FINAL

SAN DIEGO BAY EELGRASS BLUE CARBON STUDY
2021-2022

Prepared for   October 2022
San Diego Unified Port District

ESA

Merkel & Associates, Inc

PORT of SAN DIEGO
Waterfront of Opportunity

U.S. Department of Transportation
Maritime Administration

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GLOSSARY OF TERMS

Parts of an Eelgrass Shoot

Allometric equation – A mathematical relationship between an object's dimensions or traits; for this study, an equation relating eelgrass dimensions to biomass.

Assimilation – Carbon assimilation, also called carbon fixation, is the process by which inorganic carbon, usually in the form of carbon dioxide, is converted to organic compounds by living organisms and used to store energy and as a basis for building other important biomolecules. The most prominent example of carbon fixation is photosynthesis.

Blue carbon – Atmospheric carbon dioxide that is captured and stored in coastal and marine ecosystems, including the ocean and coastal seagrass, mangroves, and saltmarsh habitats.

Bulk density – Dry weight of a sediment sample divided by its volume.

Carbon stock/storage – The amount of carbon sequestered from the atmosphere and now stored within a carbon pool, for example, within living plant biomass and soil. This study focuses on the aboveground (i.e., biomass) and the belowground (i.e., roots and sediment) pools.

Eelgrass – A common name for several species of seagrass that grow in the shallow, protected waters of coastal bays and estuaries. Species studied here are the common eelgrass (*Zostera marina*) and the Pacific eelgrass (*Zostera pacifica*).

Mean lower low water (MLLW) – The average of the lower low water elevation each day observed over the 19-year National Tidal Datum epoch[1]

Organic carbon percentage – Calculated by dividing the mass of organic carbon in a sample by the overall mass of the sample.

***p* (p-value)** – A statistical measurement of the probability of obtaining the observed results. A p-value of less than 0.05 is considered statistically significant, with smaller values indicating a stronger significance.

Quadrat – An area of defined size and random placement used to assess characteristics such as plant distribution and density.

Refusal – The point at which a sediment corer cannot be driven further into the earth.

Remineralization – The conversion of organic matter back into inorganic forms. In this study, it is essentially the opposite of carbon sequestration.

Seagrass – A flowering plant which grows in marine environments, of which eelgrasses are a subtype.

Sequestration – The capture of atmospheric carbon dioxide.

Shell hash – Coarse sediment type dominated by broken bits of shells.

Turbidity – A water quality characteristic related to the cloudiness of the water (i.e., due to the amount of suspended matter)

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[1]   https://tidesandcurrents.noaa.gov/datum_options.html

EXECUTIVE SUMMARY

The Port of San Diego was one of the first ports to adopt a Climate Action Plan in 2013, and the decarbonization of maritime-related sources is a critical component to achieve organization goals and uphold state regulations. The California Global Solutions Act of 2016 (SB-32) requires a 40% reduction in State emissions below 1990 levels by 2030. In September 2022, the State passed The California Carbon Neutrality Act, A.B. 1279, that establishes "a clear, legally binding and achievable goal" that urges carbon neutrality as soon as possible, but no later than 2045, according to the governor's office. A.B. 1279 also sets an 85 percent emissions reduction target for that in comparison to 1990 levels. As such, it is important for the Port to seek multiple strategies to decrease GHG emissions through direct source reductions and through carbon sequestration.

Growing recognition of the ability of wetlands and seagrasses to combat climate change by sequestering and storing atmospheric carbon has led to increased interest in quantifying the greenhouse gas (GHG) benefits of coastal ecosystems. So-called "coastal blue carbon" is of great significance for both carbon sequestration and storage, as wetlands (both freshwater and saline) store 20–30% of global sediment carbon while making up just 5–8% of global land surface (Nahlik and Fennessy 2016). Mechanisms and procedures have also been developed to connect coastal wetland management to the carbon market, where appropriate.[2] For example, this year, The Nature Conservancy launched the first blue carbon credit project in the U.S. with the Virginia Eastern Shore seagrass restoration project.[3]

San Diego Bay is of special interest for quantifying the carbon of seagrass meadows, as it contains about 17% of the eelgrass habitat within California (Merkel & Associates 2020). Due to its statewide importance, the eelgrass in the bay has been mapped, monitored, and managed by the Port of San Diego (Port) and the Navy since the early 1990s. Seagrass meadows not only trap and store carbon generated by the seagrass itself, but up to 50% of the stored carbon in the sediments of seagrass meadows originates from somewhere else (Kennedy et al. 2010).

Quantifying blue carbon in San Diego Bay can be a means of assessing the benefits of seagrass bed restoration on GHG offsets. The addition of climate mitigation benefits is expected to broaden the pool of potential funds for the Port and others to do restoration and conservation, particularly as ecosystems like seagrass meadows are threatened by climate change and sea-level rise. Where carbon financing is not appropriate, recognition of the climate values of seagrasses

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[2]   http://www.v-c-s.org/methodologies/methodology-tidal-wetland-and-seagrass-restoration-v10
[3]   https://registry.verra.org/app/projectDetail/VCS/2360

could help the Port and its partners prioritize actions that improve and conserve these habitats in the context of climate adaptation.

ESA and Merkel & Associates prepared this study for the Port to evaluate and inventory carbon sequestration and storage potential of seagrass beds in San Diego Bay, including both the common eelgrass (*Zostera marina*) found throughout San Diego Bay and the broad-leaved, slower-growing Pacific eelgrass (*Zostera pacifica*) that grows near the bay's mouth. Given the spatial and biological heterogeneity across San Diego Bay, it was anticipated that carbon storage may differ across eelgrass beds based on a number of factors, including:

- Species of eelgrass (*Z. marina, Z. pacifica*);

- Ecoregion (Outer Bay, North Bay, North-Central Bay, South-Central Bay, South Bay);

- Depth of eelgrass occurrence (shallow margin, mid-bed, deep fringe), and;

- Age of eelgrass beds.

The ESA team sampled 12 locations across San Diego Bay, selecting sites to facilitate comparisons across the environmental variables listed above. Following the methods established by Howard et al. (2018) and Short and Duarte (2001), each site was analyzed for biomass carbon, sediment carbon, and eelgrass productivity. The results of the sampling and laboratory analysis show that, in total, San Diego Bay's eelgrass habitats store around 170,600 tonnes of CO_2 equivalent currently. This is comparable to just under half a years' worth of emissions from Port operations (Port of San Diego 2013). Continuing to manage these habitats will be important to maintaining blue carbon storage in San Diego Bay.

Sampling at the 12 locations across the bay provided the following results around the variability of carbon storage:

- The *Z. pacifica* bed had lower sediment carbon storage compared to *Z. marina* despite *Z. pacifica*'s larger biomass. However, aboveground and belowground carbon for the two species were not significantly different from each other ($p > 0.05$).

- Across the bay, the results show a general trend of increasing sediment carbon going southward. In particular, the Outer Bay stored significantly less carbon ($p < 0.05$) than North Central, South Central, and South Bay sites, and storage was also significantly different ($p < 0.05$) between the South Bay and the two ecoregions just north of it (North Central and South Central).

- The data show that the average carbon content may increase with increasing depth. The middle depth (-5 ft MLLW) showed significantly ($p < 0.05$) more carbon than the shallowest depth (-1 ft MLLW). The deepest cores (-7 ft MLLW) showed a substantial amount of variability, so this site was not statistically significant from the other two depths.

- The older sites had significantly ($p < 0.01$) greater amounts of carbon in the soils than the younger sites. For example, the site that was planted in 1987, had significantly ($p < 0.01$) more carbon than the site that was restored in 2006-2007, which had significantly ($p < 0.05$) more carbon than the site that was restored more recently in 2017. The data depicts a strong linear relationship between eelgrass bed age and carbon content although this is based on n=4.

The ESA team also estimated eelgrass productivity by measuring eelgrass growth over a period of 12 days, similar to the timeframe employed in other studies (Kentula and McIntire 1986; Solana-Arellano 2000; Solana-Arellano et al. 2008). The analysis showed that *Z. marina* assimilates 98.0 ± 41.0 mg C/m^2/day and *Z. pacifica* assimilates 237.1 ± 64.4 mg C/m^2/day. Note that assimilation in this context refers to biological sequestration, or what is taken into biomass—it does not guarantee that the carbon will be buried into the sediments. Comparing the assimilation rate to estimates of carbon sequestration in the literature (Duarte et al. 2005, 2011; McLeod et al. 2011) shows an order of magnitude discrepancy between carbon assimilation rates and carbon sequestration rates. As discussed in Tomasko 2015, this is a fairly common result, and at least a portion of the discrepancy may be due to sequestration into bicarbonate ions in the water column, which is something that will be analyzed in Year 2 of this study.

ESA also developed a habitat evolution model to estimate how eelgrass habitat and blue carbon sequestration could change over time with sea-level rise. The model assumes that eelgrass colonization continues to be correlated with depth as sea levels change. The model forecasts that the total extent of habitat will decrease over time. However, this habitat loss does not occur uniformly. Over time, eelgrass encroaches closer to the present-day shoreline, while habitat loss occurs largely in the interior of the bay. Habitat gain is concentrated in the South Bay, while habitat loss is concentrated first in the South Central Bay but is eventually modeled to occur in all other ecoregions.

Expansion of seagrasses into newly inundated areas throughout the bay where other important blue carbon habitats may be lost is crucial to slowing the loss of eelgrass habitat with sea-level rise and maintaining the bay's overall carbon sequestration potential. If this seagrass expansion with sea-level rise does not occur, then it is likely that carbon sequestration would decrease. Additionally, if sea-level rise stresses the ecosystem, loss of eelgrass could become part of a positive feedback loop leading to further losses, as seagrass meadows filter particulates out of the water column, and thus improve water clarity, which is needed for eelgrass to thrive.

While the existing eelgrass in San Diego Bay is already protected by regulations, and therefore would not meet the additionality requirements to sell blue carbon credits, this study provides new research to inform future blue carbon projects. To bring a blue carbon project to market, local data is needed to accurately predict how much carbon will be sequestered by the project. This study provides needed information on how carbon content varies by eelgrass species, location, depth, and age of the bed. In particular, the trend showing that older restored eelgrass beds have higher amounts of carbon in the sediments compared to newer restored beds could provide justification for restoring eelgrass beds to sequester blue carbon with the understanding that carbon would build up in the sediments over time.

The following recommendations are made for future studies:

1. Developing a San Diego Bay–specific sequestration rate would allow for a direct comparison to assimilation rates and would provide more accurate carbon evolution modeling results.

2. Further investigations into inorganic carbon pathways and carbon sequestration within the bicarbonate pool should be undertaken to better understand the difference between assimilation and sequestration rates.

3. Water quality data could provide additional information on the bicarbonate pathway (through changes in pH) and could be used to estimate productivity through the air-water CO_2 flux to compare against measurements in this study.

4. Refinements in sea-level rise estimates could affect the findings of this study and should be considered as new studies become available.

5. Grain size or other supplementary sediment analyses (e.g., isotope measurements) could help further illuminate patterns and causes of carbon storage in the sediment.

6. Follow-up sampling of eelgrass productivity could be conducted when drought conditions end and eelgrass returns to more "normal" above ground biomass conditions.

SECTION 1
Introduction

Growing recognition of the ability of wetlands and seagrasses to combat climate change by sequestering and storing atmospheric carbon has led to increased interest in quantifying the greenhouse gas (GHG) benefits of coastal ecosystems. To date, much of the science and practice of biological carbon sequestration and the development of associated carbon offset projects has focused on forestry, where the science and tools necessary to calculate GHG benefits are fairly well developed. However, more recently, organizations and agencies from the local to the international scale have begun to quantify the carbon storage and sequestration capacities of wetlands and aquatic habitats, especially salt marshes, mangroves, and seagrass beds (see, for example, National Wetlands Newsletter 36:1). So-called "coastal blue carbon" is of great significance for both carbon sequestration and storage, as wetlands (both freshwater and saline) store 20–30% of global sediment carbon while making up just 5–8% of global land surface (Nahlik and Fennessy 2016).

Mechanisms and procedures have also been developed to connect coastal wetland management to the carbon market, where appropriate.[4] A growing number of case studies are amassing to inform management agencies and policy developers on coastal wetland management and carbon finance markets (Sheehan et al. 2019; Crooks et al. 2014). This year, The Nature Conservancy launched the first blue carbon credit project in the U.S. with the Virginia Eastern Shore seagrass restoration project.[5]

San Diego Bay is of special interest for quantifying the carbon of seagrass meadows, as it contains about 17% of the eelgrass habitat within California (Merkel & Associates 2020). Due to its statewide importance, the eelgrass in the bay has been mapped, monitored, and managed by the Port of San Diego (Port) and the Navy since the early 1990s. Seagrass meadows not only trap and store carbon generated by the seagrass itself, but up to 50% of the stored carbon in the sediments of seagrass meadows originates from somewhere else (Kennedy et al. 2010). Researchers estimate that the global carbon burial of seagrasses is 48 to 112 teragrams of carbon (Tg C) per year; by comparison, forests' carbon burial rates range from 49 to 79 Tg C per year (Mcleod et al. 2011).

Quantifying blue carbon can be a means of assessing the benefits of seagrass bed restoration on GHG offsets. The addition of climate mitigation benefits is expected to broaden the pool of potential funds for the Port and others to do estuarine restoration and conservation, particularly as ecosystems like seagrass meadows are threatened by climate change and sea-level rise. Where

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[4]   http://www.v-c-s.org/methodologies/methodology-tidal-wetland-and-seagrass-restoration-v10
[5]   https://registry.verra.org/app/projectDetail/VCS/2360

carbon financing is not appropriate, recognition of the climate values of seagrass could help the Port and its partners prioritize actions that improve and conserve these habitats in the context of climate adaptation.

1.1 Project Context

The Port of San Diego was one of the first ports to adopt a Climate Action Plan in 2013, and the decarbonization of maritime-related sources is a critical component to achieve organization goals and uphold state regulations. The California Global Solutions Act of 2016 (SB-32) requires a 40% reduction in State emissions below 1990 levels by 2030. In September 2022, the State passed The California Carbon Neutrality Act, A.B. 1279, that establishes "a clear, legally binding and achievable goal" that urges carbon neutrality as soon as possible, but no later than 2045, according to the governor's office. A.B. 1279 also sets an 85 percent emissions reduction target for that in comparison to 1990 levels. As such, it is important for the Port to seek multiple strategies to decrease GHG emissions through direct source reductions and through carbon sequestration.

In addition to upholding state standards, the Port of San Diego has also developed a Maritime Clean Air Strategy (MCAS) to reduce emissions of criteria pollutants as well as greenhouse gases (GHGs) from its maritime industry beyond what is mandated by California standards. With a vision of Health Equity for All, the MCAS is a strategic planning document, identifying both short- and long-term goals and objectives to reduce emissions from ocean-going vessels, commercial harbor craft, cargo handling equipment, heavy-duty trucks, and locomotives. The MCAS focuses on the transition to zero emission technologies such as increased use of shore power for ocean-going vessels while at berth and electric trucks that aim to reduce diesel particulate matter (DPM) emissions as well as GHG emissions. The initiatives outlined in the MCAS will reduce health risk impacts on receptors such as nearby residents, children at schools and day care centers, and patients at local hospitals and others.

