished artificially through industrial-scale geoenginering capture and storage systems, or naturally by preserving and restoring ecosystems with natural high carbon storage capacity. Some of the earliest and most thorough research has been conducted on changes in agricultural practices, the slowing of deforestation and the promotion of reforestation and afforestation as natural mitigation methods (Winjum et al. 1992) . However, the amount of C stored in soils, 1576 Pg C, is estimated to be three times that stored in aboveground biomass and double that in the atmosphere (Eswaran et al. 1993). Insufficient attention has been given to the massive storage of C in soils and the important role soils play in carbon sequestration.

Forty percent of global soil carbon stores are estimated to be contained in wetland soil, despite their making up only about 5% of the Earth's surface (Post 1982; Eswaran et al. 1993; Mitsch and Gosselink 2000). In order to understand why wetlands are superior at C sequestration, it is necessary to understand the factors which enhance gaseous CO_2 becoming sequestered in the soil. The primary mechanism of sequestration occurs when plants remove CO_2 from the atmosphere, allowing them to create carbohydrates and grow. When plants die, their tissues return to the soil and some of the CO_2 they removed from the atmosphere becomes soil organic matter (Brevik 2004; Lal et al. 1998). Annually, an average of 210 ± 20 g C m^{-2} is accumulated in coastal salt marsh soils (Chmura 2003). Several factors are thought to enhance the process of carbon sequestration in salt marsh soils, including high primary productivity (Donato et al. 2011), slow decomposition rates (Craft 2007) and high soil accretion rates (Chmura 2003).

Coastal wetlands are widely recognized as one of the most productive natural ecosystems, annually producing up to 80 metric tons of plant biomass per hectare(Mitsch and Gosselink 2000). Anaerobic conditions slow decomposition and wetland vegetation traps sediments during tidal and freshwater flow, adding organic matter to the surface and preventing soil erosion (Hussein et al. 2004). This accretion of new sediment allows the soil to continue to maintain the capacity to hold carbon without becoming saturated. Coastal salt marshes sequester 10 times more carbon per unit area than other wetland ecosystems (Bridgham et al. 2006).

Although wetlands have exceptional C sequestration rates, concern has arisen that methane gas emissions may counteract the positive influence of high C sequestration. Methane is 22 times more potent as a greenhouse gas (GHG) than CO_2 in absorbing long-wave radiation. Wetlands are generally known to have high methane emissions (Zhuang et al. 2009) . However, methane flux emissions in estuarine wetlands are low (1.3 g /m^2-yr) compared to freshwater marshes (7.6 g/m^2-yr) (Bridgham et al. 2006). Poffenbarger et al. (2011) demonstrated that CH_4 flux from high salinity tidal marshes was minimal, presumably because of competitive dominance by sulfate reducing bacteria in these ecosystems. Research conducted in southern California has confirmed that net flux of methane in coastal salt marshes is negligible (Jason Keller, Chapman University, unpublished data).

Little is known about soil organic carbon (SOC) in California coastal wetlands. Southern California has a mediterranean-type climate characterized by hot, dry summers and temperate wet winters. The hydrologic regime this climate pattern facilitates plays an important role in vegetation patterns, distribution and soil carbon cycle dynamics. *Salicornia virginica* is a small shrub which dominates many Southern California salt marshes. It provides important habitat for local and migratory birds, including the endangered Belding's Savannah sparrow*, Passerculus sandwichensis beldingi* (Boyer et al. 2001). *Salicornia* is also highly relied upon in Southern California restorations because of its fast growth, resilient nature and valuable role as habitat. Despite this, few studies have investigated soil organic carbon dynamics in *Salicornia* dominated wetlands.

In addition, characterization of SOC content of coastal salt marshes in Southern California has generally been limited to surface soils (<10cm deep). Patrick and Delaune (1990), among others, showed that SOC varies with depth in south San Francicso Bay marshes. In order to estimate the C storage potential of southern California salt marshes, it is important to understand how SOC varies with depth.

Interest in restoration and wetland creation is growing due to the possibility of gaining carbon credits for carbon sequestered in tidal wetland soil. But, the extent to which a restored wetland would be able to carry out the carbon sequestering ability of a natural ecosystem must be quantified. Many studies have already investigated this (Lindau and Hossner 1981; Craft et al. 1991; Langis et al. 1991; Moy and Levin 1991; Craft et al. 1999; Zedler and Callaway 1999; Havens et al. 1995; Edwards and Proffitt 2003). However, these studies have generally been restricted to very shallow depths (<10 cm) or have focused on *Spartina*-dominated wetlands, and so have limited relevance to the main type of wetland restored in California.

The goals of this study were to (1) quantify the soil organic matter of southern California *Salicornia*-dominated coastal salt marshes and (2) compare the soil organic carbon content of restored and natural wetlands. High resolution soil profiles were analyzed in natural and restored habitats of three wetlands in southern California, allowing us to quantify soil organic matter and assess differences in soil carbon content. We looked at the effect of bulk density, grain size, soil moisture content and vegetation type on soil carbon distribution in three *Salicornia*-dominated wetlands characteristic of a mediterranean-type climate. This allowed us to characterize and quantify C in southern California coastal salt marsh soils and evaluate how restoration changes the C sequestration pattern of coastal wetland ecosystems. These data are an important contribution to the characterization of coastal salt marshes in mediterranean-type climates, but they also have broader implications for future GHG mitigation, wetland restoration and C markets.

Methods

Site Description

Estuaries in Southern California are shaped by a semi-arid mediterranean-type climate characterized by episodic rainfall throughout the winter months and drought during the summer and fall. Two types of sites were sampled at each of three estuaries: habitats within the estuary that had been restored and those that remained relatively natural, with minimal anthropogenic disturbance. Vegetation at all sampling sites were dominated by *Salicornia virginica* with *Jaumea, Frankenia, Distichlis, Monanthochloe, Suaeda,* and *Batis* interspersed.

Mugu Lagoon (34°06‘N, 119°05‘W) is a 1073-ha coastal estuary in Ventura County at the base of the Callegaus Creek watershed. It is situated within Naval Base Ventura County (NBVC) at Point Mugu, bordering the Pacific Ocean. Sixty four percent of the lagoon is salt marsh, 20% is open water, 11% mudflats and tidal creeks and 5% salt pans (Onuf 1987). Three natural cores were taken in Mugu’s Central Basin and an additional three natural cores were collected in the Eastern Arm, areas that have remain relatively unmodified (Figure 1 A). Six cores were taken from salt marsh restoration sites, two from the project at L Avenue and four from two different phases in the Ponds Restoration area. L Avenue 1 is a 1.42 hectare parcel of land and was restored in 1997 by removing fill to reintroduce tidal influencee. The Ponds restoration project utilized a mixture of sewage sludge and clay as substrate fill. The Ponds Pilot Restoration was completed in 1998, and the Ponds Phase 2 Restoration was completed in 2003 (Ambrose and Vance 2006).

