Office of National Marine Sanctuaries
National Oceanic and Atmospheric Administration

NATIONAL MARINE SANCTUARIES CONSERVATION SERIES

Blue Carbon in Marine Protected Areas Part 3: An Evaluation of Sedimentary Carbon Stocks in Greater Farallones and Cordell Bank National Marine Sanctuaries

November 2023 | sanctuaries.noaa.gov
National Marine Sanctuaries Conservation Science Series ONMS-23-09

U.S. Department of Commerce
Gina Raimondo, Secretary

National Oceanic and Atmospheric Administration
Richard W. Spinrad, Ph.D., Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator

National Ocean Service
Nicole LeBoeuf, Assistant Administrator

Office of National Marine Sanctuaries
John Armor, Director

Report Authors:
Hutto, S.V.[1], George, D.[2], Tezak, S.[1]

[1] Greater Farallones Association
[2] NOAA Office for Coastal Management

Suggested citation: Hutto, S. H., George, D. & Tezak, S. (2023). *Blue carbon in marine protected areas: Part 3; An evaluation of sedimentary carbon stocks in Greater Farallones and Cordell Bank National Marine Sanctuaries*. National Marine Sanctuaries Conservation Series ONMS-23-09. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries.

Cover photo: An octopus rests on the carbon-rich seafloor in Cordell Bank National Marine Sanctuary. Photo: NOAA

About the National Marine Sanctuaries Conservation Series

The Office of National Marine Sanctuaries, part of the National Oceanic and Atmospheric Administration, serves as the trustee for a system of underwater parks encompassing more than 620,000 square miles of ocean and Great Lakes waters. The 15 national marine sanctuaries and two marine national monuments within the National Marine Sanctuary System represent areas of America's ocean and Great Lakes environment that are of special national significance. Within their waters, giant humpback whales breed and calve their young, coral colonies flourish, and shipwrecks tell stories of our nation's maritime history. Habitats include beautiful coral reefs, lush kelp forests, whale migration corridors, spectacular deep-sea canyons, and underwater archaeological sites. These special places also provide homes to thousands of unique or endangered species and are important to America's cultural heritage. Sites range in size from less than one square mile to almost 583,000 square miles. They serve as natural classrooms and cherished recreational spots, and are home to valuable commercial industries.

Because of considerable differences in settings, resources, and threats, each national marine sanctuary has a tailored management plan. Conservation, education, research, monitoring, and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The National Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the National Marine Sanctuary System. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific or historical research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and social sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries website.

Disclaimer

Report Availability

Contact

Sara Hutto
Conservation and Climate Program Coordinator
NOAA Affiliate, Greater Farallones Association
Greater Farallones and Cordell Bank National Marine Sanctuaries
991 Marine Drive, The Presidio San Francisco, CA 94129
sara.hutto@noaa.gov

Table of Contents

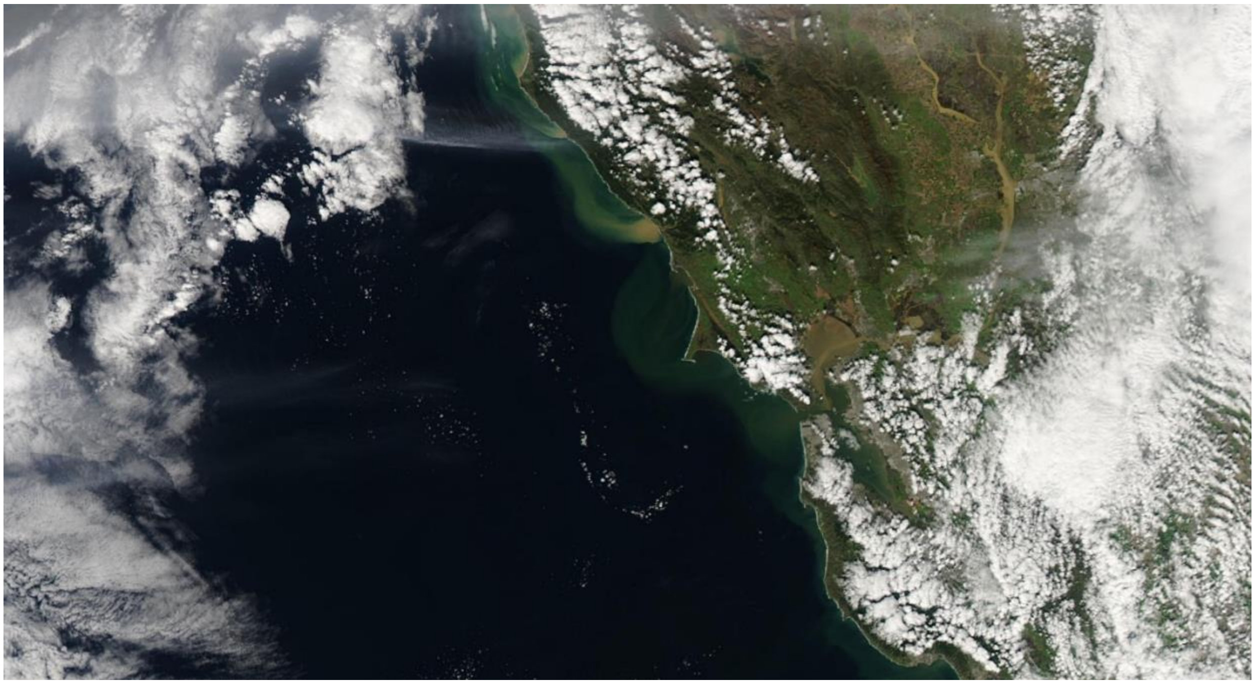
Abstract

Blue carbon processes, including sequestration by marine plants and algae, as well as deep-sea carbon export by marine megafauna and phytoplankton, are critical components of natural sequestration in the ocean. Long-term storage of carbon sequestered in the marine environment occurs in the ocean's sediments, which represent the largest non-fossil pool of organic carbon on the planet, yet are not well studied or protected. Current understanding of the spatial distribution of carbon in marine sediment (sediment or seabed carbon) remains limited along the U.S. west coast, constraining meaningful management and protection of these critically important carbon sinks. As requested by Greater Farallones and Cordell Bank National Marine Sanctuaries in response to parts 1 and 2 of this series, the Greater Farallones Association, in partnership with NOAA Office for Coastal Management, conducted the first systematic evaluation of marine sedimentary carbon stocks in north-central California. This report provides a first-order estimate of the marine sedimentary carbon stock within surficial (top 10 cm) marine sediments in Greater Farallones, Cordell Bank, and the northern portion of Monterey Bay national marine sanctuaries, and presents a spatial model of carbon density based on a novel relationship between sediment grain size and percent organic carbon. Results show surficial sediments in these sanctuaries, which accumulated over hundreds to thousands of years, hold approximately 9 ± 3.4 million metric tons of carbon (32 million metric tons of CO_2), which is equivalent to the emissions from burning 3.5 billion gallons of gasoline. As carbon stocks extend much deeper into the seabed below the surficial stocks reported here, this estimation represents only a fraction of sedimentary carbon stocks in the sanctuaries. Areas of high carbon content include a mid-shelf mud belt spanning approximately 100 km (63 miles) from Gualala to Point Reyes, 5 km (3 miles) offshore of California, and a large mud swath west of the shelf in the northern portion of Greater Farallones National Marine Sanctuary. Results are largely consistent with similar studies from other geographic regions and expectations based on prior knowledge of the seafloor within the study sanctuaries. Activities that disturb or alter the surficial seabed, including bottom-contact fishing, resuspend carbon-rich sediments, potentially remineralizing the carbon into CO_2, decreasing the pH of the surrounding waters, and reducing the ocean's capacity to absorb atmospheric carbon dioxide. These findings can be applied to spatial planning and management of the seabed to ensure adequate protection of carbon sinks in sanctuaries.

Key Words

blue carbon, carbon storage, carbon sequestration, carbon stock, Cordell Bank National Marine Sanctuary, Greater Farallones National Marine Sanctuary, Monterey Bay National Marine Sanctuary, marine protected area, climate change, mitigation, sediment carbon, surficial sediment

Introduction



This image, captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on February 28, 2019, shows multiple sediment plumes from rivers into the study region. Image: NASA

Coastal and ocean ecosystems play a critical role in the global carbon cycle and global carbon sequestration, storing and cycling 93% of Earth's carbon dioxide (CO_2) and holding over half the world's biological carbon in living marine organisms (Nellemann et al., 2009). The ocean absorbs approximately 31% of CO_2 emissions (Gruber et al., 2019), significantly buffering the continued emissions from human activity and helping to mitigate the impacts of climate change. Blue carbon processes, including sequestration by marine plants and algae and deep-sea carbon export by marine megafauna and phytoplankton, are critical components of this natural sequestration. Long-term storage of carbon sequestered in the marine environment, which can be of marine or terrigenous origin, occurs in the ocean's sediments, which represent the largest non-fossil pool of organic carbon on the planet. The global ocean stores 2,322 petagrams of organic carbon in the top 1 meter of sediment (or 2.3×10^{12} metric tons), nearly twice that of terrestrial soils (Atwood et al., 2020). Nearly four times as much organic carbon is stored, by volume, in deep-sea sediment (water depths >1000 m) compared to the continental shelf; however, greater organic carbon *per unit area* is found in sediments along continental shelves, with the least organic carbon per unit area in deep-sea sediments (Atwood et al., 2020). These organic carbon hotspots along continental shelves are driven by the large supply of organic-rich sediments from land runoff and river discharge and the production of large phytoplankton blooms in upwelling areas (Atwood et al., 2020).