In advance of the State's goals, the Port seeks to install additional shorepower capacity at its marine terminals as well as utilize an emission capture and control system to reduce emission from non-shorepower capable vessels; and advance 100% zero emission truck trips and cargo handling equipment by 2030. Additional goals include transitioning Port-owned vehicles and equipment to zero/near zero emission technologies in a manner that meets operational needs.

1.2 Project Overview

ESA and Merkel & Associates prepared this study for the Port to evaluate and inventory carbon sequestration and storage potential of seagrass beds in San Diego Bay, including both common eelgrass (*Zostera marina*) and the broad-leaved, slower-growing Pacific eelgrass (*Zostera pacifica*) that grows near the mouth of San Diego Bay. The goal of this work is to:

1. Establish typical baseline carbon stocks that currently exist in eelgrass beds throughout San Diego Bay.

2. Characterize variation in carbon pools associated with variation in local environmental conditions.

3. Assess and better understand the carbon sequestration capacity of both newly established (as a result of restoration projects or other human intervention) and existing eelgrass beds to support future natural resources management efforts.

Given the spatial and biological heterogeneity across San Diego Bay, it was hypothesized that carbon storage may differ across eelgrass beds based on a number of factors, including:

- Species of eelgrass (*Z. marina, Z. pacifica*);

- Ecoregion (Outer Bay, North Bay, North-Central Bay, South-Central Bay, South Bay; see **Figure 1-1** below);

- Depth of eelgrass occurrence (shallow margin, mid-bed, deep fringe), and;

- Age of eelgrass beds.

Seagrass meadows are generally composed of three major carbon pools: aboveground living biomass (i.e., the leaves of seagrass), belowground living biomass (roots and rhizomes), and sediment carbon stock. The baseline sampling plan has been designed to capture the carbon stock in all three pools as they vary across these different environments.

San Diego Bay Eelgrass Blue Carbon Study

Figure 1-1
San Diego Bay Site Map

Legend:
- ★ Sampling locations
- — Annual eelgrass survey transects (Merkel & Associates)
- — Ecoregion boundaries
- ▬ 2020 Eelgrass extent (Merkel & Associates)

1.3 Conceptual Framework

The term "carbon stock" refers to the quantity of carbon stored in a reservoir, or pool (e.g., soil, vegetation, water, the atmosphere). Each pool can sequester and release carbon. In eelgrass beds, the main pools of carbon are biomass and sediment carbon (IPCC 2013).

Vegetation sequesters carbon, in the form of carbon dioxide (CO_2), from the atmosphere through photosynthesis and transforms it into biomass. The biomass carbon stock includes the total mass of carbon stored aboveground (e.g., in leaves of seagrass) and belowground (e.g., in roots and rhizomes) at a site.

Sediments comprise another important carbon pool. This stock increases over time according to the sediment sequestration rate of the habitat, i.e., the rate at which dead organic matter is incorporated back into the sediment. Coastal wetland sediments are primarily anaerobic, or oxygen-poor, because they are submerged in water which slows the decomposition of dead organic matter and allows carbon to remain buried in the sediment. Because of the unique anaerobic chemistry of wetland and other aquatic habitats' sediments, wetlands and seagrasses store a disproportionately large amount of carbon per area compared to terrestrial habitats, making this stock of particular interest in the context of global climate change.

Dead organic matter is important in woody wetlands (e.g., forested wetlands), where it comprises a large fraction of the aboveground carbon stock. Since San Diego Bay does not include forested wetlands, we did not analyze this pool for the project.

1.4 Analysis Accuracy

The Intergovernmental Panel on Climate Change's (IPCC's) tier system reflects the degree of certainty or accuracy of a carbon assessment:

- Tier 1 – These assessments have the least accuracy and certainty and are based on simplified assumptions and published IPCC default values for activity data[6] and emissions factors. Tier 1 assessments may have a large error range of +/- 50% for aboveground pools and +/- 90% for the variable sediment carbon pools.

- Tier 2 – These assessments include some country- or site-specific data and hence have increased accuracy and resolution. For example, a country may know the mean carbon stock for different ecosystem types within that country.

- Tier 3 – These assessments require highly specific data of the carbon stocks in each component ecosystem or land use area, and repeated measurements of key carbon stocks through time to provide estimates of change or flux of carbon into or out of the area. Estimates of carbon flux can be provided through direct field measurements or by modeling.

This assessment will provide Tier 3 data for San Diego Bay, which is the most accurate level of data. Analyzing the carbon stocks at a Tier 3 level will facilitate future use of the data to analyze changes to carbon stocks and GHG fluxes over time with sea-level rise, restoration, or other

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6   Geographical data showing the types of land coverage and use in a given area.

changes to the bay. Additionally, Tier 3 data would be required to validate blue carbon credits if a market project is developed in the future.

SECTION 2
Field Data Collection and Laboratory Methods

The ESA team sampled 12 locations across San Diego Bay, selecting sites to facilitate comparisons across the environmental variables listed in Section 1.2 Project Overview. Each site was analyzed for biomass carbon, sediment carbon, and eelgrass productivity following the methods established by Howard et al. (2018) and Short and Duarte (2001).

Table 2-1 summarizes the sampling locations. Sampling depths were intended to be around -4 ft mean lower low water (MLLW) except for sample D-1, which was shallower, and D-3, which was deeper. However, achieving this exact elevation in the field proved to be more difficult than expected, so depths vary across the sites, as listed in Table 2-1. Additionally, seagrass in the outer bay has been dynamic in recent years and so the location of Site B was shifted slightly north, closer to the entrance of the bay.

TABLE 2-1
SAMPLE LOCATION SUMMARY

Replicates	Location	Ecoregion	Depth	Species	Year established
1-3	A	Outer Bay	-7.4 ft MLLW	*Zostera pacifica*	Since at least 1992
4-6	B	Outer Bay	-4.6 ft MLLW	*Zostera marina*	Since at least late 1970s
7-9	C	North	-7.0 ft MLLW	*Zostera marina*	Since at least late 1970s
10-12	D-1	North Central	-1.6 ft MLLW	*Zostera marina*	Since at least 1992
13-15	D-2	North Central	-5.5 ft MLLW	*Zostera marina*	Since at least 1992
16-18	D-3	North Central	-7.7 ft MLLW	*Zostera marina*	Since at least 1992
19-21	E	South Central	-5.2 ft MLLW	*Zostera marina*	Since at least early 1980s
22-24	F	South	-1.9 ft MLLW	*Zostera marina*	1974 or earlier (native)
25-27	G	South	-4.3 ft MLLW	*Zostera marina*	2017 (BAE Pier 1)
28-30	H	South	-6.3 ft MLLW	*Zostera marina*	2006-2007 (South Bay Borrow Pit)
31-33	I	South	-8.9 ft MLLW	*Zostera marina*	Unknown
34-36	J	South	-3.4 ft MLLW	*Zostera marina*	1987 (Chula Vista Wildlife Reserve)

NOTES:

Elevations were collected in ft NAVD88 in the field. A conversion of NAVD – 0.43 ft = MLLW was used throughout the bay (NOAA Tides and Currents for San Diego Bay, Stn. 940170).

To collect biomass carbon data, triplicate quadrats were set at each site. Within each 25 cm by 25 cm quadrat, the average eelgrass height and the number of shoots were measured. At both a quadrat in a *Z. marina* bed and one in a *Z. pacifica* bed, 50 individual shoots over the range of

observable heights and widths were cut and sent to Wallace Laboratories (El Segundo, CA) for analysis of carbon content.

Triplicate sediment cores were collected at each site to understand belowground carbon storage. Cores were taken to 1-meter depth or to refusal (i.e., where the core cannot be pushed further), and one core per ecoregion (Figure 1-1) was taken to 3-meter depth or to refusal. These cores were subsampled on-site into 10-cm intervals for the top half meter and into 50-cm intervals thereafter. These samples were sent to Weck Laboratories, Inc. (City of Industry, CA) for analysis of dry bulk density and carbon content.

Eelgrass productivity was determined by measuring eelgrass growth over a period of 12 days, similar to the timeframe employed in other studies (Kentula and McIntire 1986; Solana-Arellano 2000; Solana-Arellano et al. 2008). Following established methods of directly marking shoots to obtain a growth rate over time, individual eelgrass shoots were marked just above the meristem at the blade-sheath junction with a hypodermic needle (Tomasko et al. 2001; Ibarra-Obando and Boudouresque 1994; Short and Duarte 2001). Multiple shoots were marked in 20 clusters of approximately five shoots per cluster in order to ensure that 20 shoots could be easily relocated and collected from two sampled locations: one *Z. marina* bed (at the mouth of the Sweetwater River in the south ecoregion[7]) and one *Z. pacifica* bed (Site A, Outer Bay). These blades were marked with zip ties to facilitate recovery at the end of the 12 days, when shoots were collected and taken to the laboratory to measure the upward displacement of the scar on the "new" blade compared to the needle mark remaining on the older, outside blade where the puncture was first made.

Figure 2-1. Zip Ties Identifying Marked Shoots of *Z. Pacifica*

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[7] The productivity sampling was originally conducted in the fall of 2021 at Site B, but due to the small eelgrass blades, the marked shoots could not be found or recovered. The sampling was repeated in the spring of 2022 near the Sweetwater River where eelgrass grows taller.

SECTION 3
Aboveground Carbon Data Analysis

3.1 Biomass Data

Table 3-1 summarizes the number of shoots, density, dimensions, and weight at each site in the study. Weight was measured in the lab only for sites A and F and with values for the other sites derived from allometric equations, as discussed in Section 3.3 below.

Measurements at Site A for *Z. pacifica* show that this species is much larger than *Z. marina* (Sites B–J) with a mean and standard deviation leaf area of 75 ± 40 cm^2 compared to 9 ± 6 cm^2. The weight of *Z. pacifica* (1.99 ± 1.26 g) was correspondingly greater than that of *Z. marina* (0.06 ± 0.09 g). However, there was no statistical difference between the eelgrass weight at any of the sites ($p > 0.05$).

Measurements of *Z. pacifica* are rare in the literature, but Duarte (1991) compiled eelgrass architecture data across 27 seagrass species, including *Z. marina*. Based on 16 papers, Duarte found an average leaf surface area and shoot weight for *Z. marina* of 34.65 cm^2 and 0.272 g, respectively. Assuming 4.2 leaves per shoot (Duarte 1991), the San Diego Bay *Z. marina* has an average leaf surface area of 37.8 cm^2 and shoot weight of 0.06 g.

Notably, the leaf area and biomass for eelgrass in this study was substantially lower than both means reported by Duarte (1991), and the historic conditions observed in San Diego Bay eelgrass beds. This may be the result of a long-term shortage in nutrient load to the bay due to persistent drought conditions that have prevailed from 2011-2019 as well as improved watershed controls on runoff. Over this period, a notable expansion of eelgrass to deeper bay depths has been noted (Merkel & Associates 2020). There has also been a notable reduction in overall canopy height and biomass throughout the beds over the past many years (K. Merkel, pers. Obs.). The link between prevailing drought and nutrient and turbidity reduction benefiting eelgrass extent in deeper waters through improved water clarity is discussed in the long-term monitoring program report; however, the ramifications of nutrient load reduction impacting eelgrass vigor is only touched on as this concern is only recently emerging as long-term monitoring is beginning to reveal patterns of increasingly diminutive size of plants comprising the beds within low-influx embayments of Southern California (Merkel, unpublished data).

TABLE 3-1
MEASURED BIOMASS DATA

Site	Quadrat	# of Shoots	Shoot Density (shoot/m²)	Average Shoot Density (shoot/m²)	Average Leaf Length (cm)	Average Leaf Area (cm²)	Average Shoot Weight (g)[1]
A (*Z. pacifica*)	1	12	192	197	69	75	1.99
	2	10	160				
	3	15	240				
	Extra[2]	13	n/a				
B (*Z. marina*)	1	41	656	619	42	14	0.13
	2	40	640				
	3	35	560				
C (*Z. marina*)	1	15	240	245	39	12	0.08
	2	15	240				
	3	16	256				
D-1 (*Z. marina*)	1	34	544	891	25	6	0.03
	2	81	1296				
	3	52	832				
D-2 (*Z. marina*)	1	27	432	629	26	7	0.03
	2	43	688				
	3	48	768				
D-3 (*Z. marina*)	1	49	784	731	27	7	0.03
	2	49	784				
	3	39	624				
E (*Z. marina*)	1	38	608	677	32	9	0.05
	2	36	576				
	3	53	848				
F (*Z. marina*)	1	17	272	384	35	12	0.08[3]
	2	28	448				
	3	27	432				
G (*Z. marina*)	1	17	272	416	29	10	0.07
	2	37	592				
	3	24	384				
H (*Z. marina*)	1	22	352	485	30	8	0.05
	2	27	432				
	3	42	672				
I (*Z. marina*)	1	23	368	480	27	7	0.04
	2	28	448				
	3	39	624				

TABLE 3-1 (CONTINUED)
MEASURED BIOMASS DATA

Site	Quadrat	# of Shoots	Shoot Density (shoot/m²)	Average Shoot Density (shoot/m²)	Average Leaf Length (cm)	Average Leaf Area (cm²)	Average Shoot Weight (g)[1]
J (*Z. marina*)	1	16	256	363	38	12	0.08
	2	22	352				
	3	30	480				

NOTES:

1. Only sites A and F were tested for weight. Values for the other sites are derived from allometric equations, as discussed in Section 3.3.
2. Extra samples were collected to reach the 50 samples that were tested for weight.
3. Twenty-two of the samples in quadrat 3 were not analyzed for weight since 50 samples had already been reached with quadrat 1 and quadrat 2

3.2 Aboveground Carbon Content

The average carbon contents measured for *Z. pacifica* and *Z. marina* were 24.2 ± 0.04 and $29.9 \pm 0.02\%$ dry weight, respectively. The difference in carbon content for the two species was found to be statistically significant ($p < 0.001$).

Duarte (1990) reviewed carbon content reported in the literature across 27 seagrass species at 30 locations and found an average carbon concentration of $33.6 \pm 0.31\%$ dry weight. Ten studies with 46 measurements looked at *Z. marina*, and no data was provided for *Z. pacifica*. Data for *Z. marina* spanned a large range (29-42%) but averaged closer to 36 percent. More recent studies have found *Z. marina* carbon content ranging from 34.4 to 38.8 percent dry weight in Europe (Dahl et al. 2016), $35 \pm 0.32\%$ in Denmark, and $38 \pm 0.24\%$ (Röhr et al. 2016). The San Diego Bay *Z. marina* carbon content appears low based on the literature, although it is within the range found by Duarte (1990).

Note that the sample mass collected resulted in fairly low weights sent to the lab (near the minimum mass required). If carbon crediting is pursued in the future, additional samples with a greater combined sample weight should be collected and tested to confirm these results. Further, a broader distribution of sampling should be undertaken.