Tijuana Estuary (32°34’N, 117°07’W) is located in Imperial Beach, just north of the Mexican border. The 200-ha salt marsh is dominated by marine conditions during the dry season and by intermittent freshwater stream flows during the winter and early spring (Zedler and Onuf 1984). Heavy rains and large flooding events bring in massive quantities of suspended sediment from the degraded and highly polluted watershed that runs through Tijuana, Mexico. Raw sewage was discharged directly into Tijuana Estuary in the early 1900s and although those practices have ceased, modern-day sewage spills in Mexico still affect water quality in the estuary. Dredging, gravel extraction, dumping, filling and the use of off-road vehicles has greatly degraded the landscape and led to extensive erosion (Zedler et al. 1992). Six cores were taken from natural salt marsh in the northern arm of the Estuary and three cores from the restored Friendship Marsh (two from the west end and one from the east side) (Figure 1 B). The Friendship Marsh was designed as a replicated restoration experiment. Nearly 2 m of fill was removed and tidal circulation was restored in February 2000 (Wallace et al. 2005).

Carpinteria Salt Marsh (34°24’N, 119°31’W) is a 93-ha estuary 12 km east of Santa Barbara. The outlet to the ocean occurs at the southern border of Carpinteria Salt Marsh and freshwater enters the marsh along six drainage channels along the northern border (Page et al.

1995). Six cores were taken from the natural marsh, five from Basin 3 and one from Basin 2 (Figure 1 C). Our three restoration samples were taken at the Ash Avenue restoration site, which was originally tidally connected to the rest of the marsh but was filled-in in the 1950s. A restoration project to restore the Ash Avenue parcel was completed in October 1997 (Huspeni and Lafferty 2004). The fill was removed and the soil was graded down to an elevation that restored tidal influence.

Field sampling

Samples were collected from June to September 2010. Each wetland was visually divided into thirds from the region closest to the inlet (lowest elevation) to the farthest upland. Within each third, cores were collected at a haphazardly identified site without evidence of surface disturbance at least 20 meters from a tidal creek, if possible, to avoid bioturbation and sediment mixing. One to two cores were taken from each third of the marsh and the coordinates of each location were recorded. This method of core site selection was implemented in both the natural and restored sections of each marsh where logistically feasible.

Plant matter was trimmed to the soil surface at the sampling location. The species of vegetation present and the presence of a surface algal mat or standing water were recorded. A 15.24 cm diameter, 60 cm long corer with a serrated razor bottom was pushed into the soil with a twisting motion to minimize compaction (Hargis and Twilley, 1994). We attempted to remove 50 cm length cores, but were unable to obtain this length for every sample due to the presence of rocks or dense sediment. Short cores were discarded and a replacement core taken nearby, but it still was not always possible to obtain a full-length core. Cores ranged in length from 32 to 50 cm. The height from the ground to the top of the corer was measured on the inside and outside of the corer to assess compaction. If the difference between the inside and outside was greater than 2 cm, the core was considered compacted and a new core was taken. A hole was dug in the soil to the side of the corer to ease the removal of the corer. The presence and depth of any standing water in the core hole was recorded. The soil core was extruded from the corer by laying the core in a wooden trough and pushing against the plunger at the top of the corer with a length of PVC.

The sediment core was marked in 2 cm sections beginning from the surface side. Using an 8-inch knife, the core was sliced along each 2 cm marking and placed in a pre-labeled quart size plastic bag. Occasionally, garden sheers were required to cut through tough roots connecting adjacent core sections. The presence of rocks and cracks in each 2 cm section was recorded.

Once the core was extracted, the sample hole was back filled and the disturbed vegetation replaced. The soil samples were placed in a cooler on ice for no longer than 8 hours, then stored at 5° C until processed.

Soil Processing

Every 2 cm soil sample was weighed wet, dried at 50-70° C to a constant weight and reweighed to determine water content. Loss on ignition (LOI) was determined by calculating mass lost following 10 hours in a muffle furnace at 400° C. LOI provides an estimate of organic matter (OM) in the soil, which we converted to soil organic carbon (SOC). Several studies have evaluated the relationship between LOI and SOC. The relationship determined by Craft (1991b) for tidal salt marsh soils has been used extensively (e.g., Connor et al. 2001, Chmura et al. 2003, Morgan et al. 2009, Elsey-Quirk et al. 2011), and was applied here. This relationship is:

(1) $\%\text{ organic C} = (0.40)\,\text{LOI} + (0.0025)\,\text{LOI}^2$

Grain size was determined for each 2 cm sample of each core using the hydrometer method (Bouyoucos 1962). Approximately 50 g of dry sample was gently crushed and non-soil debris greater than 3mm was removed and weighed. Each sample was placed in a 600 mL beaker with 5 g of Sodium Metaphosphate and 300 mL deionized (DI) water. The beakers were placed on a shaker table at 125 rpm for a minimum of 24 hours. The contents of each beaker were transferred to a 1L cylinder and filled to the 1L mark with DI water. Parafilm was placed over the top of each cylinder to allow for thorough mixing by inversion. Once placed back on the table, the hydrometer was gently inserted into the cylinder and read after 40 seconds and then again 2 hours later. Water temperature in the cylinders was recorded prior to inversion and after 2 hours.

The following equations were used to calculate grain size using the hydrometer method where TAHR = Temperature Adjusted Hydrometer Reading.

(2) Corrected hydrometer reading=hydrometer reading –hydrometer reading of the blank
(3) TAHR=[(temperature-20degrees)*0.35]+corrected reading
(4) % Silt and Clay =TAHR at 40 seconds*Volume (L)/grams of dry soil
(5) % Sand=100-%silt and clay
(6) %Clay= (TAHR at 2 hrs *volume (L)/grams of dry soil
(7) %Silt= % silt and clay - % clay

Data Analysis

In order to attain a high resolution analysis by depth, bulk density of each 2 cm section per core was determined by dividing the dry mass in grams (g) by the volume of the soil section in cm^3. We used a running average for mass based on three sections to minimize the effect of slicing inconsistencies in the field. Average soil organic carbon (SOC) density by depth was found by multiplying the bulk density by the percent soil organic carbon from equation (1) at each depth. SOC and organic matter had a log-normal distribution and were log-transformed for analyses.

To determine whether there was a statistically significance difference among soil organic carbon density between wetlands, by depth and between natural and restored treatments, Systat 13 was used to perform a three-way Analysis of Variance (ANOVA) at the 5% level (alpha=0.05). One-way ANOVAs were performed to investigate significant interactions in the three-way ANOVA.

Pearson correlations were performed to analyze the relationship between bulk density and organic matter and percent sand and organic matter.

Results

Soil organic carbon (SOC) density varied significantly with depth (Table 1). The SOC density was high at the surface and decreased to a relatively stable concentration at about 12 cm (Figure 2). The mean SOC density for natural cores (≤ 32 cm in depth) was 0.020 ± 0.001 g C cm^{-3} (Mean ± SE)at Mugu Lagoon, 0.023 ± 0.001 g C cm^{-3} at Tijuana Estuary and 0.022 ± 0.001 at Carpinteria Salt Marsh. Mean SOC density in restored cores (≤ 32 cm in depth) was 0.013 ±0.001 at Mugu Lagoon, 0.012±0.001 g C cm^{-3} at Tijuana Estuary and 0.021±0.002 g C cm^{-3} at Carpinteria Salt Marsh.