The carbon in these sediments can remain stored for thousands to millions of years (Estes et al., 2019); however, activities such as mining, oil and gas exploration, and bottom-contact fishing can disturb sediment, resuspending it into the water column and potentially resulting in the remineralization of carbon into aqueous CO_2 (Epstein et al., 2022). Remineralization may decrease the pH of surrounding waters, exacerbating ocean acidification, and reduce the ocean's overall capacity to absorb atmospheric carbon dioxide (Sala et al., 2021). This may also result in carbon reaching surface waters and being released back to the atmosphere (Sala et al., 2021). Notably, only 4% of global marine sediment carbon stocks are currently protected from disturbance in marine protected areas (Atwood et al., 2020); the vast amount of carbon stored in marine sediments underscores the need to increase seabed protections to ensure carbon sinks remain intact.

Greater Farallones and Cordell Bank National Marine Sanctuaries, jointly managed protected areas administered by NOAA through the Office of National Marine Sanctuaries (Figure 1), seek to better understand blue carbon processes and sinks to inform restoration, protection, and other management activities. The sanctuaries, which also manage the northern portion of Monterey Bay National Marine Sanctuary, together protect approximately 5,855 square miles of coast and ocean along north-central California (Figure 2), supporting an array of marine and coastal habitats and species. This area is a highly productive ocean environment that is driven by seasonal upwelling and supports a rich and thriving ecosystem composed of a variety of habitats, including eelgrass, kelp, rocky reefs, continental shelf, and deep slope, and species ranging from plankton to apex predators.

Figure 1. Map of the National Marine Sanctuary System. Image: NOAA

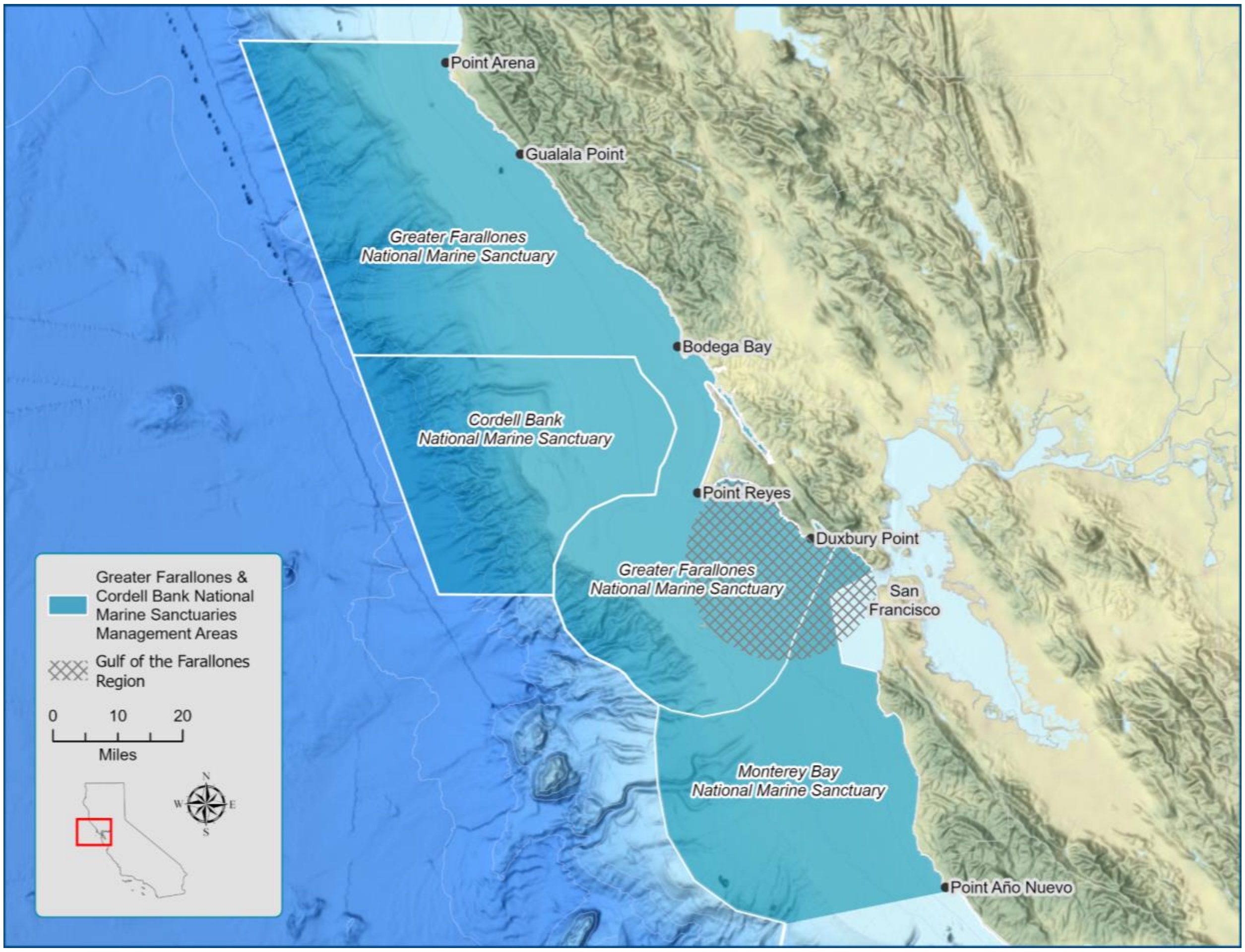


Figure 2. Map of the study area, which includes Greater Farallones and Cordell Bank National Marine Sanctuaries, and the northern portion of Monterey Bay National Marine Sanctuary. Image: NOAA[1]; Source: Esri, 2020a

Hutto et al. (2021) estimated the annual carbon sequestration in the study area via export of kelp biomass and whale falls to the deep sea, and called for the assessment of marine sediment carbon, where the bulk of the carbon protected by sanctuaries is most likely accumulated, as a critical next step. However, current understanding of the spatial distribution of marine sediment carbon along the U.S. west coast remains limited, constraining meaningful management and protection of these critically important carbon sinks. Physical and geological oceanography of the sanctuaries drives the distribution of sediment type through sediment transport, and influences carbon storage. Sediment transport depends on processes (e.g., waves, tides, and currents), sediment supply (e.g., fluvial delivery), and geomorphology (e.g., water depth, underwater features such as canyons or seamounts). Waves are the predominant force on sediments in the study area, as the orbital velocity of waves on the seafloor is the mechanism that disturbs and suspends sediment. Currents, either tidal or ocean-basin-scale subtidal ones such as the California Current, can combine with wave-driven currents to move mobilized

---

[1] Maps throughout this document were created using ArcGIS® software by Esri. ArcGIS® and ArcGISPro™ are the intellectual property of Esri and are used herein under license. Copyright © Esri.

sediment. In this region, current speeds on the inner shelf close to the seafloor are typically higher than those on the outer shelf, which prevents fine-grain sediment from settling on the inner shelf (e.g., Storlazzi & Jaffe, 2002; Storlazzi et al., 2003; Drake et al., 2005; Storlazzi & Reid, 2010). In addition to typical wave-driven bed disturbance, episodic events such as El Niño-Southern Oscillation can drive seasonal sediment mobilization and distribution (Storlazzi & Reid, 2010).

This report, part 3 in the Blue Carbon in Marine Protected Areas (MPAs) series, aims to advance understanding of the carbon stored in the sanctuaries' seabed to inform future management decisions, and demonstrate the importance of seabed protections and more broadly the role that MPAs can play in reaching carbon mitigation goals in the U.S. and around the world. Methods for this first-order estimate generally follow those presented by Smeaton et al. (2020), using a simple sediment type, geology-based approach, which relies on grain size as a proxy for organic carbon, based on a well-established relationship between the two (e.g., Keil et al., 1994). Organic matter has an affinity for fine-grained sediment such as mud due to the larger surface area to volume ratio that smaller grain sizes provide as binding agents (Keil & Hedges, 1993; Keil et al., 1994; Burdige, 2007), and studies from various locations and settings support this relationship. For example, mud (i.e., silt and clay), is the greatest predictor of organic carbon content in seagrass sediments, with proportion of fine grain size, porosity, and density of sediment strongly correlated with carbon content (Dahl et al., 2016). Mean grain size and organic carbon content were also significantly related in fjord sediments (Hunt et al., 2020), continental shelf, and nearshore sediments (Bergamaschi et al., 1997; De Falco et al., 2004), and mud content was demonstrated as a proxy to estimate organic carbon content in bare, non-vegetated sediments (Serrano et al., 2016). Therefore, by correlating grain size with organic carbon content (C_{org}) and applying established methods for sediment classification and carbon content estimates, we can estimate the amount of marine sediment carbon in surficial sediments within the study sanctuaries. This analysis is limited to the top 10 cm due to limited data availability regarding sediment thickness in the study region, as well as a lack of data regarding C_{org} and the geochemical processes occurring in deeper sediments that may impact the underlying relationship described above. Surficial sediments are also the most likely to be disturbed by activities that can be influenced or managed, and are thus most relevant for sanctuary management. Our objective for this study was to identify the type, location, and C_{org} content of sediment in the study sanctuaries to determine how much organic carbon is stored in surficial sediment and where organic carbon hotspots are located. This framework is easily transferable to other sites, and demonstrates that a modest initial investment can provide critical management-relevant information for the assessment of marine sedimentary organic carbon.

Methods

Data Assembly and Preparation

Methods from studies on ocean shelf carbon analyses in the United Kingdom (Smeaton et al., 2020) and globally (Atwood et al., 2020) were used as guides to conduct this study. These reference studies analyzed samples from both seafloor surface grabs and core tops (i.e., cores with the surface layers intact), to quantify percent organic carbon (%OC) and carbon mass in their study areas. Following the same approach, a suite of available parameters was compiled to build an offshore north-central California database for analysis. Data were required to contain, at a minimum: latitude and longitude, water depth, sample type (grab or core), subsample depth within a core, physical parameters (%mud, %sand, %gravel), and, where available, geochemical parameters (%OC, dry bulk density). Records with erroneous data (e.g., negative depth, coordinates on land, -99 values) or deeper than 51 cm were excluded from the analysis. Methods of %OC calculation (e.g., loss on ignition) were not a requirement as these data are not typically reported in public databases.