3.3 Allometric Equations Relating Size and Weight

Allometric equations have been shown to provide a consistent alternative to tedious and destructive sampling methods by providing a relationship between eelgrass dimensions and weight (Duarte 1991; Echavarria-Heras et al. 2011). Previous studies have analyzed the relationships between various size parameters and weight using exponential or linear relationships (Echavarria-Heras et al. 2009, 2013, 2011a, 2011b). Assuming the dry sample weight of a shoot of eelgrass can be allometrically scaled in terms of the area of the leaf gives the following:

$$w = \alpha A^{\beta} \text{ Equation 1}$$

where w = weight of the dried sample, A = the area of the leaf of eelgrass, and α and β are parameters. A can be estimated by multiplying the length of the leaf (measured between the ligule and the tip) and the width of the leaf (measured at a point halfway). Since the width of eelgrass leaves is fairly constant, the weight of a sample should also allometrically scale in terms of the length of the leaf,

$$w = \gamma L^\delta \quad \text{Equation 2}$$

Where L = length and γ and δ are different parameters than in Equation 1. Echavarria-Heras et al. 2011a, 2011b, and 2013 verified this model through a consistent fitting of their data. Echavarria-Heras et al. 2011a and 2011b also considered the linear relationship between weight and leaf length,

$$w = \varepsilon L \quad \text{Equation 3}$$

where ε is a parameter.

Using the eelgrass size and weight data from 50 samples each collected at sites A and F (representing *Z. pacifica* and *Z. marina*, respectively), parameters were fit for Equations 1-3 (**Table 3-2**). The coefficient of determination (R^2), which shows how well the regression model fits the data, and the concordance correlation index ($\hat{\rho}$) (Lin 1989), which measures the correlation between data, were used to test the predictive quality of the models. For both values, a higher number represents a better fit.

TABLE 3-2
VALUES OF THE PARAMETERS, R^2, AND $\hat{\rho}$ RESULTING FROM THE FITTINGS OF THE ALLOMETRIC MODELS

Equation	Model Type	Species	Parameters		R^2	$\hat{\rho}$
Equation 1	$m = \alpha A^\beta$		α	β		
		Z. marina	1.4×10^{-7}	1.85	0.77	0.81
		Z. pacifica	1.3×10^{-4}	1.08	0.89	0.94
Equation 2	$m = \gamma L^\delta$		γ	δ		
		Z. marina	1.1×10^{-10}	3.42	0.63	0.79
		Z. pacifica	6.3×10^{-4}	1.58	0.82	0.90
Equation 3	$m = \varepsilon L$		ε			
		Z. marina	2.57×10^{-4}		0.33	0.39
		Z. pacifica	3.06017×10^{-3}		0.75	0.82

Equation 1 provided the best fit for both species of eelgrass. The *Z. pacifica* data was fit with α = 0.00013 and β = 1.08 with a determination coefficient of R^2 = 0.89 and $\hat{\rho}$ = 0.94. The *Z. marina* data was fit with α = 0.00000014 and β = 1.85 with R^2 = 0.77 and $\hat{\rho}$ = 0.81. The resulting parameters based on Equation 2 show that the simpler allometric model also holds. However, since both the coefficient of determination and the concordance correlation index showed better fits for the parameters associated with Equation 1 rather than either Equations 2 or 3, the Equation 1 fit was used for the rest of this study.

3.4 Variation Across Sites

The allometric equations derived in the previous section were used to estimate the weight of each shoot based on the measured leaf width and length for the sites where leaf weight was not measured (i.e., Sites B, C, D, E, G, H, I, and J). The total biomass was then calculated by summing it across the quadrat. **Table 3-3** presents the total biomass for each site and the total aboveground carbon (biomass multiplied by carbon content).

Fourqurean et al. (2012) found a global average of 0.755 ± 0.128 Mg C/ha for aboveground carbon for seagrass. The results for this study show aboveground carbon contents an order of magnitude less than Fourqurean et al. for *Z. marina* and comparable for *Z. pacifica* (Table 3-3).

TABLE 3-3
EELGRASS BIOMASS AND CARBON BY SITE

Site	Biomass (g/m^2)	Carbon (Mg C/ha)
A (*Z. pacifica*)	366 ± 171	0.89 ± 0.41
B (*Z. marina*)	80 ± 43	0.24 ± 0.13
C (*Z. marina*)	21 ± 7	0.06 ± 0.02
D-1 (*Z. marina*)	23 ± 7	0.07 ± 0.02
D-2 (*Z. marina*)	18 ± 4	0.05 ± 0.01
D-3 (*Z. marina*)	23 ± 11	0.07 ± 0.03
E (*Z. marina*)	35 ± 16	0.11 ± 0.05
F (*Z. marina*)	22 ± 6	0.07 ± 0.02
G (*Z. marina*)	28 ± 5	0.08 ± 0.02
H (*Z. marina*)	23 ± 7	0.07 ± 0.02
I (*Z. marina*)	18 ± 10	0.05 ± 0.03
J (*Z. marina*)	29 ± 11	0.09 ± 0.03

3.4.1 Species

Figure 3-1 compares aboveground carbon between Sites A and B to illustrate the difference between *Z. pacifica* and *Z. marina*. Likely because of its larger size, *Z. pacifica* had greater biomass (366 ± 171 g/m^2) and carbon content (0.89 ± 0.41 MgC/ha) than *Z. marina* (biomass: 80 ± 43 g/m^2 and carbon content: 0.24 ± 0.13 MgC/ha). However, this difference is not significant ($p > 0.05$).
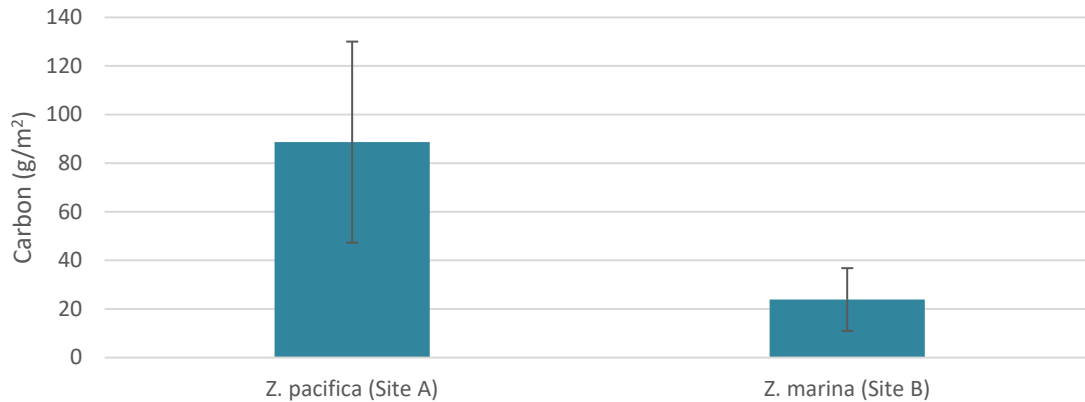
Figure 3-1. Carbon in Biomass by Species[8]

3.4.2 Ecoregion

Figure 3-2 compares aboveground carbon between Sites B, C, D-2, E, and F to illustrate the difference between the ecoregions within the bay. The Outer Bay site showed the greatest biomass and carbon content, although it was not significantly different from the other sites ($p > 0.05$).
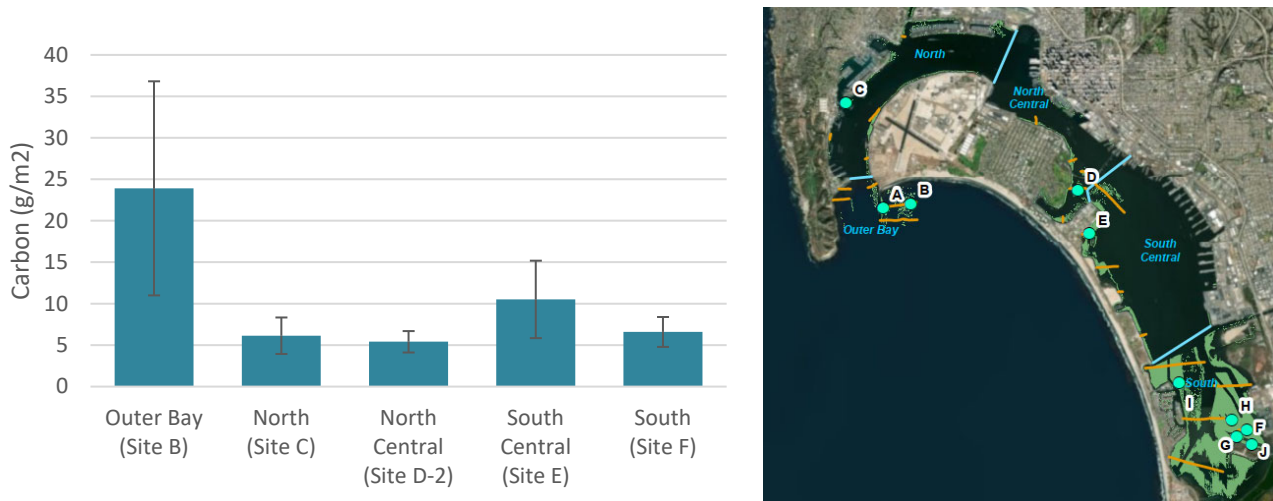
Figure 3-2. Carbon in *Z. marina* Biomass by Ecoregion

Sites I and F, both within the South Bay, provide a comparison between the denser east bay vegetation and the more fragmented west bay vegetation. However, the average biomass within the quadrat was similar between the east (22 ± 6 g/m^2) and the west (18 ± 10 g/m^2) as was the average carbon content (east: 7 ± 2 gC/m^2 and west: 5 ± 3 gC/m^2).

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8   For this and the following plots, the bar represents the average value across the triplicate samples and the whisker represents ± one standard deviation.

3.4.3 Bed Depth

Figure 3-3 depicts the aboveground carbon between Sites D-1, D-2, and D-3 to illustrate the difference between bed elevations. While Serrano et al. (2014) found that water depth could be associated with higher primary production and larger biomass carbon stock, the sampling results showed minimal differences between the varying depths.
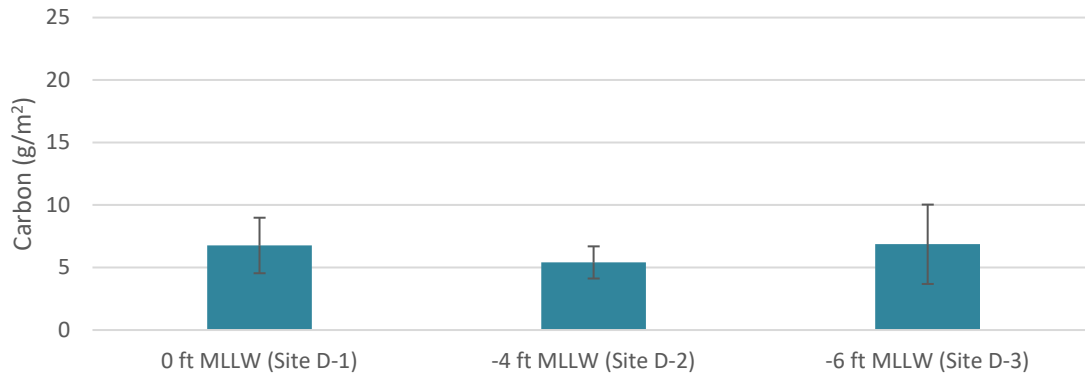
Figure 3-3. Carbon in *Z. marina* Biomass by Elevation

3.4.4 Bed Age

Figure 3-4 depicts the aboveground carbon between Sites F, J, H, and G, to illustrate the difference in bed age. The sampling results for biomass showed minimal differences between the varying bed ages.

Figure 3-4. Carbon in Biomass by Bed Age

3.5 Productivity

The tables below summarize the growth and biomass accumulation on a daily basis for eelgrass within the study. The mean growth was calculated per shoot for *Z. marina* and *Z. pacifica* based on dry weight mass over the duration of the field study (**Table 3-4**). The measured density of

eelgrass beds was determined to range considerably between the more robust *Z. pacifica* plants (88.00 ± 22.71 shoots/m^2) and smaller *Z. marina* (165.60 ± 47.09 shoots/m^2). Finally, the productivity was determined on a *per square meter* basis by multiplying the average productivity of a shoot by the average number of shoots within a square meter of the eelgrass beds, as shown in **Figure 3-5**. The analysis showed that *Z. marina* has a productivity of 327.89 ± 137.10 mg/day/m^2 while *Z. pacifica* has a productivity of 979.88 ± 265.91 mg/day/m^2.

TABLE 3-4.
EELGRASS PRODUCTIVITY FOR SAN DIEGO BAY EELGRASS (MAY 2022)

Productivity Sample #	*Z. marina* Shoot Growth (mg/day/shoot)	*Z. pacifica* Shoot Growth (mg/day/shoot)
1	2.76	13.95
2	2.69	11.51
3	2.23	9.18
4	1.29	13.98
5	0.93	7.07
Mean Growth (± SD)	**1.98 ± 0.83**	**11.14 ± 3.02**
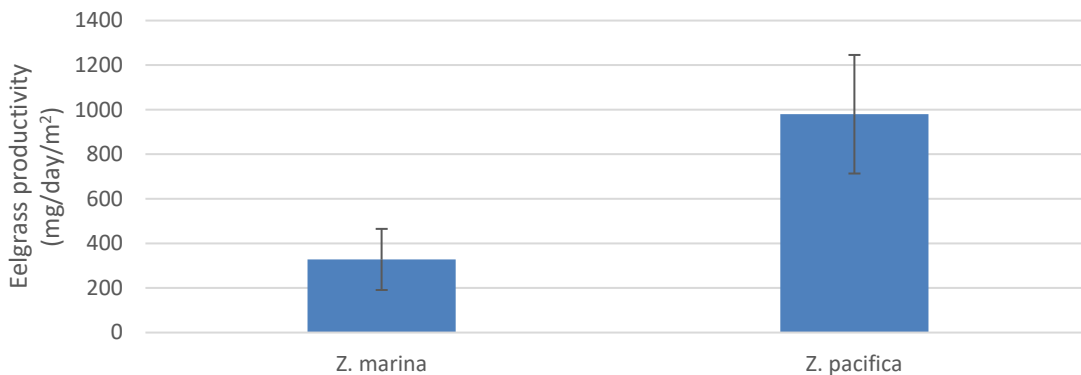
Figure 3-5. Eelgrass Productivity

Multiplying the carbon content results from Section 3.2 with the eelgrass biomass productivity results in the carbon assimilation of the biomass. *Z. marina* assimilates 98.0 ± 41.0 mg C/m^2/day and *Z. pacifica* assimilates 237.1 ± 64.4 mg C/m^2/day. Note that assimilation in this context refers to biological sequestration, or what is taken into biomass—it does not guarantee that the carbon will be buried into the sediments. **Table 3-5** shows the productivity by site.