The SOC density profiles for natural and restored cores were similar with depth, but there was a significant interaction between wetland and treatment; i.e., the effect of treatment (whether the wetland was natural or restored) on percent organic carbon density varied across wetlands. The SOC density profiles for natural cores at Tijuana Estuary and Mugu Lagoon are clearly higher than the profiles for the restored cores at those sites. However, at Carpinteria Salt Marsh, there is little difference between natural and restored cores (Figure 2). The average SOC density (0.021±0.002 g C cm^{-3}) for the Carpinteria restored cores is similar to the SOC density value for the natural cores for all three wetlands. A one-way ANOVA conducted to evaluate the wetland by treatment effect for each wetland showed a statistically significant difference in percent organic matter between treatments for Mugu Lagoon and Tijuana Estuary ($p<0.001$) but not Carpinteria Salt Marsh ($p=0.151$).

A graph of percent organic matter by depth for restored habitats at all three wetlands shows that the restored Carpinteria Salt Marsh had the highest percent organic matter with depth (Figure 3A) and that the profiles of cores from Tijuana Estuary and Mugu Lagoon were similar. Because the two restoration projects at Mugu Lagoon were constructed in substantially different ways, we plotted the percent organic matter of each restoration in Figure 3B. The sewage pond restoration, which was constructed from a mixture of clay and sewage sludge, had higher organic matter with depth than the L Avenue restoration, which was constructed by excavating fill.

In the top 10 cm, Mugu Lagoon had an average percent organic matter of 11.64 ± 1.14% for natural sites and 6.34 ± 1.23% for restored sites (Table 2). Percent organic matter decreased steadily from the surface and then dropped off asymptotically at about 10 cm in restored sites (Figure 4). Between 10 and 30 cm deep, average percent organic matter was 5.33 ±0.36 % at natural sites and 1.65 ±0.17% at restored sites. The natural sites showed a gradual decline of organic matter with depth. Bulk density for both natural and restored sites followed a similar trend, beginning low and increasing with depth. The natural sites continued increasing with depth, with a maximum density of approximately 1.5 g cm^{-3}, while the restored sites reached this density at about 22 cm and had no further increase in bulk density. Proportion silt and clay steadily declined from the surface for Mugu Lagoon natural sites, with a similar pattern for the restored sites.

In the top 10 cm, Tijuana Estuary had an average percent organic matter of 17.45 ± 1.67% for natural sites and 8.90 ± 1.24% for restored sites (Table 2). Percent organic matter decreased steadily from the surface and then dropped steeply off after 14 cm in the restored cores (Figure 5). Between 10 and 30 cm deep, average percent organic matter was 7.79 ±0.51% at natural sites and 2.27 ± 0.23% at restored sites. Natural cores show a steep decline to about 12 cm at which point organic matter becomes relatively stable. As with Mugu, bulk density was low at the surface for both natural and restored cores and generally increased with depth, although there was greater variance than at Mugu Lagoon. The restored and natural cores had different silt and clay profiles, although both were around 70% silt and clay near the surface. In the natural marsh cores, the proportion of silt and clay increased in the deeper portions of the core, whereas the proportion of silt and clay decreased in the deeper portions of the restored marsh cores.

In the top 10 cm, Carpinteria Salt Marsh had an average percent organic matter of 15.28 ± 1.60% for natural sites and 12.63 ± 3.09% for restored sites (Table 2). Percent organic matter was high at the surface and decreased with depth for both natural and restored sites. Between 10 and 30 cm, average percent organic matter was 6.10 ± 0.53% at natural sites and 4.19 ± 0.50% at restored sites. Bulk density was lowest at the surface and increased with depth for both treatments. In both natural and restored wetlands, bulk density decreased at approximately 30 cm; however, it increased again at 44 cm for natural sites. Grain size did not vary substantially with depth for either treatment (Figure 6).

Across all wetlands, percent organic matter decreased with increasing bulk density. A Pearson's correlation of log organic matter and bulk density across all sites gave a coefficient of -0.861. The general trend in all cores was low bulk density and high organic matter content near the surface and increased bulk density and decreased organic matter with depth. Dry bulk density ranged from 0.245 g cm^{-3} to 1.98 g $cm^{-3}$with a mean of 0.800±.021 g cm^{-3} for natural cores and 1.164±0.028 g cm^{-3} for restored cores.

A Pearson's correlation of log organic matter and proportion sand across all sites gave a correlation of -0.538, showing an association, although not as strong as for bulk density. Sediment characteristics varied greatly within cores, ranging in some cores from dense silt and clay to sand within just a few centimeters. Percent sand ranged from 4.0% to 96.7%. Average percent sand was 43.2±1.4% for natural cores and 52.2±2.0% for restored cores.

Discussion

Natural wetlands

Our data for all three natural wetlands show high organic matter in the top 10 cm, averaging 14.8 ±0.9 %, with the top 2 cm of soil having the highest organic matter content at all sites. High organic matter in the surface soil decreased and then stabilized with depth. Organic matter between 10 and 30 cm averaged 6.4 ±0.3 % across sites. This loss of organic matter with depth may be due to oxidized microzones created around plant roots, allowing degradation by aerobic bacteria in the root zone. Some loss of organic matter is also expected as a result of soil aging and normal decomposition by a diverse community of invertebrates, microbes and physical processes (Brix 1987);

Brevik and Homberg's (2004) research investigating a Southern California coastal wetland is the most thorough study of SOC at depth in a Southern California coastal wetland ecosystem. Their data uncovered salt marsh soils over 5000 years old and approximately 4.5 m deep. They found an average SOC of 2.82 ± 2.57% for salt marsh soil. Our SOC data (averaged over the length of our cores) align with their findings, with 2.6±0.2 % at Mugu Lagoon, 4.2 ±0.3% at Tijuana Estuary and 3.4±0.3% at Carpinteria Salt Marsh.

One caveat in our soil organic carbon estimate is that we have not verified Craft's (1991) relationship for salt marsh soils for our own samples. This relationship (equation 1) has been used as a good estimate of soil organic carbon from soil organic matter (Connor et al. 2001; Chmura 2003, Morgan et al. 2009, Elsey-Quirk et al. 2011) but should be verified in order to provide a more accurate estimate of SOC for our samples. By comparing our calculated estimates of soil organic carbon to those run through a C analyzer, we would be able to accept this relationship if the error was less than 10%. If it were higher, we could develop our own relationship as Callaway (2012) has done. Craft's relationship was developed using samples from tidal saline wetlands on the East coast. Although it has been used for coastal wetlands in other regions, physical properties such as high soil carbonates can affect the accuracy of the relationship. Therefore we have presented our measured percent organic matter values along with our soil organic carbon estimates.

Previous studies in southern California have concentrated their efforts on shallow soil cores. While these data are relevant when assessing biological correlations with SOC, it is important to look at SOC at greater depths to understand the historical pattern and predict sequestration potential. Our data show that organic matter accumulates at the surface of the soil, decreases and becomes relatively uniform at a depth of 14 to 20 cm (organic matter of approximately 5.5%). It is clear that the SOC in the top 0 to 10 cm is not representative of the soil at depth (Table 2). Over time, high organic content in surface soils decline and stabilize, likely as a result of increased microbial processes and aging, as soils are buried. The lower, more stable soil carbon at greater depths makes up the majority of the C stored in wetland soils. Quantification of wetland C sequestration potential utilizing the SOC density of the top 2 cm only may reflect the amount of C initially sequestered, but neglects the natural loss of soil C over time and thus would greatly overestimate long-term C sequestration.