Data from the broader north-central California region came from three sources: the global dbSEABED database covering 1965–2022, managed by Floor of the Ocean LLC (dbSEABED, 2022), an E/V *Nautilus* expedition in Cordell Bank National Marine Sanctuary (Ocean Exploration Trust, 2017), and Sliter et al. (2021), covering the Gulf of the Farallones region. Geographic boundaries were selected based on natural barriers to sediment movement—a major headland (Cape Mendocino) and a submarine canyon (Monterey Submarine Canyon), which create littoral cells (Patsch & Griggs, 2006; George et al., 2015). Within the final dataset, 342 records included both sediment grain size and %OC. Based on the established relationship between carbon and grain size (e.g., Keil et al., 1994), these records were linearly regressed (Figure 3) to produce a locally specific relationship:

Equation 1.

$$\%OC = 0.0188 \times \%mud + 0.0075$$

$$r^2 = 0.72, p < 0.01$$

The relationship in Equation 1 was used to estimate %OC values for the remaining records of the dataset without %OC reported (n = 4,311). All records were combined (n = 4,593)[2] and used in the analyses described below.

---

[2] This number is the sum of n = 342 and n = 4311, minus 60 duplicate records that were removed from the analysis.

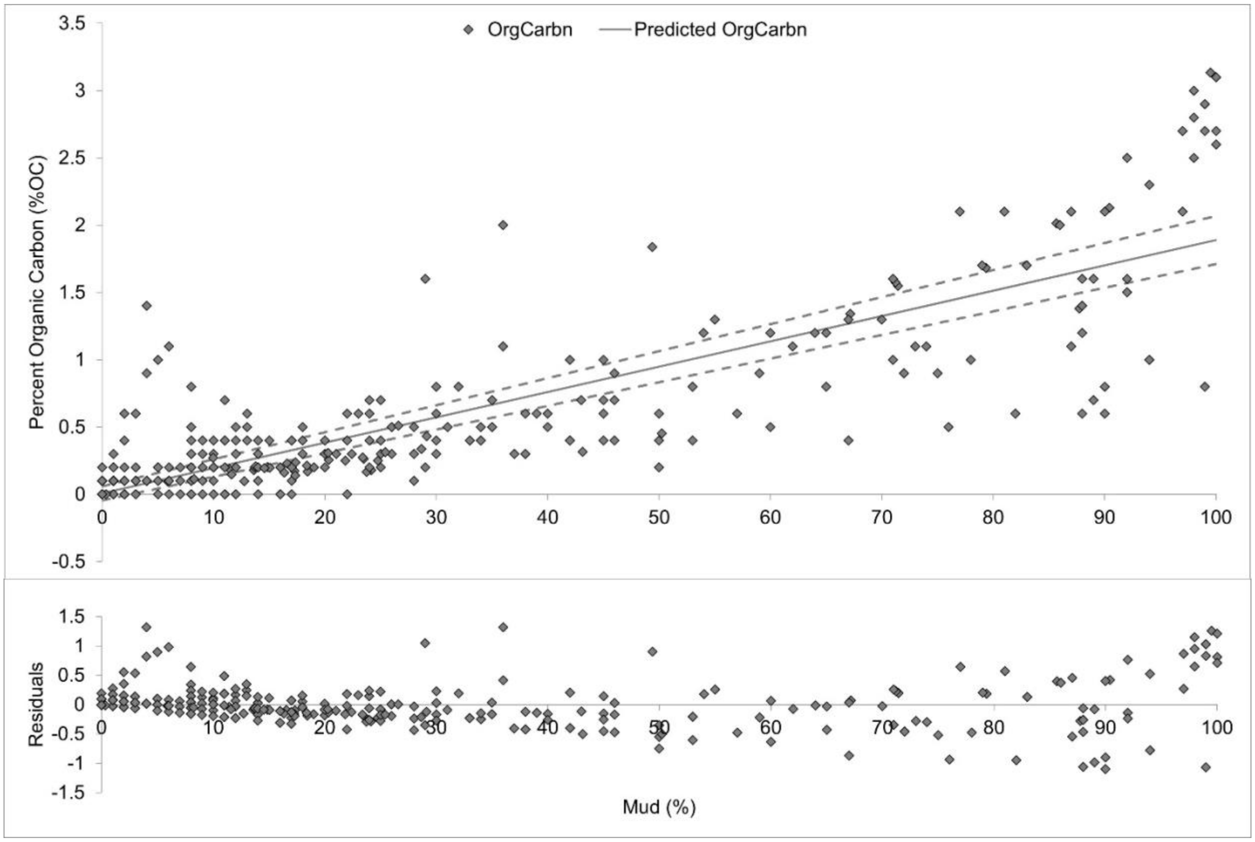


Figure 3. Regression relationship ($r^2 = 0.72$, $p < 0.01$) between mud and organic carbon (top) and residuals (bottom) for samples in this study (n=342). The dashed lines represent the 95% confidence interval.

Sediment Classification

All records were classified using a sediment classification method based on proportions of mud, sand, and gravel to create substrate types. The Folk classification scheme (Folk, 1954) is the classical scheme used to determine sediment-based substrate classes. However, the Folk scheme overemphasizes the gravel classes and skews the classes to be coarser (Valentine, 2019). As a result, a classification scheme used by the United States Geological Survey (USGS) at Stellwagen Bank National Marine Sanctuary was chosen with thresholds for 20 classes because of an increased emphasis on fine-grain sediment that is more appropriate for carbon sequestration analysis (Table 1; Valentine, 2019). If sediment class percentages were equal (e.g., sand and mud both 45%), adjustments were made using grain size (i.e., gravel dominated if $\varphi < -1$; sand dominated if $-1 < \varphi < 4$; and mud dominated if $\varphi > 4$).[3] Several records were excluded from classification due to lack of grain size data or component percentages.

---

[3] Phi (φ) is a measure of grain size on a logarithmic scale. Values for grains coarser than one millimeter (larger than coarse sand) are negative, while those for grains finer than one millimeter (coarse sand and smaller) are positive.

Table 1. The 20 grain size classes used in sediment classification. Capitalization scheme was defined by Valentine (2019) to denote the dominant grain size class. Comparison refers to a secondary step needed to classify sediment when two aggregates are over the specified thresholds. Source: Valentine, 2019

Class ID	Name	Abbreviation	Gravel (%)	Sand (%)	Mud (%)	Comparison
1	Mud	M	<25	<10	≥50	
2	gravelly Mud	gM	≥25	<10	≥50	
3	sandy Mud	sM	<25	≥10	≥50	
4	sandy gravelly Mud	sgM	≥25	≥10	≥50	S<G
5	Sand	S	<25	≥50	<10	
6	gravelly Sand	gS	≥25	≥50	<10	
7	muddy Sand	mS	<25	≥50	≥10	
8	muddy gravelly Sand	mgS	≥25	≥50	≥10	M<G
9	Gravel	G	≥50	<10	<10	
10	sandy Gravel	sG	≥50	≥10	<10	
11	muddy Gravel	mG	≥50	<10	≥10	
12	sandy muddy Gravel	smG	≥50	≥10	≥10	S<M
13	muddy sandy Gravel	msG	≥50	≥10	≥10	M<S
14	mud and sand and gravel	MSG	≥25	≥10	≥10	
15	sand and mud	SM	<25	≥10	≥10	S<M
16	mud and sand	MS	<25	≥10	≥10	M<S
17	gravel and sand	GS	≥25	≥10	<10	G<S
18	sand and gravel	SG	≥25	≥10	<10	S<G
19	gravel and mud	GM	≥25	<10	≥10	G<M
20	mud and gravel	MG	≥25	<10	≥10	M<G

Geospatial Analysis

Spatial interpolation was conducted using ArcGIS Geostatistical Analyst extension to create a continuous surface of sediment distribution, sediment class, and %OC to estimate these values at locations with no data. Before creating an interpolated surface, the distribution of the data was explored to determine whether any trends were apparent, and the stationarity of the data was examined to validate the assumption that the statistical properties of the data samples do not change over time or space (Interstate Technology & Regulatory Council, 2016). Empirical Bayesian Kriging (EBK) was determined to be the best option for interpolating the data. EBK is a reliable automatic interpolator that creates local models using subsets of the input data, which are defined by nearby values, in order to create a complete and accurate prediction, particularly of nonstationary data. Two specific metrics of EBK interpolation can be used to validate the model by indicating model accuracy (root mean square error) and model bias (mean error). Model results showed the root mean square error was 0.25%, which means that the predictions differed from the measured values by approximately 0.25%. Mean error was -0.018, which indicates the model slightly underpredicted measured values. EBK was found to be a reliable interpolation method and was selected as the geospatial analysis approach for this study.