TABLE 3-5
EELGRASS CARBON ASSIMILATION BY SITE

Site	Average Shoot Density (shoots/m^2)	Average Assimilation (g C/m^2/yr)
A (*Z. pacifica*)	197 ± 40	194 ± 73
B (*Z. marina*)	619 ± 51	609 ± 263
C (*Z. marina*)	245 ± 9	241 ± 103
D-1 (*Z. marina*)	891 ± 379	876 ± 527
D-2 (*Z. marina*)	629 ± 176	619 ± 315
D-3 (*Z. marina*)	731 ± 92	719 ± 318
E (*Z. marina*)	677 ± 149	666 ± 319
F (*Z. marina*)	384 ± 97	378 ± 187
G (*Z. marina*)	416 ± 162	409 ± 236
H (*Z. marina*)	485 ± 167	478 ± 261
I (*Z. marina*)	480 ± 131	472 ± 238
J (*Z. marina*)	363 ± 112	357 ± 188

Carbon sequestration rates for seagrass vary widely in the literature, as shown in **Table 3-6**. Duarte et al. (2005) estimated a global carbon sequestration rate of 83 g C/m^2/yr, while McLeod et al. (2011) estimated 138 g C/m^2/yr. Duarte et al. (2011) measured a sequestration rate of 52.4 g C/m^2/yr for *Z. marina*.

TABLE 3-6
EELGRASS SEQUESTRATION RATES IN THE LITERATURE

Source	Sequestration Rate (g C/m^2/yr)	Notes
Duarte et al. (2005)	83	global
Greinier et al. (2013)	38	Virginia
Chiu et al. (2013)	20	Korea
McLeod et al. (2011)	138	global
Duarte et al. (2011)	52.4	NW Mediterranean; *Z. marina*
Samper-Villarreal et al. (2018)	50.5	NE Australia

Comparing the values in Tables 3-5 and 3-6 show an order of magnitude discrepancy between carbon assimilation rates and carbon sequestration rates. As discussed in Tomasko 2015, at least a portion of the discrepancy may be due to sequestration into bicarbonate ions in the water column, which is something that will be analyzed in Year 2 of this study.

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SECTION 4
Belowground Carbon Data Analysis

The belowground carbon stock was determined based on the dry bulk density and organic carbon content found in each of the samples within a core. Several terms are commonly used in the study and quantification of blue carbon, including the following:

- **Bulk density**: This describes the mass of sediment per unit volume (i.e., grams of sediment per cm^3 [g/cm^3]). This is used in conjunction with the measured organic carbon percentage to determine the carbon density.

- **Organic carbon percentage**: This describes the mass of carbon per the mass of sediment in a sample (i.e., grams of carbon per grams of soil [gC/g soil] as a percentage).

- **Sediment carbon density**: This describes the amount of carbon per volume of sediment (i.e., grams of carbon per cm^3 [gC/cm^3]). It is calculated by multiplying bulk density (g/cm^3) and the organic carbon percentage (g C/g soil).

- **Total carbon per sample**: This term describes the mass of carbon (in grams) contained in the sampling interval or entire core. It is expressed on a per-surface area basis (i.e., gC/cm^2) to allow for spatial extrapolation. It is calculated by multiplying the sediment carbon density (gC/cm^3) by the sample thickness (cm). Note the distinction between carbon density and total carbon per sample: *carbon density* is a per volume metric (i.e., is not dependent on sample thickness/size), while *total carbon per sample* is affected by the size of the sample. For example, a 0.1-meter sample may have more carbon mass than a 0.5-meter sample because the soil carbon density is greater in the shorter sample.

4.1 Belowground Carbon Content

Table 4-1 provides the elevations at which the sediment cores were taken, the core lengths, the average bulk density, average organic carbon percentage, average sediment carbon density, and total carbon within each core. For the complete dataset, see Section 4.3.

All sites were sampled to a depth of 1-meter or to refusal, whichever was reached first. We attempted to sample one core in each ecoregion (i.e., at Sites B, C, D-3, E, and F) to 3-meters' depth, but in all cases the Vibracore met refusal (i.e., the corer could not be pushed any deeper) before reaching that depth. Carbon content typically varies most in the upper 20 cm to half-meter (Fourqurean et al. 2012), but sampling deeper cores allowed further exploration of carbon patterns with depth.

Bulk density for sediments in *Z. marina* beds vary between 0.71 and 1.4 g/cm^3 in the literature (Dahl et al. 2016; Kauffman et al. 2020) and between 0.93 and 1.44 g/cm^3 in San Diego Bay,

based on these study results. Bulk density for sediments in *Z. pacifica* beds averaged 1.04 g/cm^3 at the outer bay sampling site, slightly lower than the measurements for *Z. marina*.

Dahl et al. (2016) reported sediment carbon contents between 0.05 and 0.35 g/cm^2 for *Z. marina* eelgrass beds in Europe, compared to the lab results that showed a range from 0.02 to 1.08 g/cm^2 for *Z. marina* in San Diego Bay. The sediment carbon content for *Z. pacifica* ranged from 0.06 to 0.07 g/cm^2.

In aggregate, the percent organic carbon data does not show a correlation with bulk density. However, stratifying the plot based on sediment texture (based on visual assessment) shows that the sandy sediment classes (mud/sand, sand, and sand/shell) appear to have the lowest carbon fractions. Clayey sediments as a group were also fairly low in carbon fraction. Muddy sediments and samples with shell hash generally show higher carbon content, but also a much larger range.

Figure 4-1 was constructed from the data for one core from each site (excluding the younger sites G and H). Note that the classification in Figure 4-1 and all references to sediment texture throughout the report are based on visual observation and not laboratory sieve analyses.
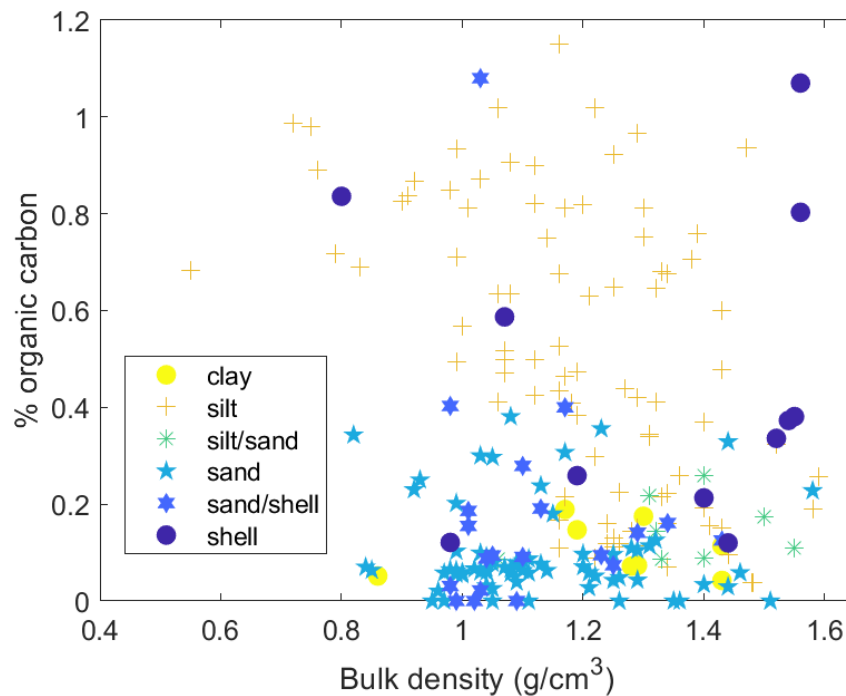

Figure 4-1. Percent Organic Carbon and Bulk Density of Various Sediment Grain Classes

TABLE 4-1
MEASURED SEDIMENT DATA

Site	Core	Sample Elevation (m NAVD)	Core Length (m)	Average Elevation (m NAVD)	Average Elevation (ft MLLW)	Bulk Density (g/cm³)	Organic Carbon Percentage	Sediment Carbon Density (gC/cm³)	Total Carbon in 1-m Core (MgC/hectare)
A (*Z.pacifica*)	1	-2.1	1	-2.1	-7	1.05	0.07%	0.0007	7.3
	2	-2.1	1			1.07	0.06%	0.0006	6.2
	3	-2.2	1.5			1.01	0.05%	0.0006	5.7
B (*Z.marina*)	1	-1.3	1	-1.3	-5	1.05	0.09%	0.0009	9.6
	2	-1.3	1			1.23	0.10%	0.0012	15.1
	3	-1.2	1			1.14	0.11%	0.0012	10.6
C (*Z.marina*)	1	-2.0	1	-2.0	-7	1.15	0.40%	0.0044	71.1
	2	-2.0	1			1.26	0.21%	0.0025	27.4
	3	-2.0	1			1.08	0.36%	0.0036	48.5
D-1 (*Z.marina*)	1	-0.3	1	-0.4	-2	0.93	0.23%	0.0022	15.9
	2	-0.4	1			1.09	0.22%	0.0024	21.0
	3	-0.3	1			1.23	0.13%	0.0016	10.7
D-2 (*Z.marina*)	1	-1.5	1	-1.6	-6	1.38	0.21%	0.0030	40.8
	2	-1.6	1			1.44	0.20%	0.0030	38.4
	3	-1.6	1			1.32	0.17%	0.0022	27.6
D-3 (*Z.marina*)	1	-2.2	1	-2.2	-8	1.28	0.13%	0.0017	8.5
	2	-2.2	1			1.36	0.43%	0.0063	87.9
	3	-2.2	2			1.29	0.25%	0.0036	32.7
E (*Z.marina*)	1	-1.5	1	-1.5	-5	1.09	0.53%	0.0053	42.9
	2	-1.5	1			1.13	0.56%	0.0056	50.1
	3	-1.5	2			1.07	0.40%	0.0037	40.9
F (*Z.marina*)	1	-1.1	1	-1.4	-2	1.10	0.76%	0.0084	86.9
	2	-1.1	1			1.25	0.81%	0.0100	99.3
	4	-2.0	2.5			1.20	0.78%	0.0090	107.9
G (*Z.marina*)	1	-1.1	1	-1.2	-4	1.36	0.02%	0.0003	1.9
	2	-1.1	1			1.01	0.04%	0.0004	2.2
	3	-1.3	1			1.02	0.04%	0.0004	2.4
H (*Z.marina*)	1	-1.9	1	-1.8	-6	1.23	0.24%	0.0023	20.4
	2	-1.8	1			1.12	0.14%	0.0014	11.1
	3	-1.6	1			1.24	0.18%	0.0022	15.2
I (*Z.marina*)	1	-2.7	1	-2.6	-9	1.28	0.31%	0.0037	24.7
	2	-2.6	1			1.21	0.40%	0.0048	37.7
	3	-2.5	1			1.36	0.23%	0.0030	17.9
J (*Z.marina*)	1	-0.9	1	-0.9	-3	1.13	0.69%	0.0077	79.5
	2	-1.0	1			1.20	0.73%	0.0085	87.2
	3	-1.0	1			1.19	0.75%	0.0087	94.5

NOTES:

Elevations were collected in ft NAVD88 in the field. A conversion of NAVD – 0.43 ft = MLLW was used throughout the bay (NOAA Tides and Currents for San Diego Bay).

4.2 Variation Across Sites

Table 4-2 summarizes average sediment carbon by site for the top one meter of sediment. This allows for a high-level comparison across the environmental variables of interest. The carbon in the top one meter ranged from 1.9 to 107.9 Mg C/ha. This is comparable to the large range found in the literature. For example, Dahl et al. (2016) measured belowground carbon in *Z. marina* beds in Europe and found total carbon from 5 to 35 Mg C/ha, while Kauffman et al. (2020) found 216.3 Mg C/ha of belowground carbon in *Z. marina beds* in the Pacific Northwest. **Figure 4-2** shows the average sediment carbon for the top 1-meter of sediment across the bay.

TABLE 4-2
EELGRASS SOIL CARBON BY SITE

Site	Carbon to 1-m depth (Mg C/ha)
A	6.4 ± 0.8
B	11.8 ± 3.0
C	48.0 ± 21.9
D-1	15.8 ± 5.2
D-2	35.6 ± 7.0
D-3	43.0 ± 40.7
E	44.6 ± 4.8
F	98.0 ± 10.5
G	2.2 ± 0.3
H	15.5 ± 4.6
I	26.8 ± 10.1
J	87.1 ± 7.5

Carbon_Content_MgC/ha
- 1
- 5
- 10
- 50
- 100

North

North Central

Outer Bay

C

B

A

D-1, D-2, D-3

E

South Central

I

South

H

F

G J

0   2
Miles

N

Maxar
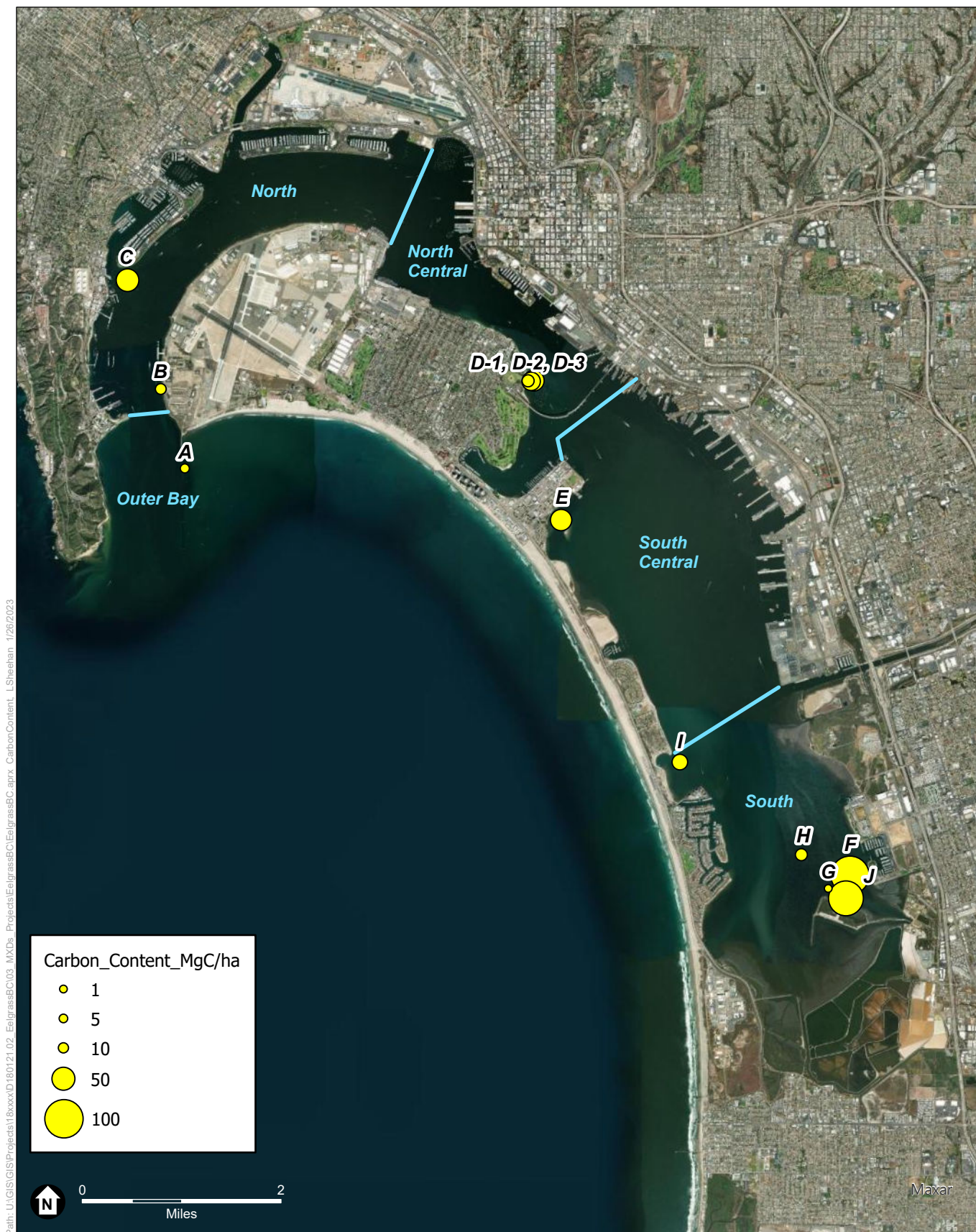
SOURCE: ESA, 2021

San Diego Bay Eelgrass Blue Carbon Study

Figure 4-2
Total Carbon in 1-m Core (MgC/hectare)