We found a strong relationship between percent SOC and bulk density in our data (Pearson's correlation coefficient of -0.70). We further examined this relationship using data from several studies that characterized tidal wetland soil characteristics (Craft 1999; Elsey-Quirk et al. 2011, Callaway et al. 1997, Callaway et al. 2012). Soil organic carbon is highly related to bulk density. A linear regression of percent SOC versus bulk density, across these studies, had an R^2 value of 0.89 (Figure 7).

Carbon sequestration is the product of SOC density and the rate of soil vertical accretion (Chmura et al. 2003). Radioisotope dating of our samples was beyond the scope of this thesis, but could provide a direct estimate of accretion rates (Callaway et al. 2012). However, utilizing previous estimates of vertical accretion rates and the SOC density data reported here, we calculated carbon sequestration estimates at our study sties. Intra-wetland variation of accretion can be substantial with regard to sampling location; however the use of these long-term accretion rates provided us with a reasonable general estimate.

Chan et al. (2012) found the average accretion rate over a 14 year period at Mugu Lagoon and Carpinteria Salt Marsh to be 1.9 ± 0.2 mm yr^{-1} and 6.7 ± 0.6 mm yr^{-1}, respectively. Weis et al. (2001) estimated accretion at Tijuana Estuary to be 7.0-12.0 mm yr^{-1} over the past 35 years.

Using the average accretion value, calculated for each wetland from these studies, we estimated sequestration rates using our SOC density data. Following Chmura et al.'s (2003) methodology for comparability, we used the SOC density of the top 2 cm in our calculations. We found Mugu Lagoon had an average sequestration rate of 83.6 ± 14.4 g C m^{-2} yr^{-1}, Tijuana Estuary 268.0 ± 155.0 g C m^{-2} yr^{-1} and Carpinteria Salt Marsh 399.0 ± 36.0 g C m^{-2} yr^{-1}.

The actual amount of C sequestered over time if below ground decomposition is factored in (Callaway et al. 1996; Mudd et al. 2009) is far less than this. If the SOC density of natural cores is averaged between 20 and 30 cm, the region in our SOC density profiles where SOC values become stable, the average SOC value drops to approximately 102.5 g C cm^{-3} yr^{-1}. This is the value that should be used when considering future C sequestration of a natural wetland, not the inflated value calculated from the SOC density in the top 2 cm, much of which is quickly degraded. The appropriate calculation for C credit for a wetland saved from destruction would be the total amount of existing C in the soil (taking soil depth into account), plus future sequestration utilizing the SOC density at a stable depth.

Restored Wetlands

The profile by depth for organic matter at restored sites is different than that of natural cores. The top 2 cm of our restored sites are indistinguishable from the profiles of our natural cores in regard to organic matter. Yet at depth, SOC in restored cores falls asymptotically to a relatively stable concentration that is substantially less than that of their natural counterparts, except at Carpinteria Salt Marsh. Carpinteria Salt Marsh is the only restored wetland with SOC higher than 1% between 10 an 30 cm (Table 2).

Many studies have found lower soil organic content in restored or created tidal salt marshes than in natural wetlands (Lindau and Hossner 1981; Craft et al. 1988; Craft et al. 1991b; Langis et al. 1991; Moy & Levin 1991; Craft et al. 1999; Zedler & Callaway 1999; Havens et al. 1995; Edwards & Proffitt 2003). The top few centimeters of a restored wetland may reach organic matter equivalency relatively quickly due to high primary productivity of salt marsh vegetation and the influx of suspended sediments, but C equivalency at depth takes hundreds of years (Craft et al. 2002; Hossler and Bouchard 2010) or may never match reference sites (Zedler and Callaway 1999). It is clear that quantification of C sequestration in restored or created wetlands cannot be estimated by data from natural wetlands nor by monitoring for the standard 5 year period.

The SOC profile of a restored wetland depends on the age, soil characteristics and type of restoration. We examined the history of the restoration at each restored tidal wetland sampled, in order to better understand our SOC profiles.

The two restoration habitats we took cores from at Mugu Lagoon (L Avenue and the Ponds restoration) were quite different. L Avenue was graded to restore tidal influence (in 1997) without any additional fill, whereas sewage sludge and the underlying clay were mixed together and then graded down to create the Ponds restoration (in 1998 and 2003). Both habitats have been sequestering carbon and have a similar organic matter profile, dropping off at a depth of 4 cm (Figure 3 B), but the Ponds restoration clearly had more organic content in the underlying soil than L avenue. This difference in organic content is also driven by the fact that the average sand content for the top 30 cm at L Avenue is 65%, far greater than the 39% at the Ponds restoration.

Two meters of sediment were removed in the construction of the Friendship marsh in Tijuana Estuary, yet our data show that the grading did not reach the historical wetland soil. We can see that approximately the top 10 cm of the restored habitat soil at Tijuana has been accumulating SOC but it is still not equivalent to that of the natural cores at depth (Figure 5). Grain size is also increasingly coarser with depth at restored habitats in Tijuana Estuary.

The similarity in soil organic content between natural and restored habitats at Carpinteria Salt Marsh was likely due to the depth of the grading during restoration. Analyses of the soil characteristics at Ash Avenue showed that natural and restored cores were similar in grain size and carbon content. We believe that the grading of sediment that occurred in the creation of the Ash Avenue restoration site at Carpinteria Salt Marsh was such that it reached historical wetland soil.

These data raise an interesting dilemma regarding restoration methodology. From a carbon market perspective, the goal is maximization of the amount of new carbon sequestered annually in the soil. If the baseline restoration conditions have virtually no organic carbon, then every measurable amount of new soil carbon sequestered could be used as an offset. From a restoration perspective, reaching structural and functional equivalency might be attained more rapidly if restorations use historical wetland soil or higher organic soil as fill. However, additional carbon sequestration capacity would be limited by accretion rate if the soil was already highly organic.

In order to calculate the C sequestered for a restoration, all of the C sequestered in the soil must be taken into account. The depth of the restoration must be assessed and future C sequestration calculations should be added to this value baseline value.

We do not have site specific accretion data for our restored sampling locations. However, accretion is often higher in restored wetlands, depending on the restoration type, driving increased C sequestration (Craft 2001; Howe et al. 2009). This increased accretion continues until restoration sites reach an elevation equivalent to that of natural sites. The average asymptotic value of SOC density across all restored sites (depth 20-30 cm) was 0.012 ±0.001 g C cm^{-3}, slightly less than that found at natural sites at depth (0.017 ± 0.001 g C cm^{-3}).

As the demands for C markets grow, we recommend a policy strategy that will prioritize the conservation of natural coastal salt marshes. Further, C sequestration calculations should be based on SOC stored at a depth greater than 10 cm for natural wetlands, rather than the highly organic root zone which is not representative of the C stored at depth. Total SOC content in restored and created coastal wetlands may not match that of natural marshes, but C sequestration rates in restored systems remain high.