Carbon Stock Analysis

Carbon stock (the total amount of organic carbon) was calculated for surficial sediments (top 10 cm) in the study region due to data limitations in deeper sediments, especially sediment thickness, %OC, and geochemical processes that may impact carbon content. To calculate the carbon stock of surficial sediments, it was necessary to determine the dry bulk density for all records, which was not a parameter reported in the dataset. Therefore, an approach detailed by Diesing et al. (2017) and Smeaton et al. (2021) was used to determine porosity (Φ) and dry bulk density (kg/m^3) for all records. This approach was determined to be the most appropriate, as it was originally based on shelf sediment data from the Gulf of Mexico and found to be consistent with shelf sediments in the United Kingdom; an assumption was made that this approach could be generalized to other shelf locations. Porosity was derived using mud content (C_{mud}), which was available in the dataset, with the following equation from Jenkins (2005):

Equation 2.

$$\Phi = 0.3805 \times C_{mud} + 0.42071$$

Dry bulk density of each sediment record was then derived from the calculated porosity and grain density (ρs = 2650 kg/m^3), as reported in Diesing et al. (2017):

Equation 3.

$$Dry\ bulk\ density = (1 - \Phi)\rho s$$

Records were binned into four broad substrate types using the 20 USGS classes (Table 1; Valentine, 2019): muds (classes 1–4), sands (classes 5–8), gravels (classes 9–13), and mixed (14–20), and the area of each substrate type was determined from the spatial model. Dry bulk density values were averaged within each substrate type, and the calculations demonstrated by Smeaton et al. (2020, 2021; Table 2) were used to calculate carbon stock for each of the substrate types within sanctuary boundaries.

Table 2. Additional equations used to calculate carbon stock. Source: Smeaton et al., 2020, 2021

Metric	Equation
Sediment volume (m^3)	Areal extent of substrate type (m^2) × sediment thickness (m)
Sediment mass (kg)	Sediment volume (m^3) × dry bulk density (kg m^{-3})
Carbon mass (kg)	Sediment mass (kg) × carbon content (%)
Carbon stock (tonnes)	Carbon mass (kg) / 1,000
Carbon stock (Mt)	Carbon stock (tonnes) / 1,000,000

The uncertainties in the data, expressed as standard deviations, were propagated through the calculations using the “adding in quadrature” method. To propagate these uncertainties, it was assumed that the errors were normally distributed and that the parameters were independent of each other.

Sediment Class	Sediment Subclass	Number of Samples	Mean %OC	%OC Range
Gravel	Gravel	381	0.01	0.01–0.10
Gravel	sandy Gravel	103	0.01	0–0.03
Gravel	muddy Gravel	10	0.57	0.55–0.57
Mixed	mud, sand and gravel	9	0.56	0.20–1.6
Mixed	sand and mud	11	0.90	0.4–0.95
Mixed	mud and sand	38	0.93	0.2–0.95
Mixed	gravel and sand	1	0.10	-
Mixed	sand and gravel	6	0.01	0.01–0.01
Unknown	unable to classify	30	-	-

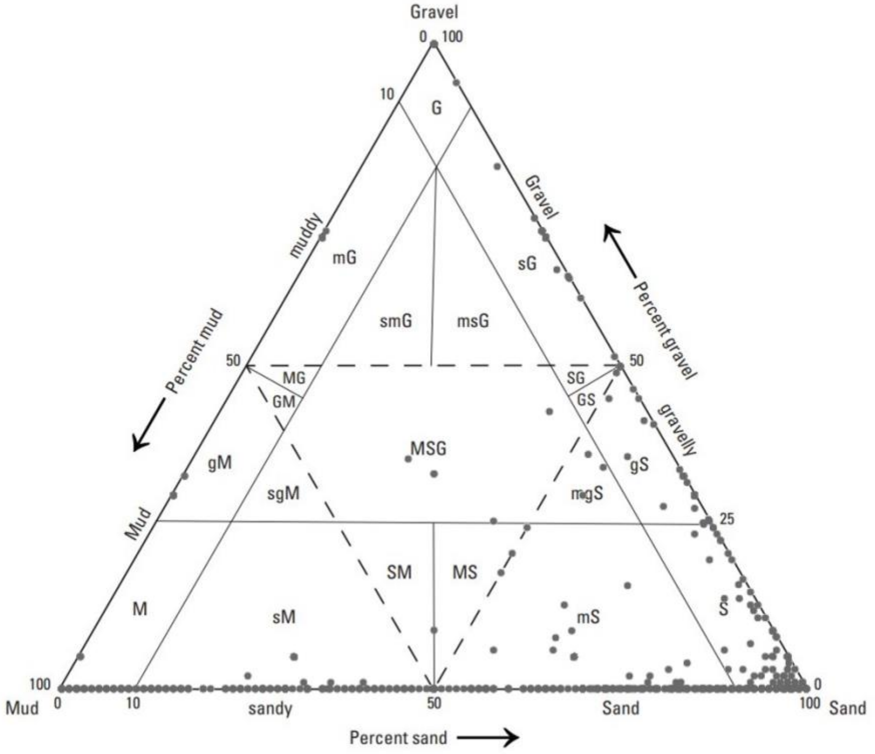


Figure 5. Ternary plot characterizing the grain size proportions of each data sample.

Boxplots of the distribution of %OC by sediment class show the highest carbon content in the mud classes, and decreasing carbon as sediment grain size increases (Table 3; Figure 6). Coarser classes that contain higher mud contents (e.g., muddy sand) show higher %OC than non-mixed classes (e.g., sand), indicating the positive correlation between higher %mud and %OC. Whereas this general relationship is consistent with studies conducted in the United Kingdom (e.g., Smeaton et al., 2020), the absolute values varied considerably among the sediment classes. The mean %OC for the mud class was 1.90% with a range of 1.0–3.2% with 17 outliers from the very compressed middle quartile. Most of the classes show similarly compressed middle quartiles. In contrast, the mixed sediment class showed a wide middle quartile and smaller range of outliers, indicating a weaker relationship between the more mixed sediment class and %OC.

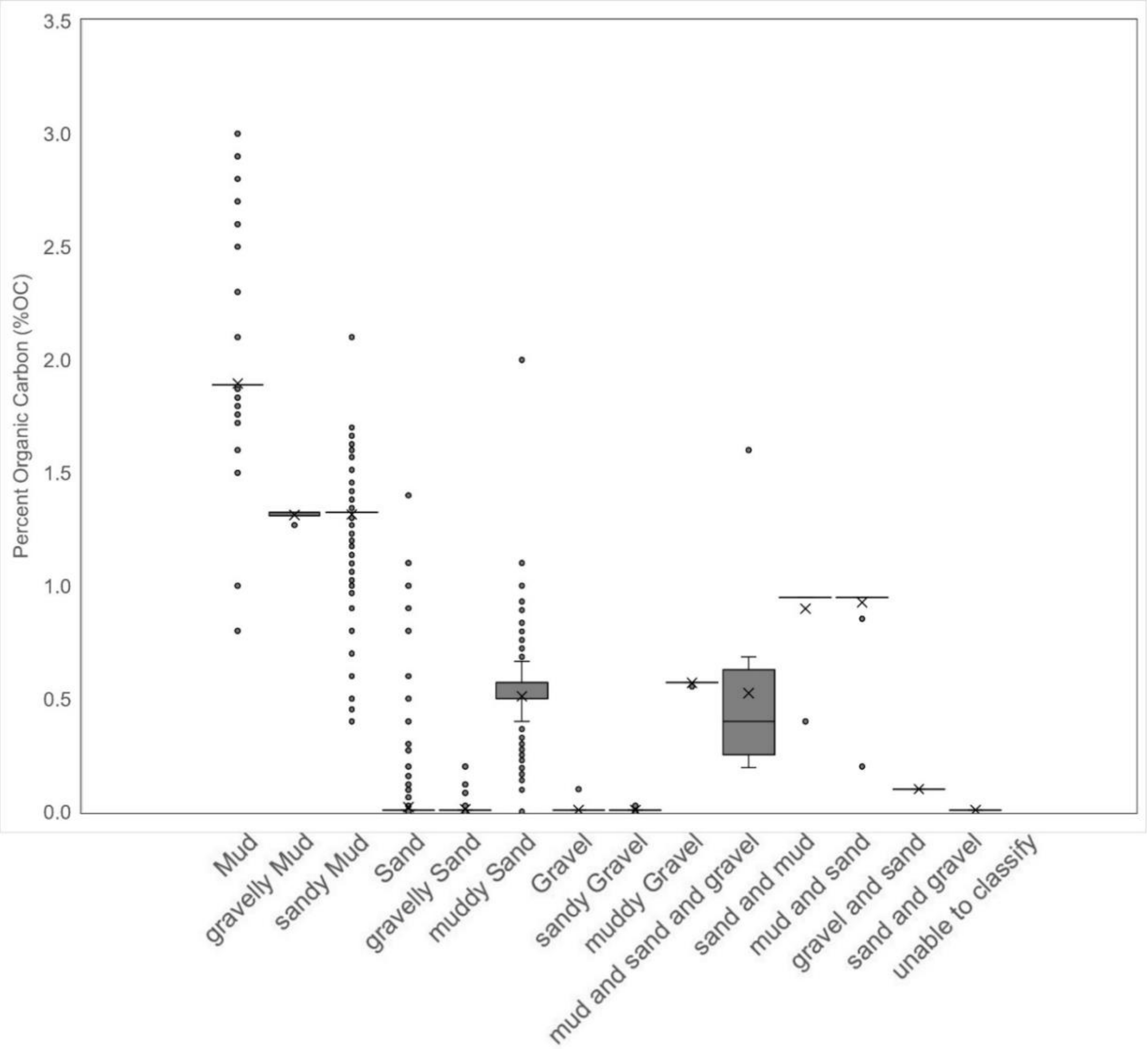


Figure 6. Boxplots of the distribution of %OC by sediment class.

Seafloor Characterization

The sediment distribution demonstrated in this study is consistent with previous studies (Chin et al., 1997; Karl et al., 2001) and observations of the region, and reflects the high variability in physical processes that occur. The percentage of mud varied with distance from the coast and water depth, although this relationship was not consistent throughout the study area (Figure 7). North and south of the Gulf of the Farallones (see Figure 2), mid-shelf mud belts (defined as elongated areas, detached from their source) emerge around the 30- and 40-m isobaths. The gulf, along with deep portions of the study area, is predominantly composed of sandy sediments. There are some exceptions within the submarine canyons and around Cordell Bank, where sediment portions of sand and mud fluctuate considerably. Tomales Bay has primarily muddy substrate. Generally, there is more mud north of the Gulf of the Farallones than south.