ESA

4.2.1 Species

Sites A and B represented *Z. pacifica* and *Z. marina* beds, respectively. The *Z. pacifica* bed had lower sediment carbon storage despite the plants' larger biomass compared to *Z. marina* (**Figure 4-3**). This may be due to non-biological factors, including the greater wave energy and detrital transport away from Site A compared to Site B, which may cause less carbon to remain in place. The sandy sediment and high circulation within the open coastal Site A would naturally be less likely to retain and sequester particulate organic matter and thus accumulate organic carbon. However, the two species were not significantly different from each other ($p > 0.05$).
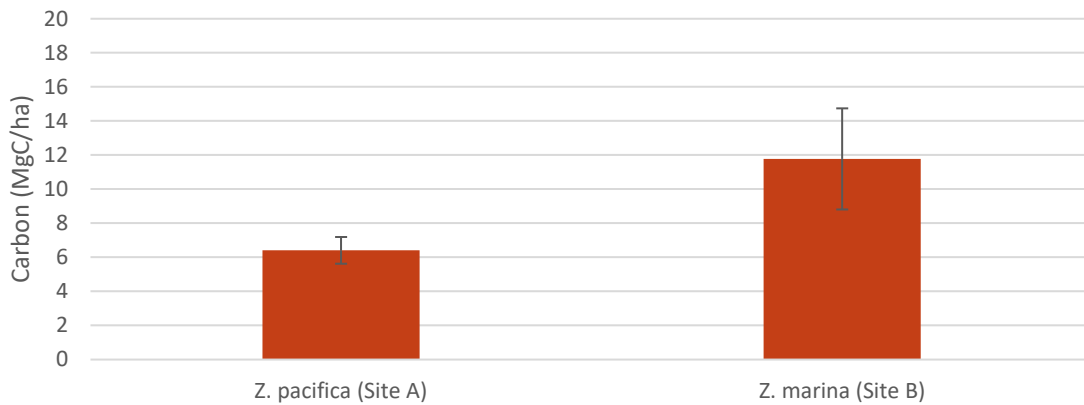
Figure 4-3. Sediment Carbon by Species

4.2.2 Ecoregion

Figure 4-4 compares the total belowground carbon between Sites B, C, D-2, E, and F to illustrate the difference between the ecoregions within the bay. This plot shows a general trend of increasing carbon going southward within the bay. In particular, the Outer Bay stored significantly less carbon ($p < 0.05$) than North Central, South Central, and South Bays, and storage was also significantly different ($p < 0.05$) between the South Bay and the two ecoregions just north of it (North Central and South Central).

By Ecoregion
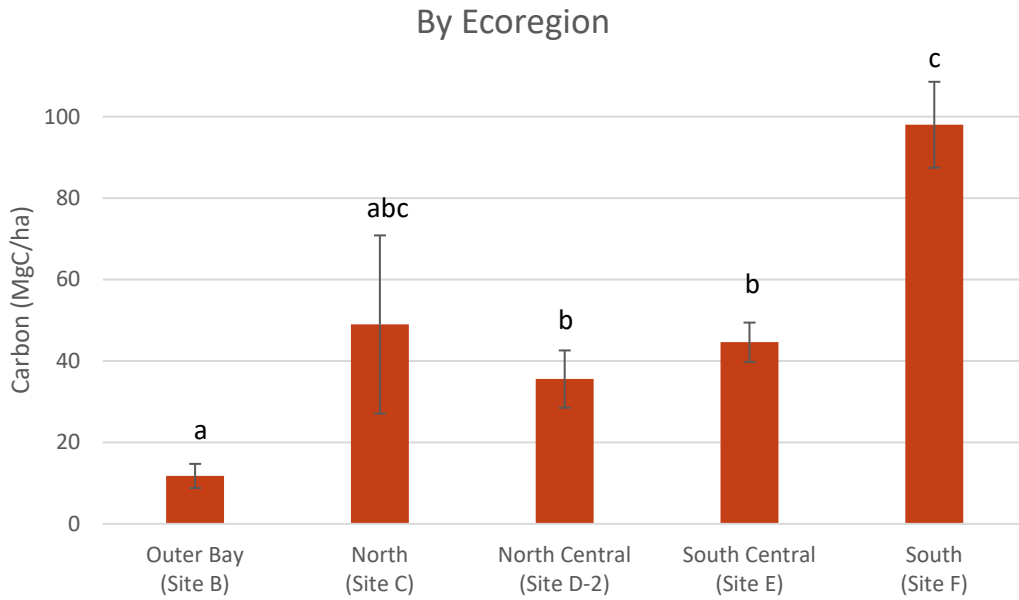
Note: The letters above each bar represent statistical significance from bars with other letters. For example, the "a" above Outer Bay
   indicates that this site was statistically different from the North Central, South Central, and South sites (which do not have "a" above the
   bar), but not statistically different from the North site (which does have an "a" above the bar).

Figure 4-4. Sediment Carbon by Ecoregion

4.2.3 Bed Depth

Sites D-1, D-2, and D-3 allow for comparison across depth. The data shows that the average
carbon content may increase with increasing depth (**Figure 4-5**). The middle depth (-5 ft MLLW)
showed significantly ($p < 0.05$) more carbon than the shallowest depth (-1 ft MLLW). The
deepest cores (-7 ft MLLW) showed a substantial amount of variability, so this site was not
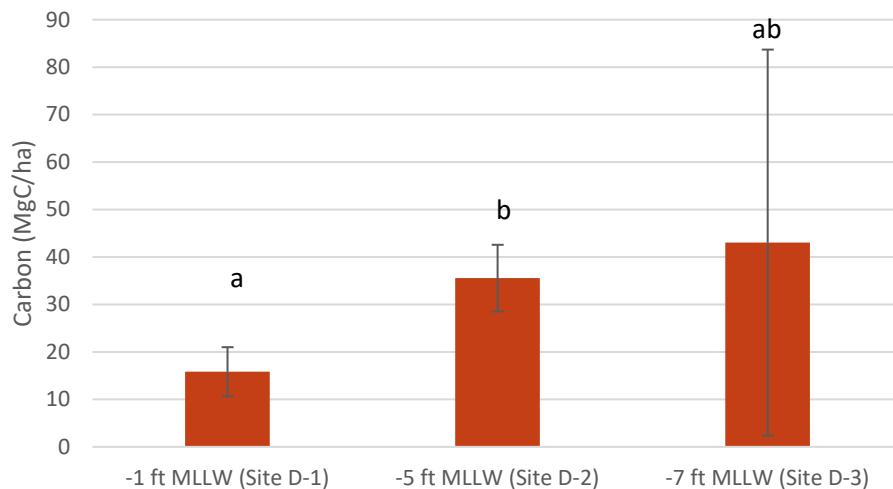statistically significant from the other two depths.

Figure 4-5. Sediment Carbon by Bed Depth

As discussed in Section 2, sampling depths varied more than intended across the other sites. When the carbon content for all sites is analyzed by depth, the pattern is less clear. As shown in **Figure 4-6**, the two highest carbon content sites (Sites F and J) were taken at shallow depths (-1.9 and -3.4 ft MLLW, respectively).
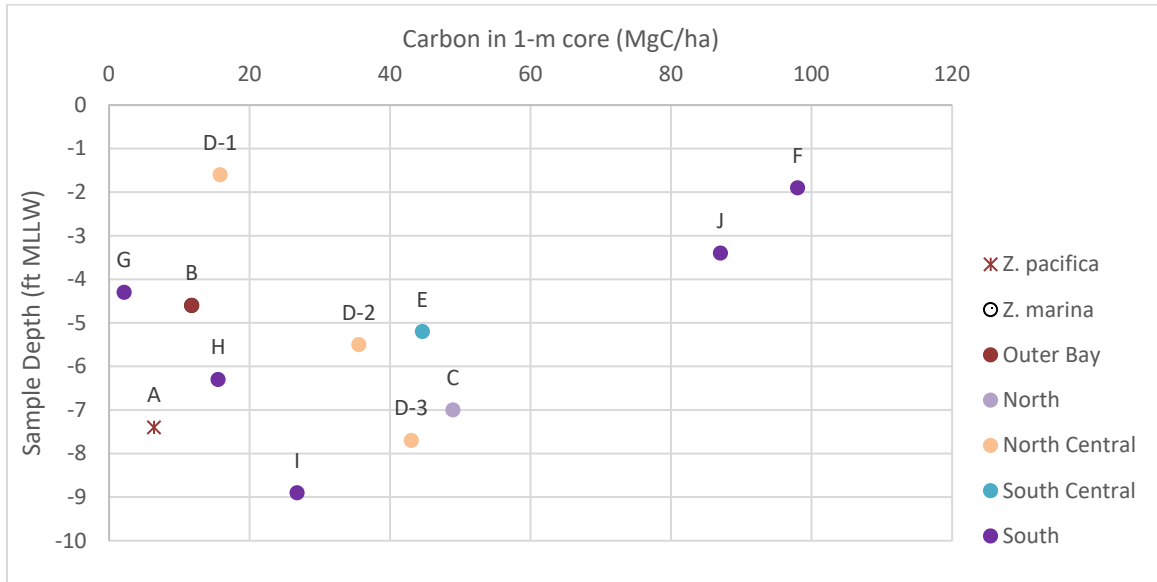
Figure 4-6. Sediment Carbon by Bed Depth for All Sites

4.2.4 Bed Age

Eelgrass beds of different ages were compared to evaluate variations in the amount of carbon stored in younger and older systems. As shown in **Figure 4-7**, the older sites (Sites F and J) had significantly ($p < 0.01$) greater amounts of carbon in the soils than the younger sites (Sites G and H). Additionally, Site J, which was planted in 1987, had significantly ($p < 0.01$) more carbon than Site H, which was restored in 2006-2007, which had significantly ($p < 0.05$) more carbon than Site G was restored more recently in 2017.

Site J was planted in 1987 on the Chula Vista Wildlife Reserve, an island constructed between 1974 and 1979 with fill material from the construction of the Chula Vista Marina Basin. Site H was planted in 2006-2007 on fill placed by scow dump in a sediment borrow site depression during the same period from a prior upland fill. Finally, Site G was planted in 2017 on sediment fill that was hydraulically placed in a decommissioned cooling water channel to develop eelgrass habitat (Merkel, pers. Obs.).

Figure 4-7. Sediment Carbon by Bed Age

As shown in **Figure 4-8**, the data depicts a strong linear relationship between eelgrass bed age and carbon content. Additionally, Sites J, H, and G were all restoration projects involving fill placement to raise bay floor elevations, so carbon accumulation may continue to develop as the sites mature. A meta-analysis of 621 wetland restoration sites around the globe showed that, while hydrologic functions are quick to recover to levels comparable to reference sites, biological and biogeochemical functions (including carbon storage) often lag behind throughout the century-long analysis period (Moreno-Mateos et al. 2012).
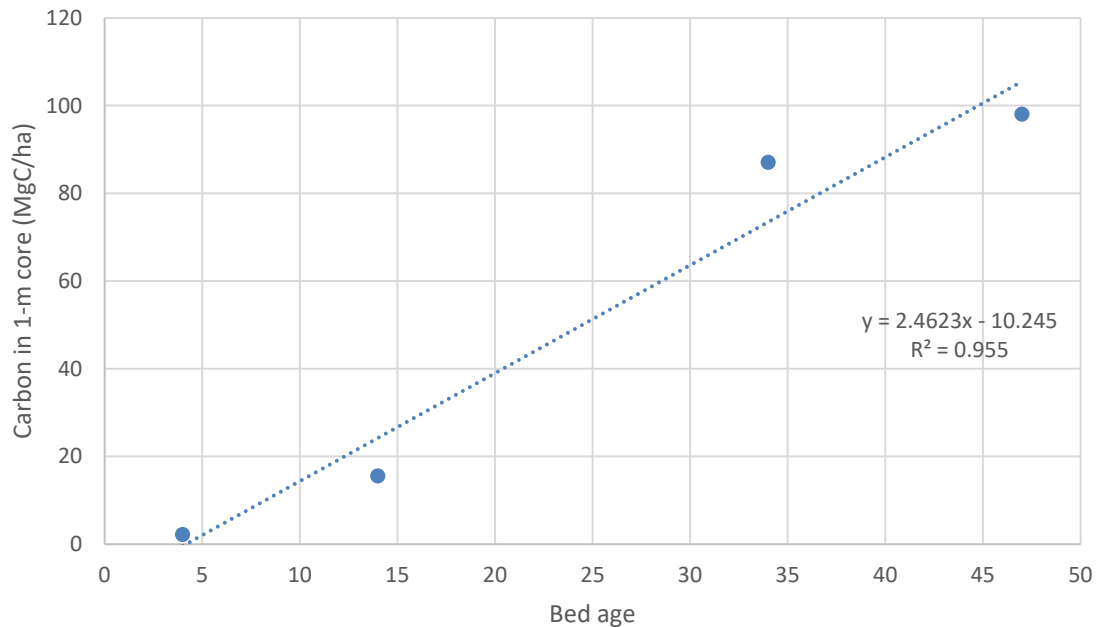

Figure 4-8. Sediment Carbon Related to Bed Age

4.3 Variation Along Depth of Core

Along with examining the spatial variability of carbon content, it is also important to understand how carbon content varies down cores. **Figure 4-9** shows all bulk density profiles, **Figure 4-10** shows all percent organic carbon profiles, and **Figure 4-11** shows all carbon density profiles.