Our study has substantially broadened the knowledge of soil organic carbon in *Salicornia*-dominated tidal wetlands and has elucidated the differences in natural versus restored habitats. Soil organic carbon is highly critical ecologically and its quantification is becoming increasingly important as C offsets, mitigation and trading markets develop. Given the ability of coastal salt marshes to sequester high amounts of C in their soils and prevent its degradation and oxidation when intact, preservation of existing wetlands is vital. The destruction and drainage of natural coastal wetlands release thousands of year’s worth of stored GHGs. While restoration and wetland creation are undoubtedly important, they cannot replace the amount of C stored in natural wetlands in a reasonable time. Thus conservation of natural coastal salt marshes should always be prioritized.

Tables

Table 1: The results of a three-way ANOVA for soil organic carbon density with treatment (restored or natural), wetland (Mugu Lagoon, Carpinteria Salt Marsh, Tijuana Estuary) and Depth (≤32 cm) as factors. Significant p-values (≤.05) in bold.

ANOVA	Type III SS	df	Mean Squares	F-Ratio	p-value
Treatment	0.005	1	0.005	53.122	**0.000**
Wetland	0.002	2	0.001	9.651	**0.000**
Depth	0.021	16	0.001	13.583	**0.000**
Treatment*Wetland	0.002	2	0.001	9.359	**0.000**
Treatment*Depth	0.002	16	0.000	1.328	0.176
Wetland*Depth	0.002	32	0.000	0.641	0.937
Treatment*Wetland*Depth	0.001	32	0.000	0.475	0.994
Error	0.038	396	0.000		

Table 2: A. Data from Natural sites divided into two depth categories. Notice the decrease in percent soil organic carbon and the increase in bulk density with depth. B. Data from Restored Sites divided into two depth categories. Notice the higher bulk density values as well as the lower percent organic matter and soil organic carbon values particularly with depth.

A.

Location	**Core Depth (cm)**	**% Organic Matter (OM)**	**% Soil Organic Carbon (SOC)**	**Bulk Density(g/cm^3)**	**% Sand**
Mugu Lagoon, CA	0-10	11.6 ±1.14	5.09±0.55	0.628±0.022	33.0±2.6
	10-30	5.33±0.36	2.09±0.15	0.887±0.029	39.7±3.7
Tijuana Estuary, CA	0-10	17.45±1.67	7.95±0.89	0.479±.024	42.5±3.3
	10-30	7.97±0.51	3.25±0.21	0.785±0.060	46.4±2.4
Carpinteria Salt Marsh, CA	0-10	15.28±1.60	6.88±0.80	0.504±0.042	45.6±3.3
	10-30	6.10±0.53	2.52±0.22	0.966±0.044	43.1±3.7

B.

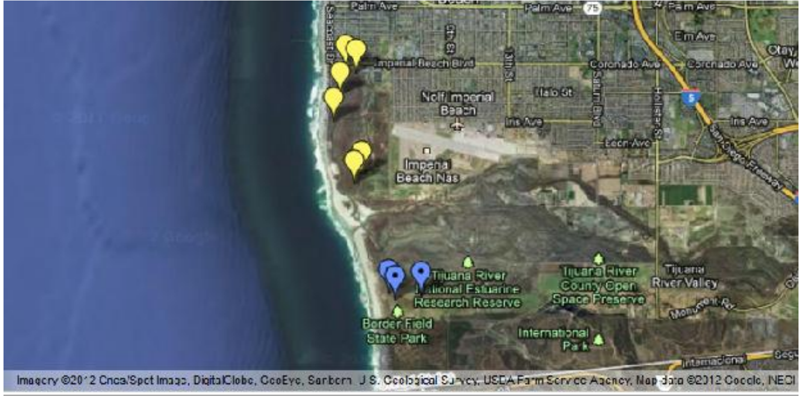
Location	**Core Depth (cm)**	**% Organic Matter (OM)**	**% Soil Organic Carbon (SOC)**	**Bulk Density(g/cm^3)**	**% Sand**
Mugu Lagoon, CA	0-10	6.34±1.23	2.75±0.56	0.974±0.060	51.4±4.6
	10-30	1.65±0.17	0.66±0.07	1.470±0.025	59.7±4.1
Tijuana Estuary, CA	0-10	8.90±1.24	3.81±0.58	0.496±0.032	26.3±2.1
	10-30	2.27±0.23	0.92±0.09	1.228±0.049	44.2±3.5
Carpinteria Salt Marsh, CA	0-10	12.63±3.09	5.79±1.50	0.826±0.121	60.7±3.9
	10-30	4.19±0.49	1.80±0.21	1.182±0.056	52.7±5.6

Figures

A) Mugu Lagoon

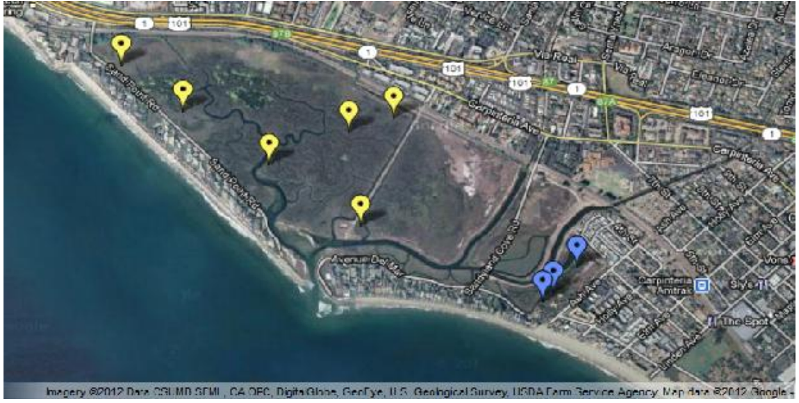
Imagery ©2012 Data CSUMB SFML, CA OPC, Data USGS, DigitalGlobe, GeoEye, U.S. Geological Survey, USDA Farm Service Agency, Map data ©2012 Google

B) Tijuana Estuary



Imagery ©2012 Cnes/Spot Image, DigitalGlobe, GeoEye, Sanborn, U.S. Geological Survey, USDA Farm Service Agency, Map data ©2012 Google, INEGI

C) Carpinteria Salt Marsh



Imagery ©2012 Data CSUMB SFML, CA OPC, DigitalGlobe, GeoEye, U.S. Geological Survey, USDA Farm Service Agency, Map data ©2012 Google

Figure 1: Maps showing our sampling locations. Yellow balloons indicated natural habitats and blue balloons indicate restored habitats. A) Mugu Lagoon B) Tijuana Estuary C) Carpinteria Salt Marsh