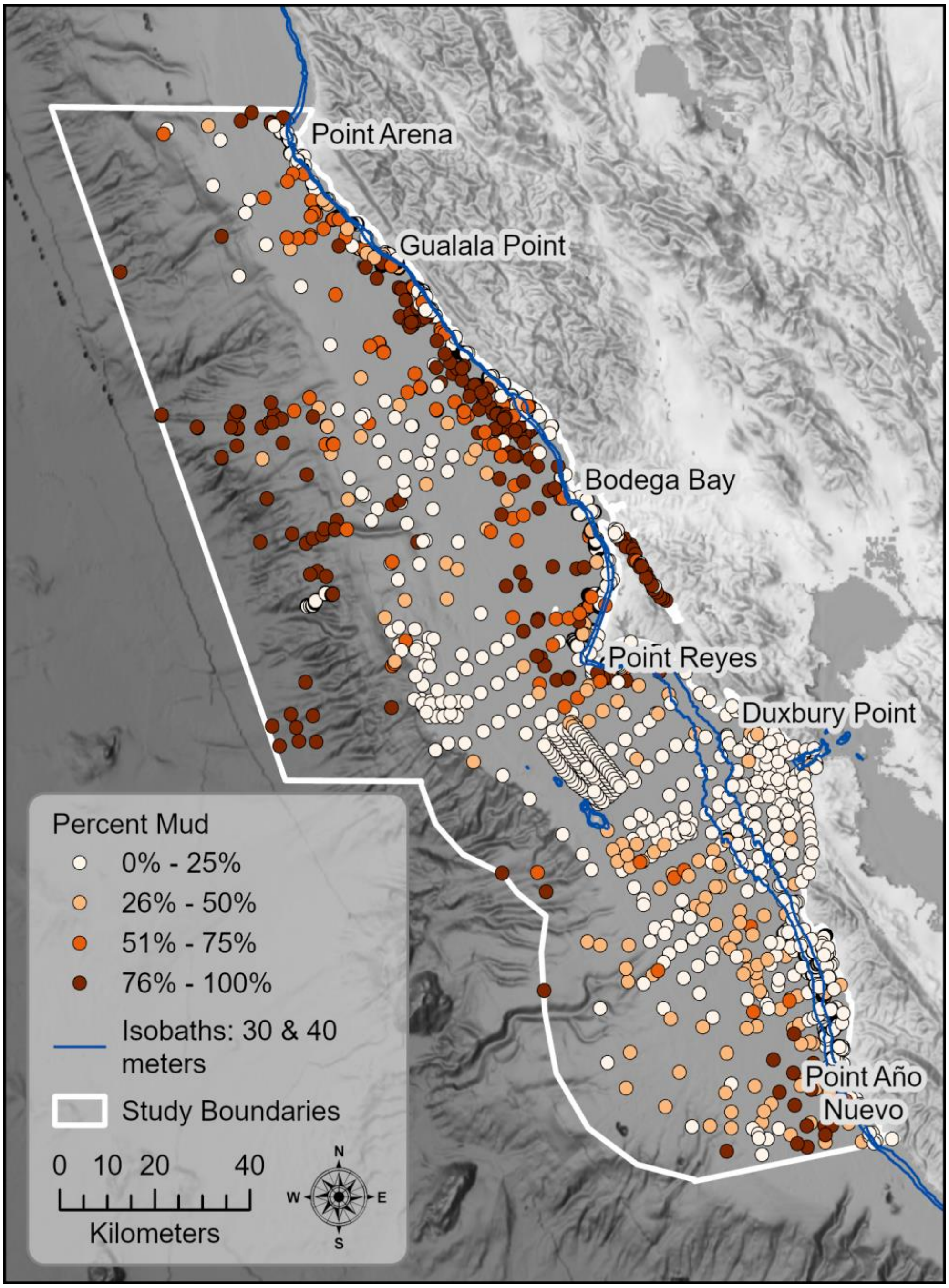


Figure 7. All data used in the analysis presented as the %mud of the sample, along with bathymetry lines. Image: NOAA; Source: dbSEABED, 2022; Ocean Exploration Trust, 2017; Sliter et al., 2021; Esri, 2020b

Data Distribution and Interpolation

Data used to develop the interpolated continuous surface are distributed unevenly across the study area (Figure 8); some areas contained a high density of records (i.e., along the coast and near the mouth of San Francisco Bay), while other areas were largely devoid of data (i.e., the northwest corner of the study area). Thus, confidence in the model for areas with low sampling density is relatively low. Most samples are within 6–32 km of the coast or within the 100-m contour depth; 95% of records were collected at 300 m or less. Results of the interpolation (Figure 8, Figure 9) indicate variable distribution of carbon density in surficial sediments throughout the study area, with highest concentrations near the coast and west of the shelf break.

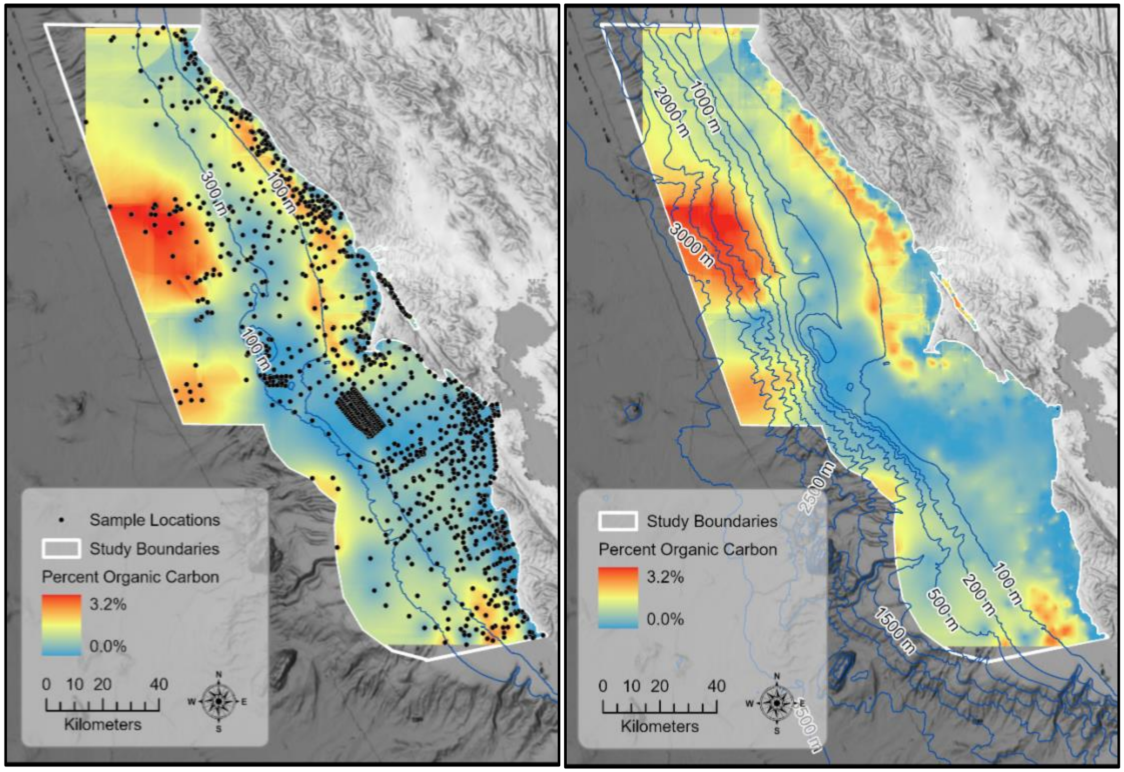


Figure 8. Predicted %OC values in the study area, with the sample locations (final dataset) used for the interpolation indicated with points (left) and contour lines showing bathymetry (right). Areas within the study boundaries not represented by the model (the northwest and southwest corners) are due to limitations in data availability and model interpolation. Image: NOAA; Source: dbSEABED, 2022; Ocean Exploration Trust, 2017; Sliter et al., 2021; Esri, 2020b

Carbon Stock Analysis

Spatial distribution (Figure 9) and geographic extent (Table 4) of the four broad substrate types (using classification in Table 3) indicates that the sanctuary seafloor is composed predominantly of sand and mud, with a small proportion of gravel and very little mixed sediment. Carbon stock in megatonnes (Table 4) is highest for the mud category, followed by sand, with very little carbon in the gravel and mixed substrate categories. The estimated total amount of organic carbon, based on available data, in the top 10 cm of sanctuary sediment is 8.7 ± 3.4 megatonnes (Mt), or 8.7 million metric tons.