Bulk density profiles do not display any outstanding patterns except a slight shift to more dense sediment compositions further south in the bay. Within each site, the triplicate profiles are generally in good agreement with one another. Bulk density of samples collected below 1-meter depth were not particularly lower than in the rest of the core.
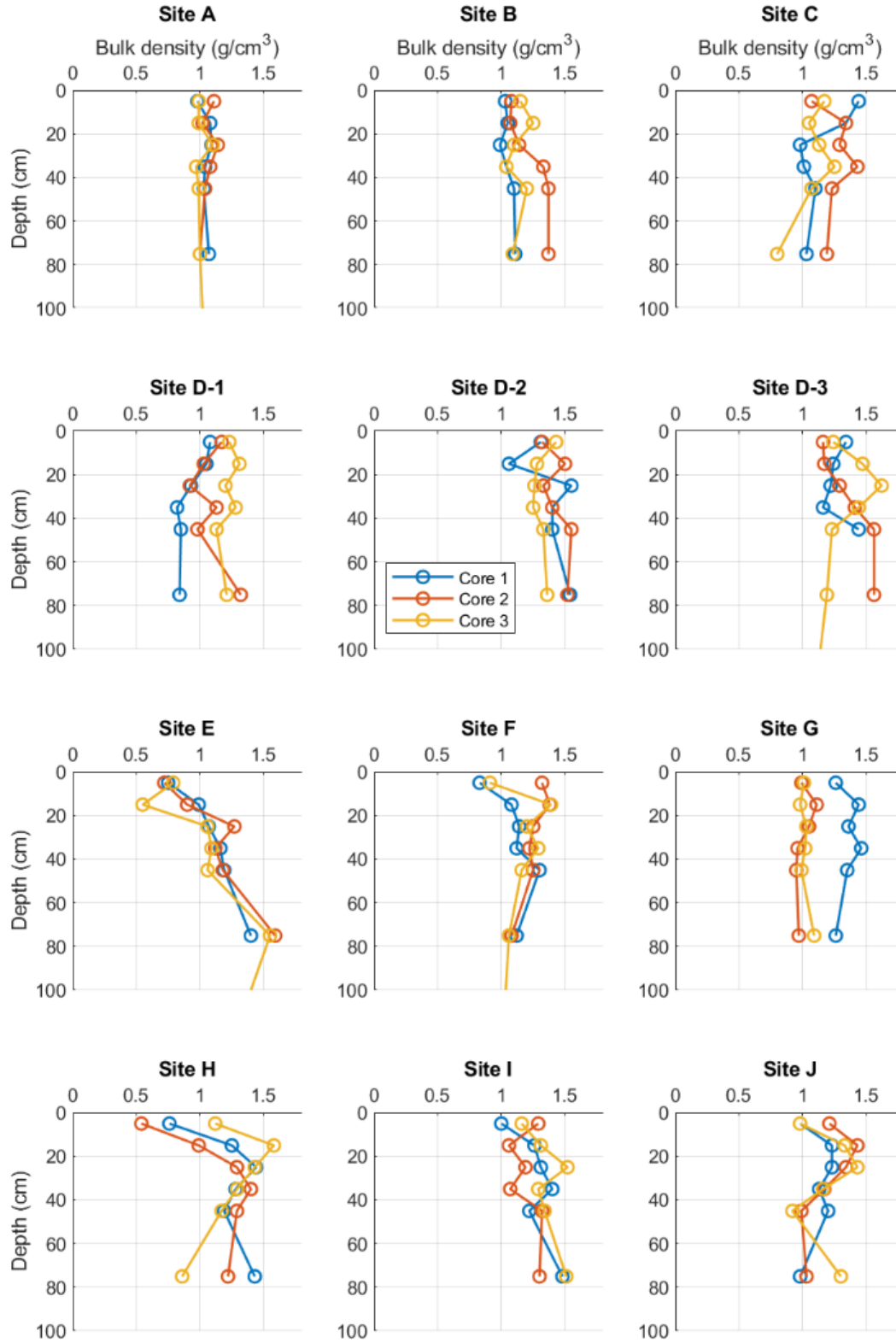
The percent organic carbon profiles display much greater variation both across the bay and within the sets of triplicates. Not including the two youngest sites (Sites G and H), the percent of organic carbon (i.e., g C / g sediments) is highest in the South Central and South Bay ecoregions. Additionally, those profiles show more variation down the core. Samples from below 1-meter depth tended to be lower in carbon than the rest of the core.

It is often expected that carbon content will be greatest at the surface (Kindeberg et al. 2019) where organic matter is input into the sediment column and will then decrease with depth as mixing and remineralization slowly decrease the carbon store. This was observed at several sites in this study (e.g., Sites D-1, G, and H), where the profiles appeared to reach an asymptote, from which we infer that carbon below that depth is buried and unlikely to change.

However, a plurality of depth profiles from this study show greater complexity and follow a more mixed or indistinct pattern. None of the profiles show monotonically increasing carbon percentage with depth, which was observed in a minority of sites (i.e., 7 of 47) in a study aggregating cores from *Z. marina* beds throughout the Northern Hemisphere (Kindeberg et al. 2019).

More mixed profiles, along with the variability between triplicates, such as those observed at Sites F, D-3, and C complicate the process of using discrete cores to extrapolate carbon estimates across areas and into the ground as the pattern is not consistent or predictable with depth. For instance, cores at Site D-3 show sharp jumps in carbon density at 40–100 cm depth (Core 2) and at 10–30 cm depth (Core 3) to values an order of magnitude larger than elsewhere in the core. Given the relatively low carbon content of these sediments, it is possible that the inclusion of a small fragment of plant matter may have caused the jumps observed above. Indeed, Kindeberg (2019) found that these mixed profiles were associated with bioturbation and high mixing.

The cores that were taken beyond 1-meter depth all showed additional carbon is stored below the top 1-meter. The longer cores showed that the top 1-meter contained 56-90% of the carbon within the core.

San Diego Bay Eelgrass Blue Carbon Study

Figure 4-9
Bulk Density by Depth
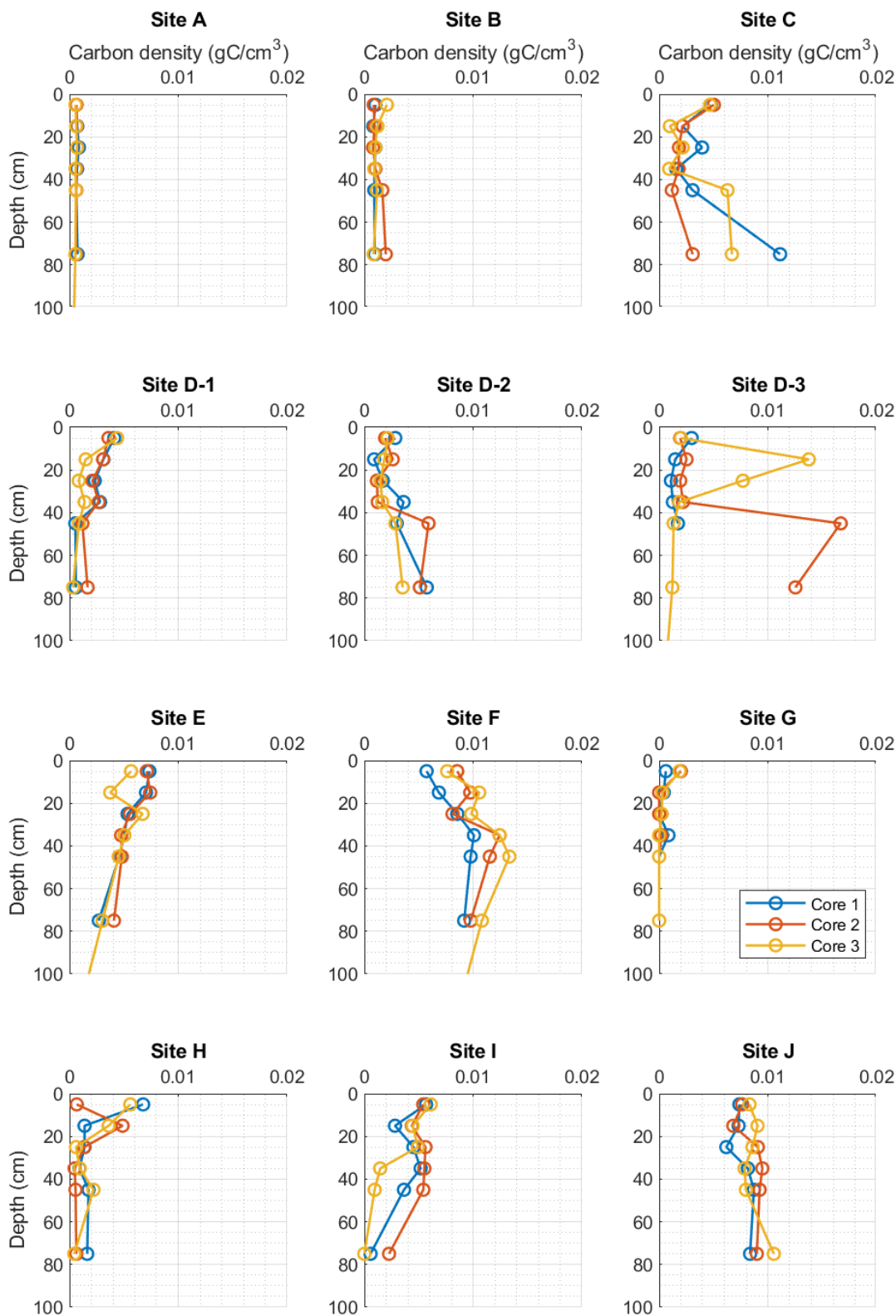
San Diego Bay Eelgrass Blue Carbon Study

Figure 4-10
Percent organic carbon profiles for all sediment cores
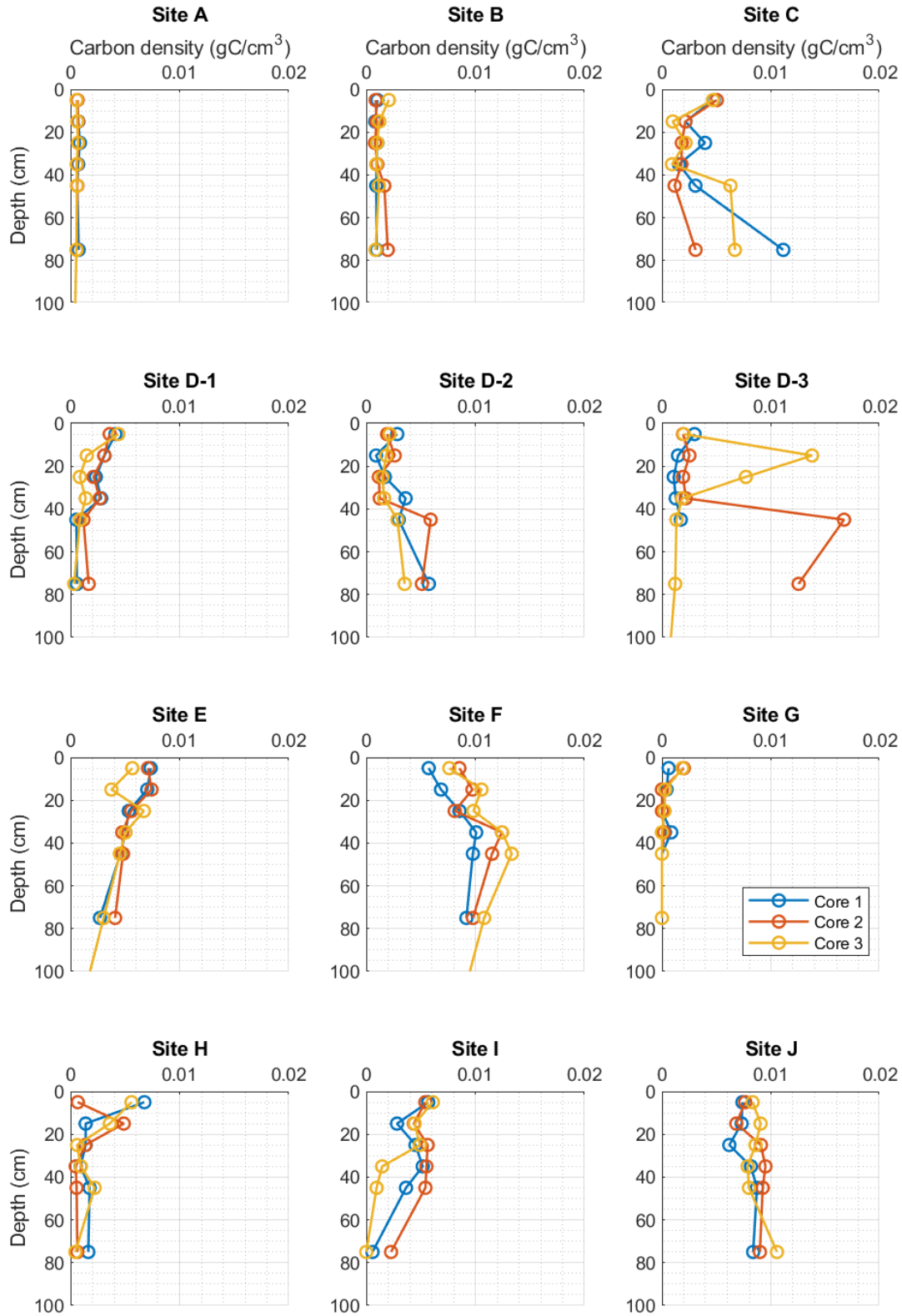
San Diego Bay Eelgrass Blue Carbon Study

Figure 4-11
Carbon density profiles for all sediment cores

Comparing sites in the South Bay (Sites F, I, and J) with the nearby younger restoration Sites H (established 2006–2007) and G (2017) reveals that while carbon content at the younger restoration sites decreases with depth, the profiles are more indistinct in the other sites. The sediment at Sites G and H was more varied, consisting of fines, sands, and shell hash. By comparison, the sediment at Sites F, I, and J was much more uniform and dominated by mud. Some cores had more compacted clay at depth (i.e., in the deepest one or two samples). The variation in sediments of Sites G and H could be a result of fill used in the restoration resulting in higher carbon near the surface from the eelgrass and less carbon below in the fill.

SECTION 5
Total Carbon Quantification

5.1 Aboveground Carbon Pool

Since 2007, Naval Facilities Engineering Command Southwest has undertaken biannual monitoring of permanently established transects at 25 locations throughout the bay. Additionally, bay-wide eelgrass surveys have been jointly performed by the Navy and the Port every three to five years. Total eelgrass acreage in San Diego Bay has varied from 1,091 acres in 1993 to a high of 2,598 acres in 2020. **Figure 5-1** shows the eelgrass extent in San Diego Bay.

The eelgrass areas from these surveys can be used to estimate the total aboveground carbon pool by ecoregion, as shown in **Table 5-1**. We assumed that 80% of the Outer Bay is made up of *Z. pacifica* and 20% is *Z. marina* (correspondence with K. Merkel, January 28, 2022). Due to the high carbon content in *Z. pacifica* (Section 3.4.1), the outer bay shows the highest aboveground carbon in the bay (**Figure 5-2**). In years when the acreage of eelgrass in the Outer Bay is lower, the total estimated aboveground carbon stored in the bay's eelgrasses is also lower. However, it should be noted that while bed area has increased over time, in recent years, the overall biomass of eelgrass is believed to have declined substantially with more diminutive plants comprising most of the *Z. marina* beds in the bay, as discussed in Section 3.1.