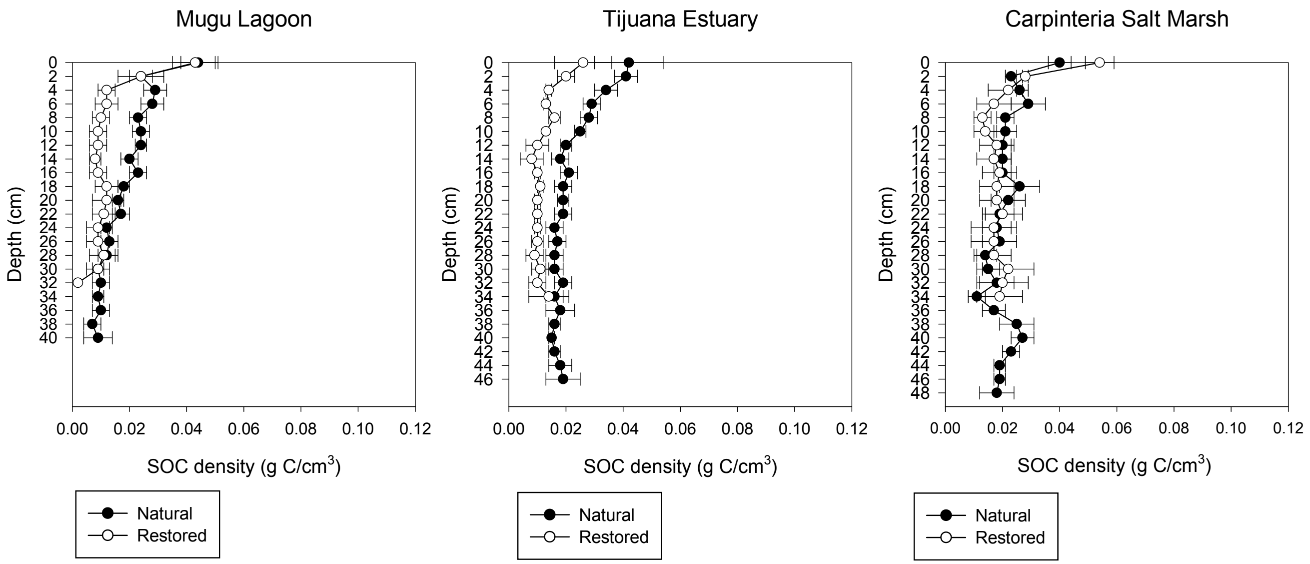


Figure 2: Mean soil organic carbon densities by depth in Mugu Lagoon, Tijuana Estuary and Carpinteria Salt Marsh. Horizontal bars indicate the standard error at each depth. Hollow circles are cores taken at natural sites and filled circles are cores taken at restored sites.

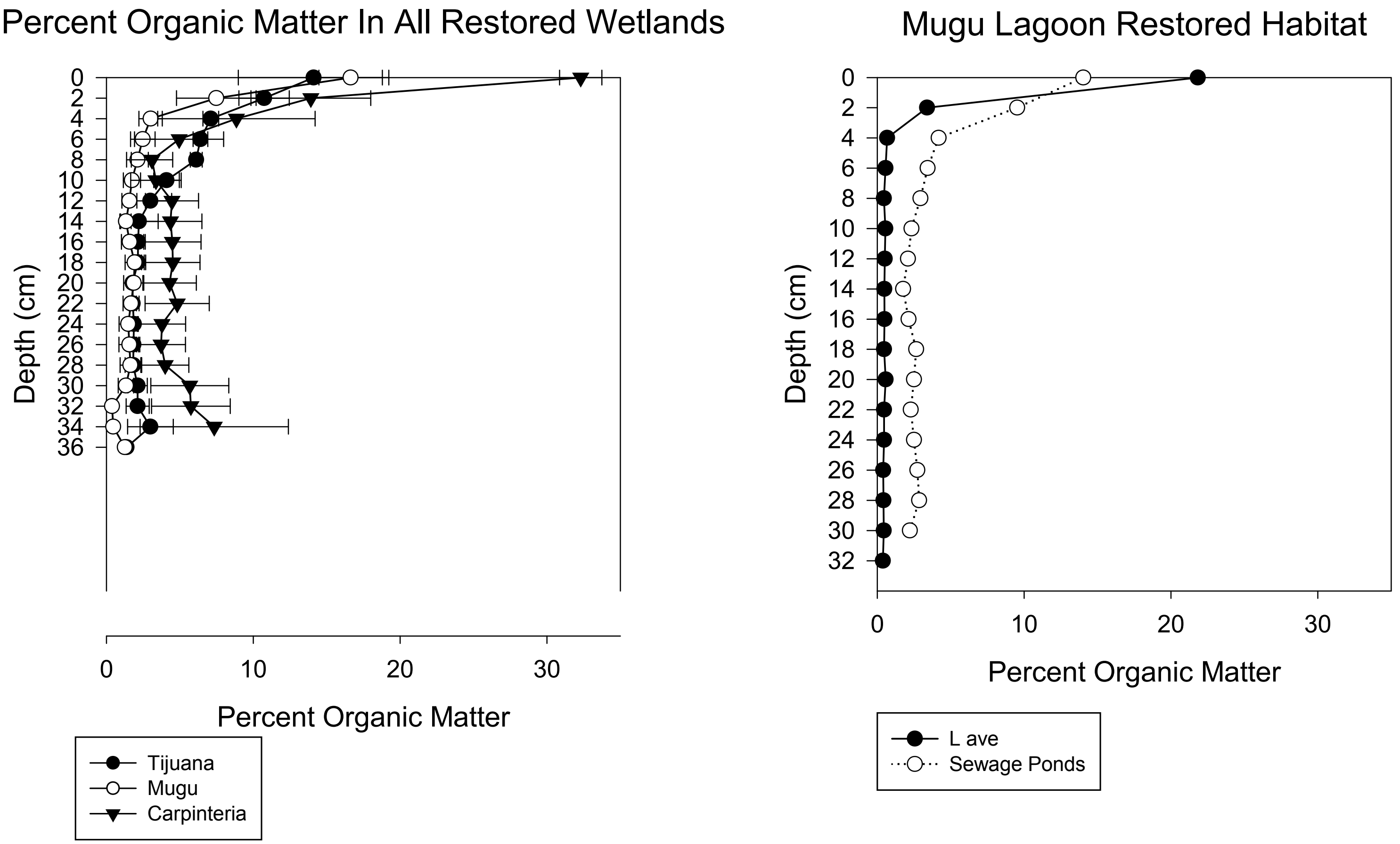


Figure 3: (Left)A. Combined organic matter data by depth for each restored wetland. Notice that Carpinteria Salt Marsh has higher organic matter with depth (Right) B. Percent organic matter in the two distinct restored habitats sampled at Mugu Lagoon. The Sewage ponds have higher organic matter with depth probably due to the restoration type.