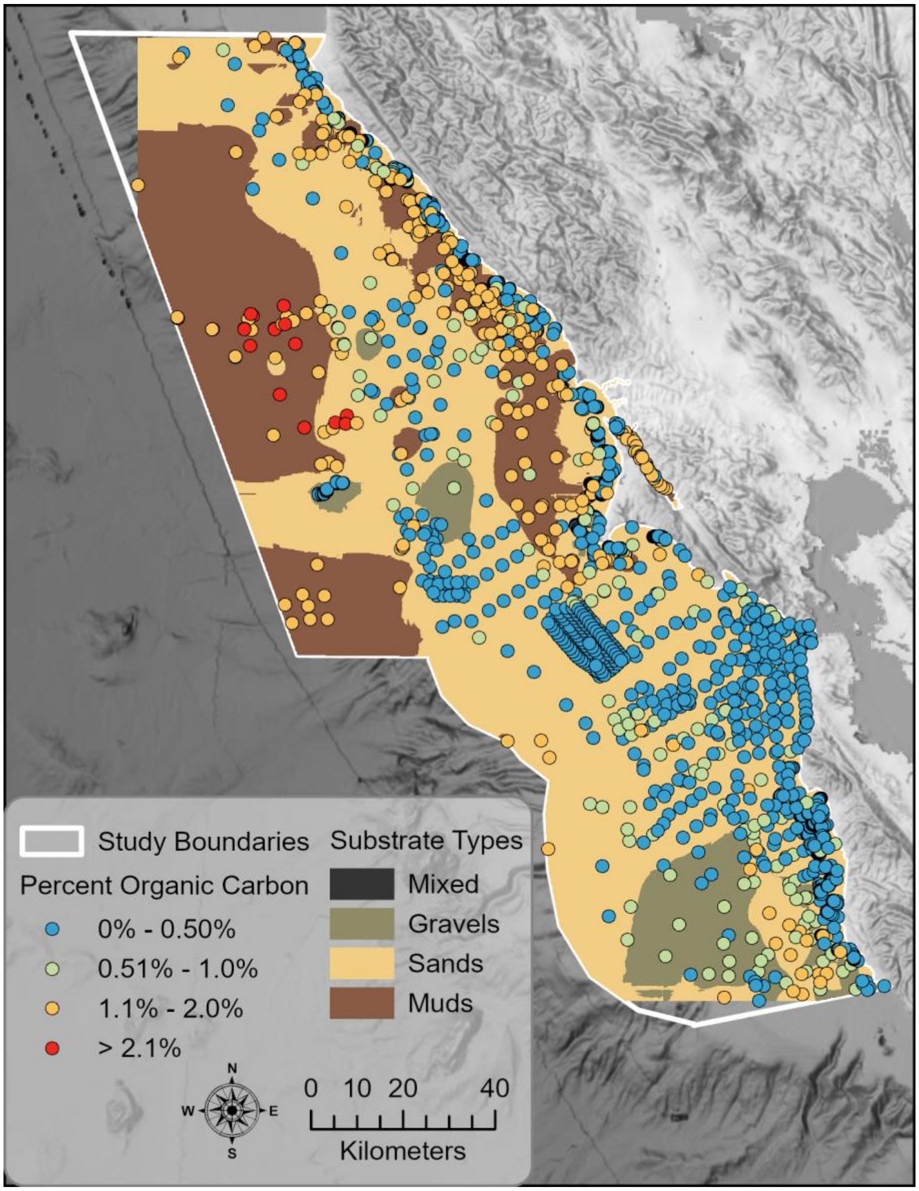


Figure 9. Predicted substrate types based on data interpolation (continuous surfaces), overlain by the %OC dataset (colored dots). The predominant substrate type is sand. Areas within the study boundaries not represented by the model (the northwest and southwest corners) are due to limitations in data availability and model interpolation. Image: NOAA; Source: dbSEABED, 2022; Ocean Exploration Trust, 2017; Sliter et al., 2021; Esri, 2020b

Table 4. Carbon stock calculation of each of the four broad sediment classes (top 10 cm) represented in the study area and data used in calculations, following methods in Smeaton et al. (2020, 2021). Records with a zero value for %OC were not included in the analysis, and therefore the sample size may differ from those reported in Table 3.

Substrate Type	Sample Size	Mean Dry Bulk Density (kg/m^3 ± standard deviation)	Mean %OC (± standard deviation)	Geographic Extent (m^2)	Carbon Stock (Mt ± standard error)
Mud	804	717.196 ± 149.407	1.541 ± 0.32	65.41 x 10^8	7.230 ± 2.131
Sand	3163	1,475.151 ± 116.535	0.121 ± 0.22	80.16 x 10^8	1.429 ± 2.598
Gravel	493	1,528.962 ± 42.545	0.019 ± 0.08	6.81 x 10^8	0.021 ± 0.083
Mixed	65	1,124.032 ± 176.194	0.773 ± 0.35	0.02 x 10^8	0.002 ± 0.001
Total	N/A	N/A	N/A	N/A	8.681 ± 3.36

Discussion

This study is the first to demonstrate that grain size can be used as a predictor of organic carbon content in this region. As shown in Table 4, despite being smaller in area than sandy substrates, muddy substrates contain almost twice as much carbon. Though the sediment in the study sanctuaries is dominated by sand (Figure 9), with extensive sand deposits across the shelf, along the coast, and in the Gulf of the Farallones, organic carbon content is relatively low in these areas. This could simply be due to the smaller surface-area-to-volume ratio of these larger grain sizes, but could also be a result of greater oxygenation in the upper 10 cm of sand compared to mud. This contrasts with the higher concentrations of C_{org} in muddy deposits, which are present in three areas: shore-parallel mudbelts, steep canyons west of the shelf, and protected bays, all of which are areas where turbulent energy decreases, allowing fine sediment to accumulate (Figure 7, Figure 9). Shore-parallel mudbelts were found north of Point Reyes and on the southern edge of the study area in 20–30 m water depth, which is consistent with mudbelts identified by Edwards (2002) in Monterey Bay National Marine Sanctuary (south of the study area) and predicted by the analytical model for the depth of a mudbelt as estimated by wave height, described by George and Hill (2008). The steep canyons that cleave the shelf break (e.g., Bodega Canyon) act as conduits of mud to low-energy deeper waters that allow fine sediments to settle out, as observed in submarine canyons around the world (Harris & Whiteway, 2011). The third geographic region of mud accumulation is in Tomales Bay, a protected shallow embayment where the substrate is predominantly mud, likely due to reduced ocean swell and proximity to terrestrial fluvial sources. These three mud-dominated zones coincided with the highest concentrations of organic carbon.

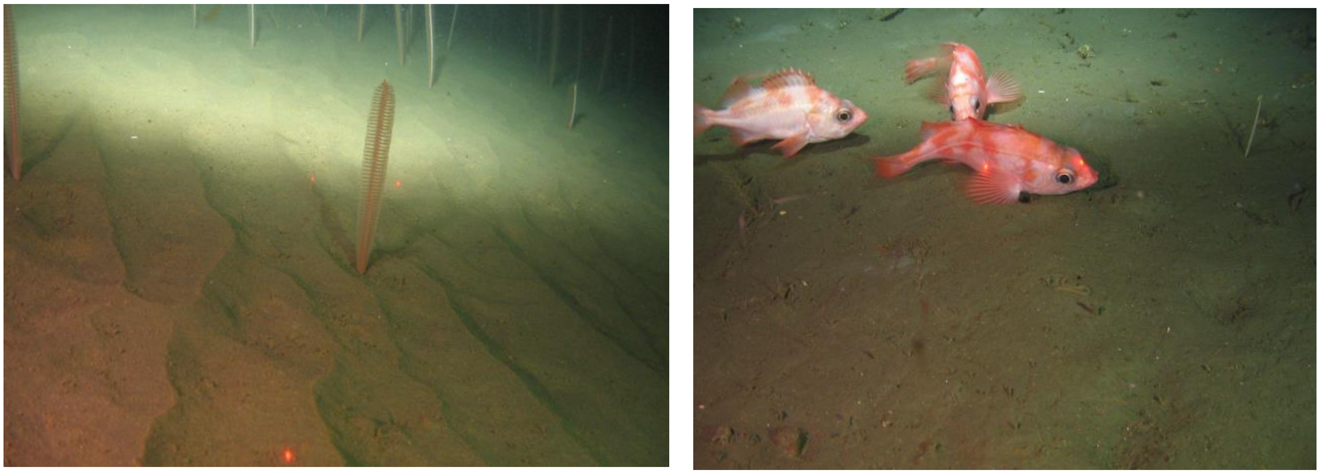


Figure 10. Representative images of sand (left) and mud (right) on the study area seafloor. Photo: Marine Applied Research and Exploration

The carbon stock of surficial (top 10 cm) sediments in the sanctuaries of study was calculated to be approximately 9 million metric tons of organic carbon, equivalent to 32 million metric tons of CO_2.[4] This is equivalent to the emissions generated by burning 3.5 billion gallons of gasoline.

---

[4] Using the standard carbon to CO_2 conversion: CO_2 equivalent = 3.67 x C_{org}.

While the area of the ocean seafloor is vastly greater than that of areas considered to be coastal blue carbon habitats, surficial seabed sediments store approximately 70x the organic carbon stored in the sanctuary's salt marsh and eelgrass-associated sediments (Hutto et al., 2021). It is important to note, however, that limiting this analysis to surficial sediments (due to limited data for sediment thickness and uncertainties regarding the relationship between grain size and %OC at greater depths) means that the stocks reported here represent only a fraction of sedimentary carbon stocks in the sanctuaries. It should also be noted that known hard-bottom reefs were not resolved with the spatial sediment distribution maps, and therefore are not accounted for in the calculated carbon stock, slightly overestimating carbon content of surficial sediments. Even so, this analysis demonstrates that marine sediments, particularly muddy sediments, act as a significant carbon store in the sanctuaries studied.

Activities that disturb or alter the seabed, such as mining, oil and gas exploration, and bottom trawling, resuspend carbon-rich sediments. This can result in remineralization of organic carbon into CO_2 (Epstein et al., 2022), decreasing the pH of the surrounding waters and reducing the ocean's capacity to absorb atmospheric carbon dioxide (Sala et al., 2021). Notably, as the study sanctuaries are located in an upwelling region, remineralized CO_2 is more likely to reach surface waters compared to other regions. Because sanctuaries have seabed protections that prohibit mining or oil and gas exploration, the leading causes of surficial seabed disturbance in the sanctuaries are likely from: violations of prohibitions of activities that alter the seabed; bottom-contact fishing; and permitted activities, such as mooring installations, salvage and recovery, and trawling for scientific purposes. Reducing or limiting these disturbances could result in increased C_{org} content over time, enhancing seabed carbon stores.