TABLE 5-1
HISTORIC ABOVEGROUND CARBON IN SAN DIEGO BAY (TONNES CO$_2$ EQUIVALENT)

Ecoregion	1993	1999	2004	2008	2011	2014	2017	2020
Outer Bay (*Z. pacifica*)	27	37	435	301	291	238	35	94
Outer Bay (*Z. marina*)	2	3	29	20	20	16	2	6
North	5	8	8	8	12	10	10	15
North Central	5	10	6	7	11	8	9	5
South Central	41	52	43	32	37	26	26	72
South	74	113	133	70	115	145	137	195
Total	**154**	**224**	**654**	**439**	**484**	**444**	**220**	**388**

NOTES:

Results from Sites D-1, D-2, and D-3 were averaged for the North Central ecoregion, while Sites F, G, H, I, and J were averaged from the South ecoregion.

Occurrence Frequency

- 100%
- 88%
- 75%
- 63%
- 50%
- 38%
- 25%
- 13%
- 8%

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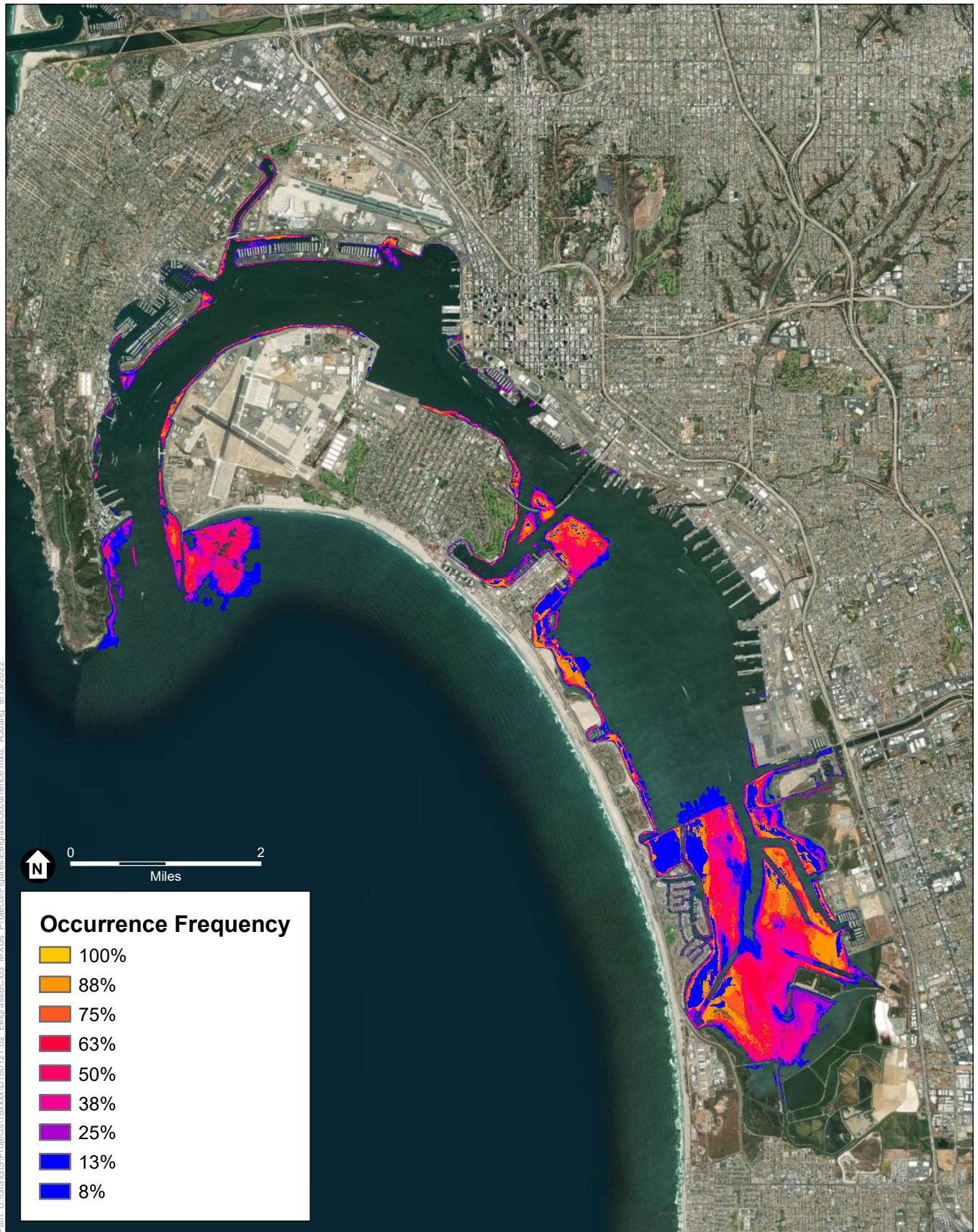
SOURCE: Merkel

San Diego Bay Eelgrass Blue Carbon Study

Figure 5-1
Eelgrass Extent and Occurrence (1993-2020)

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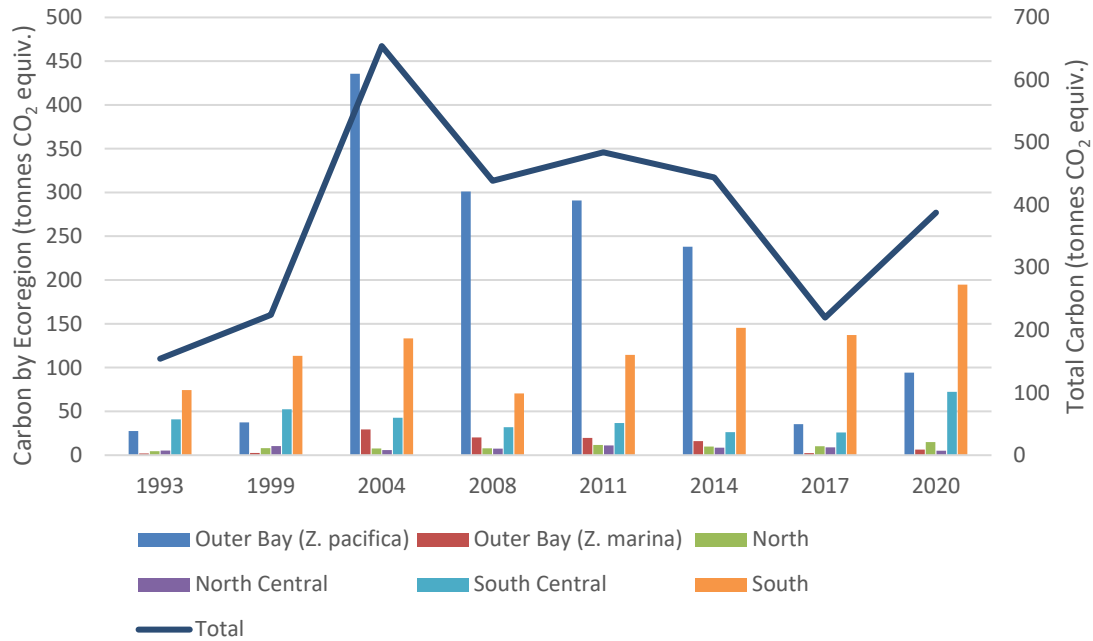
Figure 5-2. Total Aboveground Carbon in San Diego Bay Over Time

5.2 Belowground Carbon Pool

Similarly, the belowground carbon pool can be estimated by multiplying the area within an ecoregion by the carbon content. **Table 5-2** shows the resulting belowground carbon within the bay for 2020. The carbon stored in the top 1-meter of sediment is several orders of magnitude higher than the carbon stored aboveground.

TABLE 5-2
BELOWGROUND CARBON IN SAN DIEGO BAY

Ecoregion	Belowground Carbon (tonnes CO_2 equiv.)
Outer Bay	1,000
North	11,840
North Central	2,530
South Central	30,670
South	124,530
Total	**170,560**

NOTES:

Based on 2020 eelgrass areas

Since the longer cores suggested that the top 1-meter of sediment stores 56-90% of the total carbon, the total belowground carbon pool could be as large as 187,617 – 245,608 tonnes CO_2 equivalent.

5.3 Total Carbon Pool

Combining aboveground and belowground carbon gives the total eelgrass carbon pool in San Diego Bay (**Table 5-3**). The patterns are similar to the belowground carbon since the aboveground carbon is much smaller. The majority of the carbon within the bay is belowground in the South ecoregion (73.0%).

TABLE 5-3
TOTAL EELGRASS CARBON IN SAN DIEGO BAY

Ecoregion	Carbon (tonnes CO_2 equiv.)	Percentage of Total
Outer Bay	1,100	0.7%
North	11,850	6.9%
North Central	2,530	1.5%
South Central	30,740	18.0%
South	124,700	73.0%
Total	**170,900**	**100%**

NOTES:

Results for Z. pacifica and Z. marina were added together for the Outer Bay. Results from Sites D-1, D-2, and D-3 were averaged for the North Central ecoregion, while Sites F, G, H, I, and J were averaged from the South ecoregion.

The total ecosystem carbon in San Diego Bay ranged from 2-98 Mg C/ha, which is within the range that has been found in the literature (Fourqurean et al. 2012; Kauffman et al. 2020; Kim et al. 2022). **Table 5-4** presents carbon content values in the literature compared to what we have found with this study.

TABLE 5-4
CARBON CONTENT VALUES IN THE LITERATURE

Paper	Study Location	Species	Seagrass Bed Total Carbon Content (Mg C/ha)
Fourqurean et al. 2012	Global	Variable	0.001 – 23
Dahl et al. 2016[a]	Europe	Z. marina	70 – 190
Rohr et al. 2016	Finland and Denmark	Z. marina	0.2 – 43
Kauffman et al. 2020	Pacific Northwest, USA	Z. marina	46 – 389
Kim et al. 2022	Korea	Z. marina	49 – 125
This study	San Diego, CA, USA	Z. marina	2 – 98

NOTES:

a. We multiplied the reported bulk density by the percent carbon and added the aboveground and belowground biomass to develop these values.

5.4 Carbon Assimilation Rates

The eelgrass areas combined with the productivity data results in the assimilation rates within the bay. **Table 5-5** shows the assimilation rates over time.

TABLE 5-5
EELGRASS ASSIMILATION IN SAN DIEGO BAY (TONNES CO_2 EQUIVALENT/YEAR)

Ecoregion	1993	1999	2004	2008	2011	2014	2017	2020
Outer Bay (Z. pacifica)	60	82	954	659	637	521	77	207
Outer Bay (Z. marina)	47	64	748	517	499	409	61	162
North	179	314	299	306	454	381	397	584
North Central	616	1,201	676	857	1,283	988	1,042	593
South Central	2,589	3,318	2,700	2,021	2,323	1,658	1,643	4,582
South	4,333	6,619	7,778	4,108	6,681	8,484	7,998	11,359
Total	**7,824**	**11,598**	**13,154**	**8,467**	**11,878**	**12,441**	**11,218**	**17,485**

NOTES:

Results from Sites D-1, D-2, and D-3 were averaged for the North Central ecoregion, while Sites F, G, H, I, and J were averaged from the South ecoregion.

5.5 Carbon Over Time with Sea-Level Rise

5.5.1 Sea-Level Rise

In 2019, the Port of San Diego completed its Sea Level Rise Vulnerability and Coastal Resiliency Report pursuant to Assembly Bill 691. As part of this report, the Port chose sea-level rise projections representing the 50th and 95th percentiles from the 2018 Ocean Protection Council (OPC) guidance (**Table 5-6**). We used the Port's medium-term (2050) projection and the two long-term (2100) projections in order to bracket the uncertainty inherent in longer-term projections.

TABLE 5-6
PORT OF SAN DIEGO'S SELECTED SEA-LEVEL RISE PROJECTIONS (IN FEET)

	2030	2050	2100
95th Percentile Projection	0.7	1.4	4.5
50th Percentile Projection	n/a	(0.9)	2.6

Note: values in parentheses represent OPC projections that were not adopted by the Port of San Diego. They are included here for context.

5.5.2 Habitat Evolution Methods

Eelgrass can grow at specific elevation bands dictated in large part by light penetration fixing the lower depth of beds and desiccation stress establishing the upper limits of the beds. In San Diego Bay, eelgrass has colonized most of the available area within this elevation range and fluctuates in distribution based on variability in the controlling environmental parameters (Merkel &

Associates 2000; Merkel and Sutton 2000). ESA developed a habitat evolution model that assumes eelgrass colonization continues to be correlated with depth as sea levels change. Note that this model does not account for the possible influence of other factors, such as rising temperatures, water quality changes, human activity within the bay, etc. that have previously been shown to be important to the distribution of eelgrass within the bay (Merkel & Sutton 2000).

The model is based on the Port's bay-wide eelgrass occurrence frequency dataset, which is based on mapped eelgrass extent throughout San Diego Bay in 1993, 1999, 2004, 2008, 2011, 2014, 2017, and 2020 (Merkel & Associates 2020). Across these surveys, eelgrass was found between -21 and -0.4 ft NAVD88[9], and it was most likely to occur between roughly -6.4 and -0.4 ft NAVD88. *Z. pacifica* at the mouth of the bay accounts for the majority of the deeper eelgrass, while *Z. marina* accounts for the shallower eelgrass. Notably, eelgrass extended much deeper in 2020 than it has during prior survey years (Merkel & Associates 2020).

Approximate elevation ranges were selected to represent the likelihood of eelgrass occurrence. The elevation ranges were then applied to the Coastal National Elevation Database (CoNED) topobathy dataset. For example, any elevation between -4.5 and -6.5 was categorized as 33% likely to occur, while elevations between -3 and -0.5 were categorized as 88% likely to occur.

The results are compared to the actual observed occurrence in **Figure 5-3**. Since it is based solely on elevation and does not consider other biological factors, the model can only approximately predict eelgrass occurrence frequency on either end of the bay (i.e., Outer Bay and South Bay). However, it does an acceptable job of predicting the spatial extent of eelgrass. The variation in eelgrass occurrence does not correspond with elevations exactly, so the model results should be considered an approximate representation of future conditions.