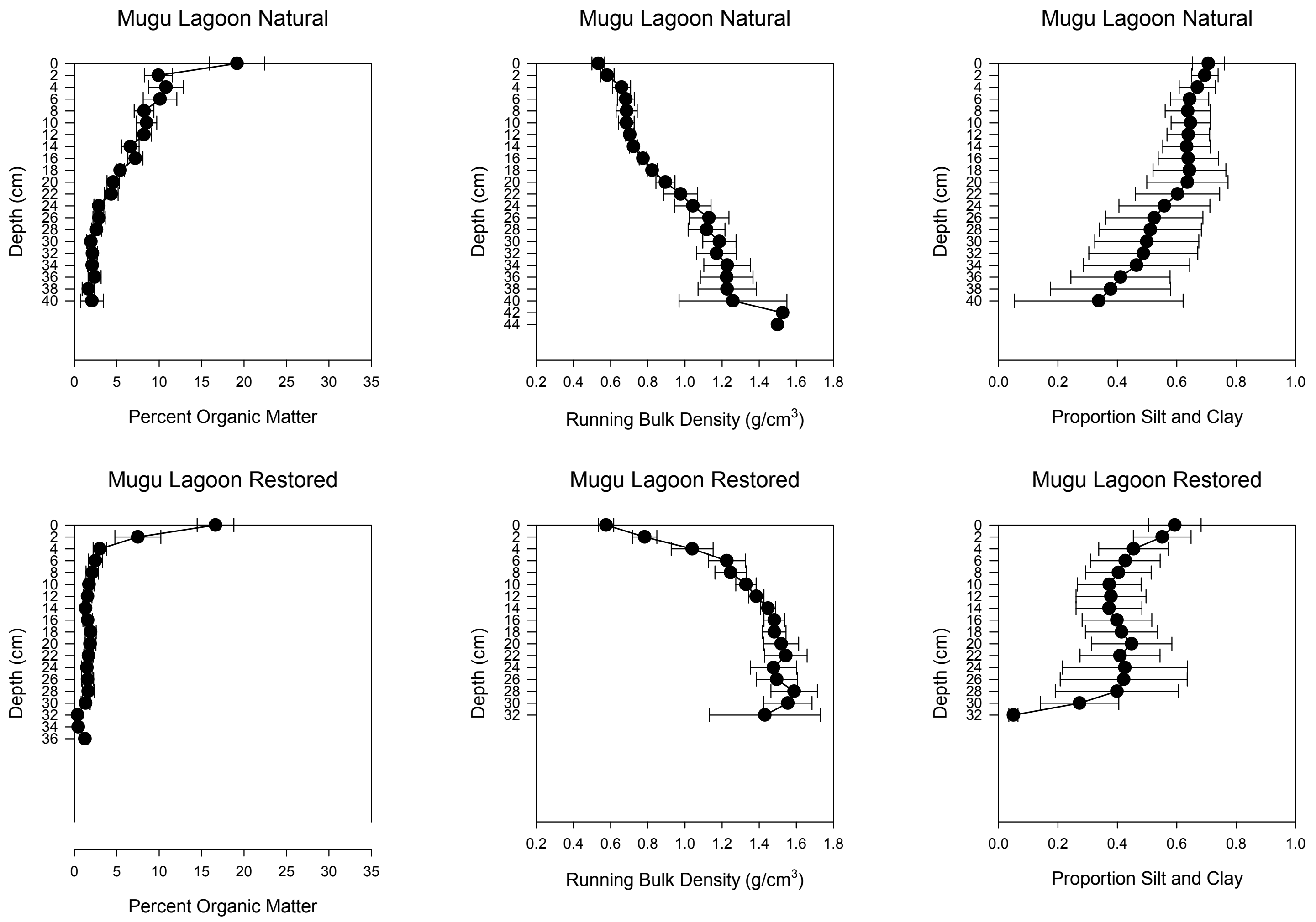


Figure 4: Percent organic matter, bulk density and proportion silt and clay profiles by depth at natural and restored sites at Mugu Lagoon. Horizontal bars indicate the standard error at each depth.

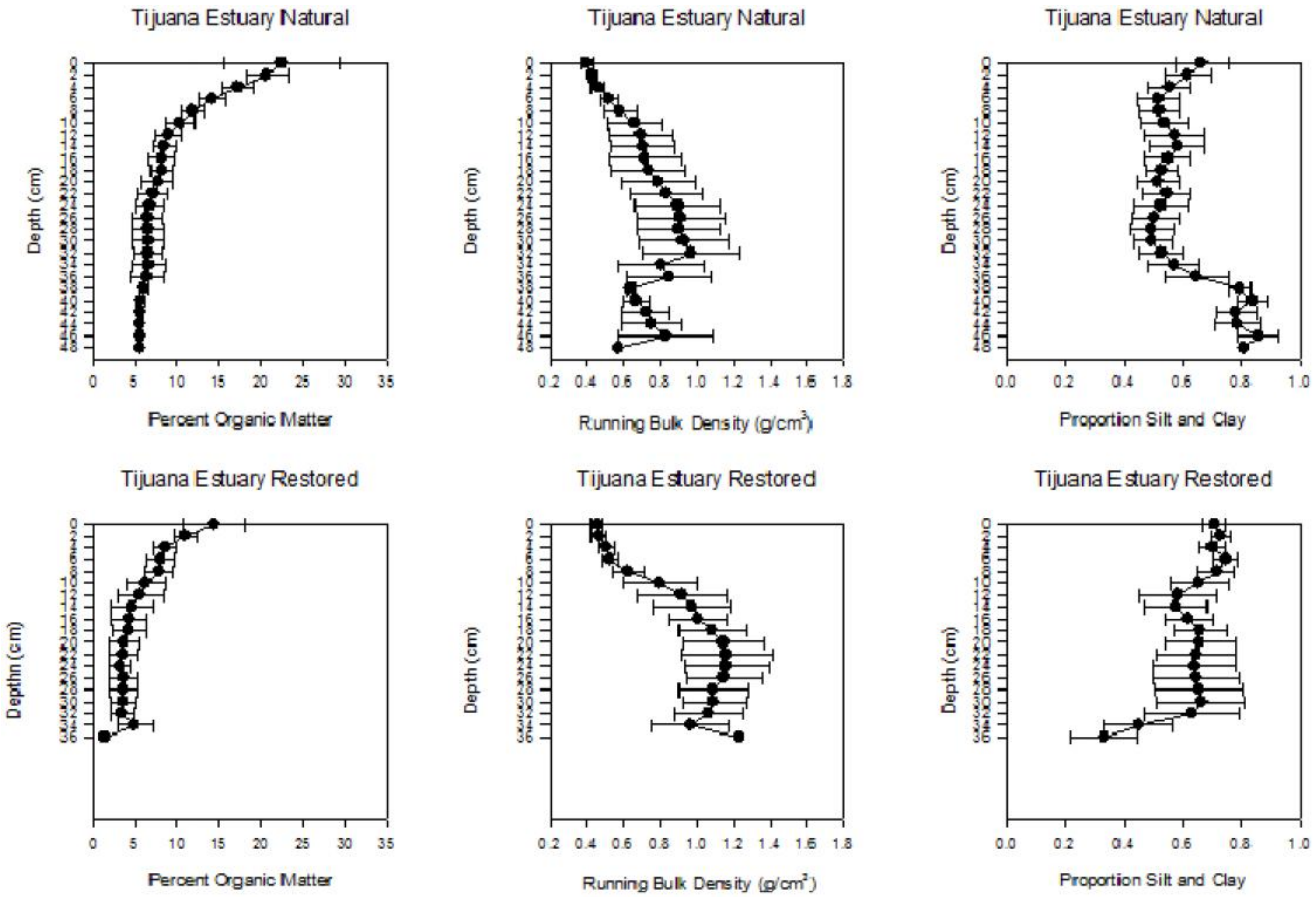


Figure 5: Percent organic matter, bulk density and proportion silt and clay profiles by depth, in natural and restored sites at Tijuana Estuary. Horizontal bars indicate the standard error at each depth.