Of all disturbance activities, bottom-contact fishing may be the most disruptive. In particular, bottom-trawl fishing has been identified extensively in the literature as a potential source of "underwater carbon dioxide emissions" in certain environmental settings due to chronic mixing, resuspension, and oxidation of surficial sediments, and subsequent remineralization of organic carbon (e.g., Paradis et al., 2021; Pusceddu et al., 2014; Oberle et al., 2016). Trawling resuspends large volumes of sediment (e.g., Durrieu de Madron et al., 2005; Palanques et al., 2014), thereby elevating near-bottom turbidity, dissolved methane, and nutrients in the water column (Bradshaw et al., 2021); alters seafloor faunal communities (Hiddink et al., 2017); and restructures surficial benthic sediments (e.g., Eigaard et al., 2016; Trimmer et al., 2005). However, although widely reported (e.g., Einhorn, 2021), there is differing evidence about the contribution of trawling to carbon emissions (e.g., Hiddink et al., 2023 in response to Sala et al., 2021; Epstein et al., 2022) and the ubiquitous impact of bottom trawling on sediment carbon stores is less clear. One review of 38 studies found mixed evidence that bottom-trawl fishing disturbs seabed carbon to the extent that carbon stocks are reduced and remineralization is increased (Epstein et al., 2022). Another review of 28 studies found that untrawled sediments sequestered significantly more carbon than areas exposed to trawling (Jacquemont et al., 2022). While it's certain that trawling has a significant impact on benthic ecosystems, the net effect of trawling on seabed carbon stocks (Legge et al., 2020), as well as the fate of disturbed organic carbon, is still uncertain. Regardless, trawling likely does limit future burial and storage of carbon in the seabed by impeding the settlement and compaction of carbon-rich sediments (Epstein et al., 2022).

The co-occurrence of seabed disturbance activities and carbon sinks can help inform management of the seabed by identifying the areas most likely to contribute to carbon remineralization and possibly informing greater seabed protections. Bottom-contact fishing, including trawling and set gear (e.g., pots and traps), does occur within the study sanctuaries, and an analysis of the locations, extent, frequency, and direct impacts of these fishing activities would inform understanding of how sediment carbon in the sanctuaries is impacted. Black et al. (2022) developed a carbon vulnerability ranking, based on sediment type and lability, as well as fishing gear type, to identify areas of the seabed that are most vulnerable to carbon disturbance and should be prioritized for protection; a similar analysis should be completed for the sanctuaries. A preliminary visualization of available trawling data within Greater Farallones National Marine Sanctuary boundaries (total number of presumed trawling vessels, based on vessel speed, per 3 km^2 over a 9-year period), indicates a potentially low co-occurrence of trawling activity with carbon hotspots (Figure 11); however, these data are incomplete and further analysis is required to fully understand the potential impacts from bottom trawl fishing in the study sanctuaries. Other bottom-contact fishing gear types, such as crab pots and traps, are likely more numerous in the sanctuaries but are harder to track and document for such an analysis.

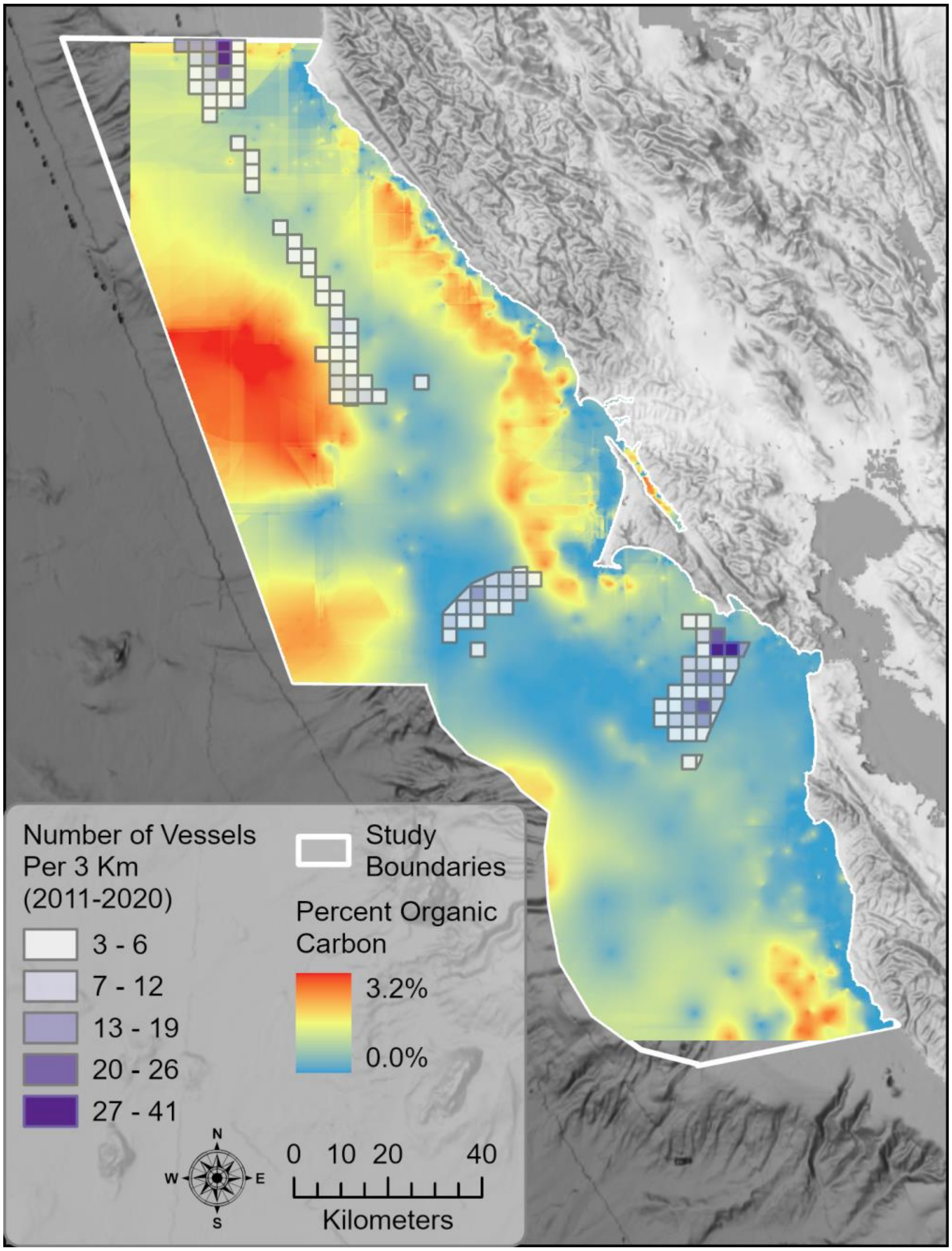


Figure 11. Trawling density in Greater Farallones National Marine Sanctuary in 2011–2020, expressed as the number of trawling vessels per 3 km^2 (squares) underlaid by predicted %OC. Image: NOAA; Source: National Centers for Coastal Ocean Science, 2020; Esri, 2020b

The results of this spatial analysis of surficial seabed carbon can also be used to inform marine spatial planning and decisions about potential future activities in the sanctuaries that may disturb the surficial seabed. This information can be used when dealing with enforcement cases involving seabed disturbance, and in prioritizing protection of sanctuary habitats.

Recommendations and Conclusions

This study builds on the strong body of evidence that marine sediments are a significant global sink of organic carbon and provide critical long-term carbon accumulation and storage. We demonstrate that areas lacking coastal vegetated ecosystems, such as Cordell Bank National Marine Sanctuary, which has no shoreline, provide significant carbon sequestration services that should be valued and protected. Carbon-rich muddy areas of the seafloor are often not priority areas for protection (as opposed to high-relief rocky areas protected for fish habitat), but could be better protected through MPAs to maximize carbon storage. Globally, only 4% of the carbon stored in marine sediments are within MPAs, and only 2% within highly protected MPAs that prevent disturbance to the seabed (Atwood et al., 2020).

For the study sanctuaries to determine if current seafloor protections are adequate to protect carbon or if more protections are needed to meet their conservation goals, we recommend *a more thorough assessment of the overlap of current leading causes of seabed disturbance with carbon hotspots*. Such an analysis would require the collection and mapping of current activities that cause seabed disturbance in the entirety of the sanctuaries, including the location and duration of: bottom-contact fishing and areas currently closed to bottom trawling; violations of seabed protections; and permitted activities. It should be noted that these analyses will not indicate the final fate of disturbed sediment carbon; significant advances in scientific research are required to better understand global impacts of carbon remineralization due to seabed disturbance. These assessments, however, can inform sanctuaries of those disturbance activities that are most likely to degrade carbon stores and cause negative local effects due to carbon remineralization. To better understand the specific impact of bottom-contact fishing, sanctuaries could employ the carbon vulnerability ranking of Black et al. (2022) to identify those areas of the seabed most vulnerable to bottom-contact fishing gear that should be prioritized for protection.

We recommend *building a stronger dataset of sediment samples to improve the predictive model by addressing sedimentological and spatial data gaps and to validate the carbon hotspots identified in this study*. Our dataset is dominated by sand samples, so building the dataset with more mud samples and identifying regions of hard substrate such as rocky outcrops would strengthen the analytical model and reduce uncertainty. Additionally, there are spatial gaps in available data in the northwest region of the study sanctuaries and off the shelf break. Validation of carbon hotspots (e.g., the mud swath identified west of the shelf) would improve confidence in both the predictive model and understanding of the substrate. Using the sediment classification maps, a sampling plan could be developed that leverages existing sanctuary projects, such as remotely operated vehicle surveys, or new partnerships with external researchers to both fill data gaps and validate the model presented in this study. This would improve the predictive model, provide additional data for estimating the sanctuaries' carbon stock, and better inform potential management actions. Additional data gaps to address in future studies include thickness of the sediment on the seafloor to improve the total carbon stock estimate, the origin of stored carbon (terrigenous vs. marine) to determine the processes that contribute most to carbon stores, sediment dating of samples to determine accumulation rates, and improved geochemical analysis to determine the lability of carbon in the sediment.