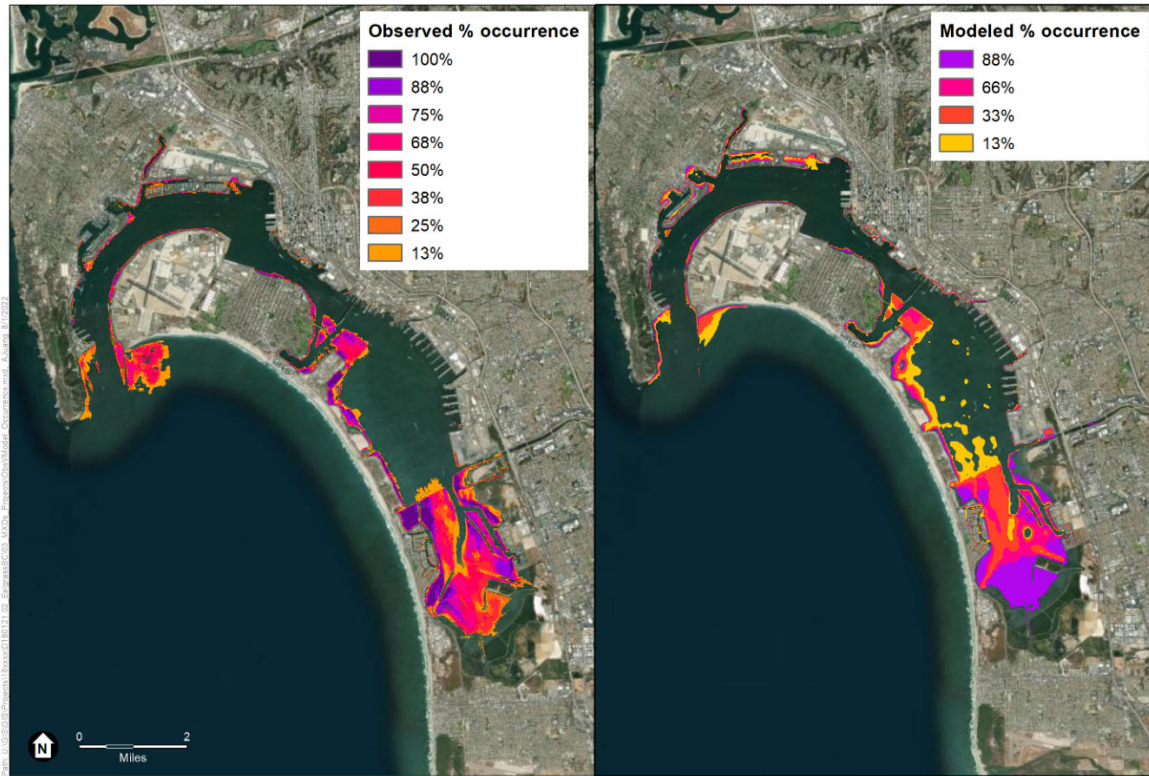[9] North American Vertical Datum of 1988

Figure 5-3. Observed vs Modeled Eelgrass Occurrence

The elevation model can be used to project how eelgrass habitat acreages may evolve over time under various sea-level rise scenarios based on habitat elevations. **Table 5-7** shows the results of the model for different amounts of sea-level rise.

TABLE 5-7
PREDICTED EELGRASS HABITAT WITH SEA-LEVEL RISE

	Area (ha) by % occurrence				
	<13%	33%	66%	88%	Weighted Total
Existing	501	326	226	451	686
0.7 ft SLR	474	292	226	464	685
1.4 ft SLR	485	284	214	448	661
2.6 ft SLR	532	278	331	258	572
4.5 ft SLR	497	398	163	119	376

Figure 5-4 shows the seagrass habitat over time for San Diego Bay from 2020 to 2100. The model forecasts that the total extent of habitat will decrease over time. However, this habitat loss does not occur uniformly. Over time, eelgrass encroaches closer to the present-day shoreline, while habitat loss occurs largely in the interior of the bay. Habitat gain is concentrated in the South Bay, while habitat loss is concentrated first in the South Central Bay but is eventually modeled to occur in all other ecoregions. The bathymetry and bay margin conditions has much to

do with whether sea-level rise will result in gains or losses within a particular location, and the heavily urbanized margins of the bay generally leave little room for shoreward migration of eelgrass in all but the South Bay. **These results should be interpreted with some caution**, as the model provides a very simplified presentation of dominant controlling factors. Additionally, accretion is not included in the model and could help seagrasses keep pace with sea-level rise.

5.5.3 Carbon Pool Evolution

Using the sequestration rates from the literature discussed in Section 3.5, we can estimate the amount of carbon sequestered in the future with different amounts of sea-level rise (**Table 5-8**).

TABLE 5-8
CUMULATIVE EELGRASS CARBON SEQUESTRATION (TONNES CO_2 EQUIVALENT)

	By 2030	By 2050	By 2100
Low carbon sequestration (rate from Duarte et al. 2011)			
95th Percentile SLR Projection	10,500	23,300	50,800
50th Percentile SLR Projection			79,600
High carbon sequestration (rate from McLeod et al. 2011)			
95th Percentile SLR Projection	27,800	61,200	133,600
50th Percentile SLR Projection			209,600

While the eelgrass habitats do continue to sequester carbon through the end of the century, these results must still be read in the context of the diminishing habitat areas projected in Table 5-7 (i.e., total seagrass habitat decreasing from 686 acres today to 376 acres with 4.5 ft of sea-level rise).

2030 (0.7 ft SLR)

Change from baseline
- Lost habitat
- Gained habitat

2050 (1.4 ft SLR)

2100 (2.6 ft SLR)

2100 (4.5 ft SLR)

0 0.5 1   2 Miles
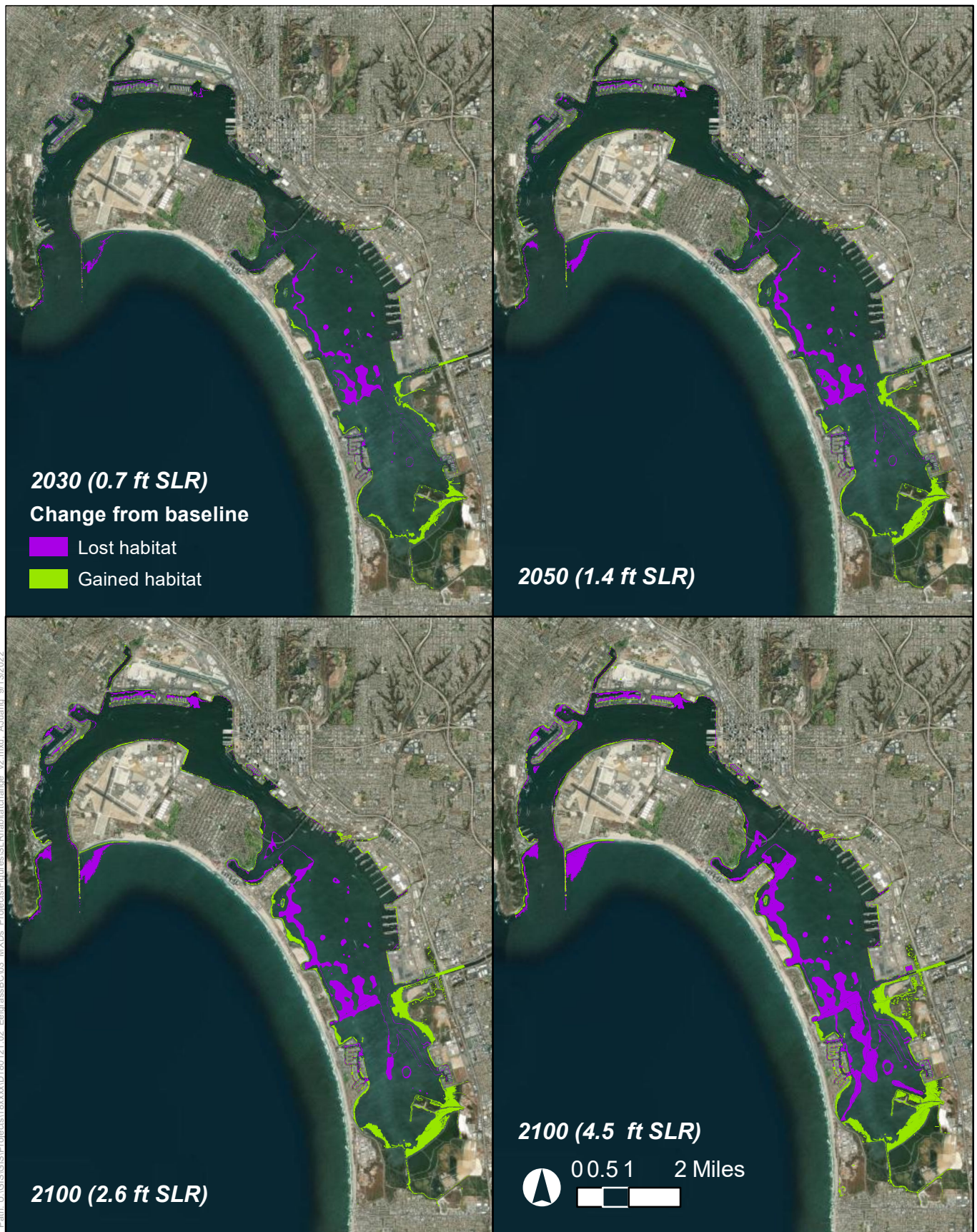
SOURCE: Merkel, USGS

San Diego Bay Eelgrass Blue Carbon Study

Figure 5-4
Habitat Evolution Model Results

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SECTION 6
Conclusions

San Diego Bay's eelgrass habitats store around 170,600 tonnes of CO_2 equivalent currently (i.e., in total, not on an annual basis). This figure is comparable to about half a years' worth of emissions from Port operations based on the predicted 2020 emissions data (Port of San Diego 2013). The Year 2 follow-up study planned for 2022-2023 will shed light on the habitats' annual sequestration abilities to facilitate a more direct estimate of annual emissions versus annual seagrass carbon sequestration.

The aboveground carbon content of the bay's seagrass beds is lower than values in the literature, potentially due to reduced nutrient load in the bay as discussed in Section 3.1. However, the total ecosystem carbon (i.e., sum of aboveground and belowground carbon) are within the range found in the literature (Fourqurean et al. 2012; Kauffman et al. 2020; Kim et al. 2022). The average ecosystem carbon for the bay is 36.0 ± 45.3 Mg C/ha, and up to 46.3 Mg C/ha if carbon below the top one meter is considered. The bay has been identified as having statewide significance for eelgrass habitat, supporting approximately 17% of California's eelgrass habitat in any given year (Merkel & Associates 2020). As a result, the Port and Navy have mapped, monitored, and managed eelgrass within the bay since the early 1990s. Continuing to manage these habitats will be important to maintaining blue carbon storage in San Diego Bay.

Management of eelgrass habitats is also important because these habitats may evolve over time due to sea-level rise. Based on the habitat evolution model results, San Diego Bay's eelgrass habitats may experience a net loss of area with sea-level rise but are nonetheless expected to remove a total of between 50,800 and 209,600 tonnes of CO_2 from the atmosphere by 2100, comparable to removing all ocean-going vessels for ten months to over 3 years (Port of San Diego 2013, 2016). If higher sea-level rise projections are realized, creating more space for landward habitat migration will be necessary to maintain eelgrass and other coastal blue carbon habitats.

Further improvements in water quality may help drive further expansion of seagrasses into deeper waters and also slow the rate of the migration of this boundary with sea-level rise. However, it is believed the increased water clarity is due to pollution control (i.e., nutrient reduction) and drought-reduced water column productivity, which has led to diminishing biomass of eelgrass bay-wide. It is critical that this benefit-cost relationship be better understood.

Additionally, expansion of seagrasses into newly inundated areas throughout the bay where other important blue carbon habitats may be lost is crucial to slowing the loss of eelgrass habitat and maintaining the bay's overall carbon sequestration potential. If this seagrass expansion with sea-

level rise does not occur, then it is likely that carbon sequestration would decrease. Additionally, if sea-level rise stresses the ecosystem, loss of eelgrass could become part of a positive feedback loop leading to further losses, as seagrass meadows filter particulates out of the water column, and thus improve water clarity.

The Port has recently (December 2021) implemented a native oyster living shoreline restoration project which was designed to protect intertidal habitats from erosion. Monitoring of this pilot project is expected to provide best practices to inform additional living shorelines projects that could help maintain elevations for eelgrass habitat into the future. Similarly, the Navy and Port are working towards seeking opportunities for in-bay beneficial reuse of dredged sediments to raise the bay floor in order to add eelgrass habitat ahead of losses predicted due to sea-level rise.

Mechanisms and procedures have also been developed to connect coastal wetland management to the carbon market, where appropriate.[10] A growing number of case studies can inform management agencies and policy developers on coastal wetland management and carbon finance markets (Sheehan et al. 2019; Crooks et al. 2014). While the existing eelgrass in San Diego Bay is already protected by regulations, and therefore would not meet the additionality requirements to sell blue carbon credits, this study provides new research to inform future blue carbon projects. To bring a blue carbon project to market, local data is needed to accurately predict how much carbon will be sequestered by the project. This study provides needed information on how carbon content varies by eelgrass species, location, depth, and age of the bed. In particular, the trend suggesting that older restored eelgrass beds have higher amounts of carbon in the sediments compared to newer restored beds could provide justification for restoring eelgrass beds to sequester blue carbon with the understanding that carbon would build up in the sediments over time.

This iteration of the Eelgrass Blue Carbon Study, along with a second year of research funded by MARAD's Maritime Environmental and Technical Assistance (META) Program on the bicarbonate pathway, will help scientists and policy makers better understand the carbon sequestration and capture rates of eelgrass habitats. Initiating this study at the Port of San Diego can lend information to other similar coastal ports throughout the nation that are investigating blue carbon sequestration to offset waterside and landside carbon emissions at ports. The MARAD META program helped to fund this study as part of a broader effort to address overall maritime decarbonization in support of a safe and efficient U.S. maritime transportation system. This knowledge will assist ports, natural resource agencies, maritime operations, and other organizations to successfully build comprehensive on-site mitigation plans to support the pursuit of carbon neutrality. The transportation sector can incorporate both on-site mitigation and potentially the creation of bankable offsets via natural systems like eelgrass habitat restoration. This will allow for more optionality within their Scope 1, 2, and 3 emissions inventories to align with regulations, environmental, social, and governance (ESG) initiatives and ultimately the pursuit of carbon neutrality.

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[10] http://www.v-c-s.org/methodologies/methodology-tidal-wetland-and-seagrass-restoration-v10

The following recommendations are made for future studies:

1. Developing a San Diego Bay–specific sequestration rate would allow for a direct comparison to assimilation rates and would provide more accurate carbon evolution modeling results.

2. A potential pathway for carbon sequestration mediated by seagrasses in carbonate sediments has been noted within this study. Further investigations into inorganic carbon pathways and carbon sequestration within the bicarbonate pool should be undertaken to test this hypothesis.

3. Water quality data could provide additional information on the bicarbonate pathway (through changes in pH) and could be used to estimate productivity through the air-water CO_2 flux to compare against measurements in this study.

4. Refinements in sea-level rise estimates, additional restoration, and changes to water quality could affect the findings of this study and should be considered.

5. Grain size or other supplementary sediment analyses (e.g., isotope measurements) could help further illuminate patterns and causes of carbon storage in the sediment.

6. Conduct follow-up sampling of eelgrass productivity when drought conditions end, and eelgrass returns to more "normal" aboveground biomass conditions.

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