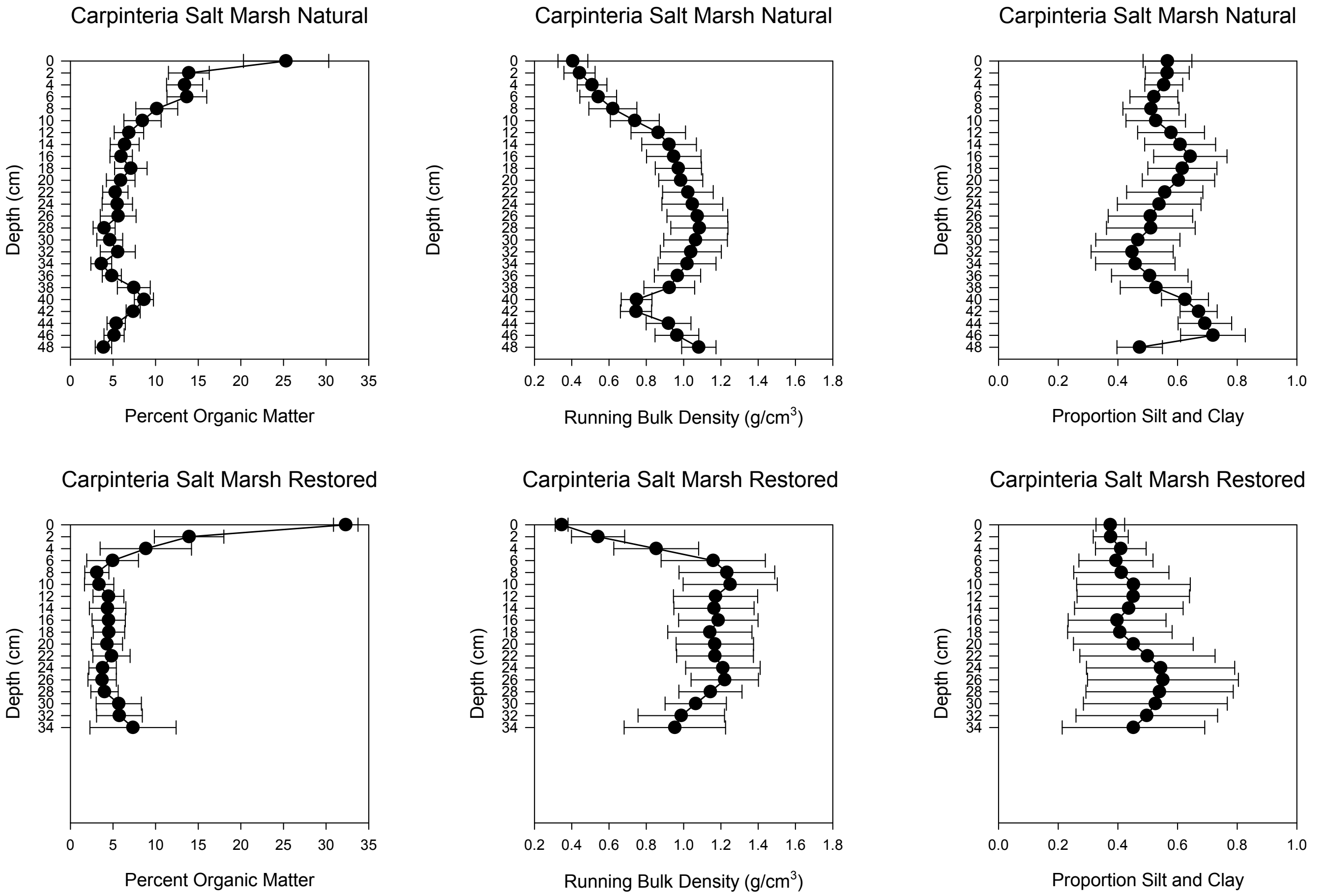


Figure 6: Percent organic matter, bulk density and proportion silt and clay profiles by depth, in natural and restored sites at Carpinteria Salt Marsh. Horizontal bars indicate the standard error at each depth.

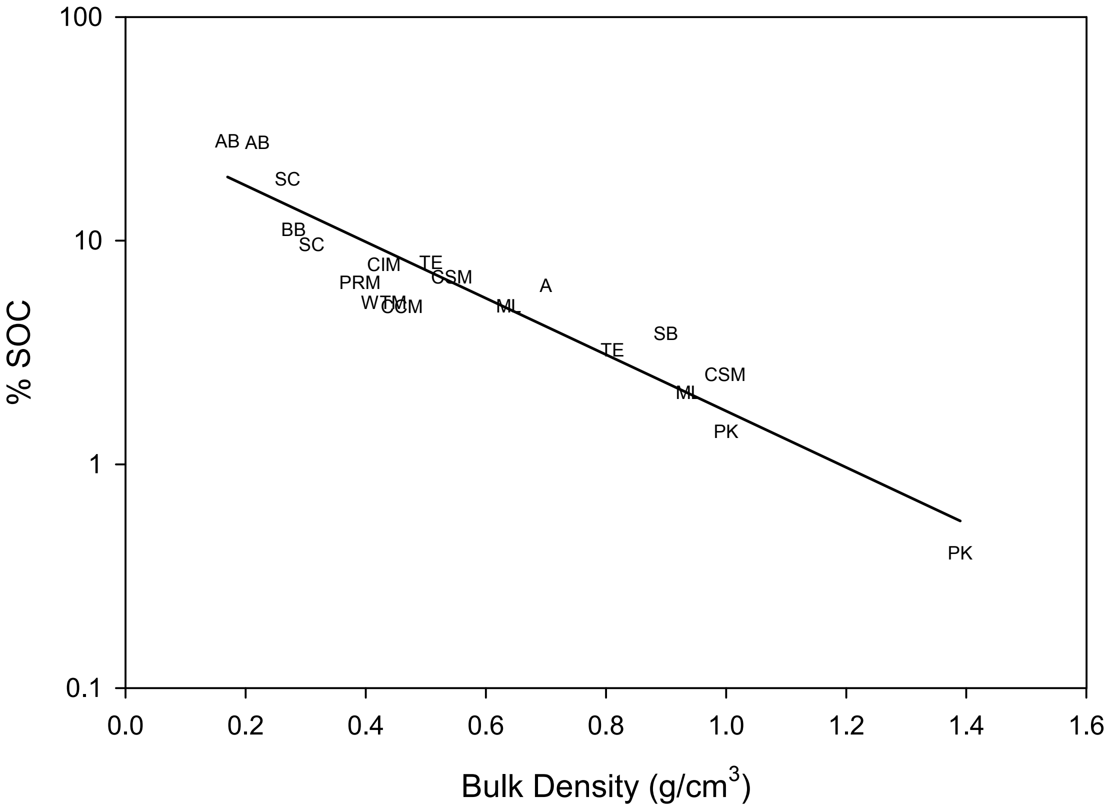


Figure 7: A. Linear regression of percent SOC vs. Bulk Density R^2=.89 PK=Pine Knoll, NC; SC=Snow's cut, NC; AB=Assawomen Bay, DE; A=Aransas, TX; SB= San Bernard, TX; BB=Biloxi Bay, MS**; ML=Mugu Lagoon, CA; TE=Tijuana Estuary, CA; CSM= Carpinteria Salt Marsh, CA;** CIM=Coon Island Mid, CA; PRM=Petaluma River Mid, CA; CCM=China Camp Mid, Ca; WTM=Whale's Tail Mid, CA.

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