We recommend *sanctuary managers consider this sediment carbon model in decision-making and issuance of permits for future activities that could disturb the seafloor*. This could occur during a permit application review or in a marine spatial planning process. The National Environmental Policy Act requires federal agencies to consider environmental effects in all decision-making. Our estimates could be used as a basis for understanding the impacts projects may have on carbon stores and sequestration.

The model we present here could also be applied in other areas to calculate sediment carbon and carbon hotspots. Greater Farallones and Cordell Bank National Marine Sanctuaries could engage other national marine sanctuaries, agencies, and MPA managers and share this model to advance a broader understanding of sediment carbon nationally. And, to better establish the results from Greater Farallones and Cordell Bank National Marine Sanctuaries in a broader regional context, engagement with other national marine sanctuaries in California, as well as the California Department of Fish and Wildlife and the Ocean Protection Council on state managed MPAs, could lead to the development of a state-wide analysis to inform a regional perspective of ocean protection priorities.

Acknowledgements

We would like to thank Dr. Craig Smeaton for advising this project and providing guidance and methodology, and Dr. Chris Jenkins for providing data for the sediment carbon analysis. This work would not have been possible without their expert input. We would also like to thank the reviewers of this report, Drs. John Baxter, Craig Smeaton, and Hope Ianiri for their thoughtful insight and expert input. Finally, we appreciate the input from our colleagues within NOAA, Drs. Chris Kinkade, Jean Brodeur, Wendy Kordesch, and Dani Lipski.

Glossary

Carbon sequestration	The process of capturing and storing atmospheric carbon dioxide.
Carbon stock	The amount of carbon stored in an ecosystem, which can either increase with sequestration or be released by disturbance.
Marine sedimentary carbon	The carbon stored in marine sediments.
Mudbelt	Elongated mud deposits, detached from their source.
Remineralization	The breakdown or transformation of organic matter into its simplest inorganic forms.
Seabed	The 3-dimensional substrate, including subsurface layers, that extend below the surface of the seafloor.
Seafloor	The surface of the seabed.
Surficial sediments	The top 10 centimeters of the seabed.

Literature Cited

Atwood, T. B., Witt, A., Mayorga, J., Hammill, E., & Sala, E. (2020). Global patterns in marine sediment carbon stocks. *Frontiers in Marine Science*, *7*, 165. https://doi.org/10.3389/fmars.2020.00165

Bergamaschi, B. A., Tsamakis, E., Keil, R. G., Eglinton, T. I., Montluçon, D. B., & Hedges, J. I. (1997). The effect of grain size and surface area on organic matter, lignin and carbohydrate concentration, and molecular compositions in Peru Margin sediments. *Geochimica et Cosmochimica Acta*, *61*(6), 1247–1260. https://doi.org/10.1016/S0016-7037(96)00394-8

Black, K. E., Smeaton, C., Turrell, W. R., & Austin, W. E. N. (2022). Assessing the potential vulnerability of sedimentary carbon stores to bottom trawling disturbance within the UK EEZ. *Frontiers in Marine Science*, *9*, 892892. https://doi.org/10.3389/fmars.2022.892892

Bradshaw, C., Jakobsson, M., Brüchert, V., Bonaglia, S., Morth, C.-M., Muchowski, J., Stranne, C., & Skold, M. (2021). Physical disturbance by bottom trawling suspends particulate matter and alters biogeochemical processes on and near the seafloor. Frontiers in Marine Science, 8, 683331. https://doi.org/10.3389/fmars.2021.683331

Burdige, D. J. (2007). Preservation of organic matter in marine sediments: Controls, mechanisms, and an imbalance in sediment organic carbon budgets? *Chemical Reviews*, *107*(2), 467–485. https://doi.org/10.1021/cr050347q

Chin, J. L., Karl, H. A., & Maher, N. M. (1997). Shallow subsurface geology of the continental shelf, Gulf of the Farallones, California, and its relationship to surficial seafloor characteristics. *Marine Geology*, *137*(3–4), 251–269. https://doi.org/10.1016/S0025-3227(96)00091-6

Dahl, M., Deyanova, D., Gütschow, S., Asplund, M. E., Lyimo, L. D., Karamfilov, V., Santos, R., Björk, M., & Gullström, M. (2016). Sediment properties as important predictors of carbon storage in *Zostera marina* meadows: A comparison of four European areas. *PLoS ONE*, *11*(12), e0167493. https://doi.org/10.1371/journal.pone.0167493

dbSEABED. (2022). *dbSEABED: Information integration system for marine substrates* [Data set]. https://instaar.colorado.edu/~jenkinsc/dbseabed/

De Falco, G., Magni, P., Teräsvuori, L. M. H., & Matteucci, G. (2004). Sediment grain size and organic carbon distribution in the Cabras lagoon (Sardinia, Western Mediterranean). *Chemistry and Ecology*, *20*, 367–377. https://doi.org/10.1080/02757540310001629189

Diesing, M., Kröger, S., Parker, R., Jenkins, C., Mason, C., & Westin, K. (2017). Predicting the standing stock of organic carbon in surface sediments of the North–West European continental shelf. *Biogeochemistry*, *135*, 183–200. https://doi.org/10.1007/s10533-017-0310-4

Drake, P. T., McManus, M. A., & Storlazzi, C. D. (2005). Local wind forcing of the Monterey Bay area inner shelf. *Continental Shelf Research*, *25*, 397–417. https://doi.org/10.1016/j.csr.2004.10.006

Durrieu de Madron, X., Ferré, B., Le Corre, G., Grenz, C., Conan, P., Pujo-Pay, M., Buscail, R., & Bodiot, O. (2005). Trawling-induced resuspension and dispersal of muddy sediments and dissolved elements in the Gulf of Lion (NW Mediterranean). *Continental Shelf Research*, *25*(19–20), 2387– 2409. https://doi.org/10.1016/j.csr.2005.08.002

Edwards, B. D. (2002). Variations in sediment texture on the northern Monterey Bay National Marine Sanctuary continental shelf. *Marine Geology*, *181*(1–3), 83–100. https://doi.org/10.1016/S0025-3227(01)00262-6

Eigaard, O. R., Bastardie, F., Breen, M., Dinesen, G. E., Hintzen, N. T., Laffargue, P., Mortensen, L. O., Nielsen, J. R., Nilsson, H. C., O'Neill, F. G., Polet, H., Reid, D. G., Sala, A., Sköld, M., Smith, C., Sørensen, T. K., Tully, O., Zengin, M., & Rijnsdorp, A. D. (2016). Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions. *ICES Journal of Marine Science*, *73*(Supplement 1), i27– i43. https://doi.org/10.1093/icesjms/fsv099

Einhorn, C. (2021, March 17). Trawling for fish may unleash as much carbon as air travel, study says. *New York Times*. https://www.nytimes.com/2021/03/17/climate/climate-change-oceans.html

Epstein G., Middelburg, J. J., Hawkins, J. P., Norris, C. R., & Roberts, C. M. (2022). The impact of mobile demersal fishing on carbon storage in seabed sediments. *Global Change Biology*, *28*(9), 2875–2894. https://doi.org/10.1111/gcb.16105

Esri. (2020a). *GEBCO bathymetric contours (NOAA NCEI visualization)* [Data set]. https://www.arcgis.com/home/item.html?id=5f98dbc4708e4a7e99c0a7fe043d70a1

Esri. (2020b). *GEBCO grayscale basemap (NOAA NCEI visualization)* [Data set]. https://noaa.maps.arcgis.com/home/item.html?id=cb6a7e0e8a594c388f4833a8fae66a94

Estes, E. R., Pockalny, R., D'Hondt, S., Inagaki, F., Morono, Y., Murray, R. W., Nordlund, D., Spivack, A. J., Wankel, S. D., Xiao, N., & Hansel, C. M. (2019). Persistent organic matter in oxic subseafloor sediment. *Nature Geoscience*, *12*, 126–131. https://doi.org/10.1038/s41561-018-0291-5

Folk, R. L. (1954). The distinction between grain size and mineral composition in sedimentary rock nomenclature. *The Journal of Geology*, *62*(4), 344–359.

George, D. A., & Hill, P. S. (2008). Wave climate, sediment supply and the depth of the sand–mud transition: A global survey. *Marine Geology*, *254*(3–4), 121–128. https://doi.org/10.1016/j.margeo.2008.05.005

George, D. A., Largier, J. L., Storlazzi, C. D., & Barnard, P. L. (2015). Classification of rocky headlands in California with relevance to littoral cell boundary delineation. *Marine Geology*, *369*, 137–152. https://doi.org/10.1016/j.margeo.2015.08.010

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Key, R. M., Kozyr, A., Lauvset, S. K., Monaco, C. L., Mathis, J. T., Murata, A., Olsen, A., Perez, F. F., Sabine, C. L., Tanhua, T., & Wanninkhof, R. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science*, *363*(6432), 1193–1199. https://doi.org/10.1126/science.aau5153

Harris, P. T., & Whiteway, T. (2011). Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins. *Marine Geology*, *285*(1–4), 69–86. https://doi.org/10.1016/j.margeo.2011.05.008

Hiddink, J. G., Jennings, S., Sciberras, M., Szostek, C. L., Hughes, K. M., Ellis, N., Rijnsdorp, A. D., McConnaughey, R. A., Mazor, T., Hilborn, R., Collie, J. S., Pitcher, C. R., Amoroso, R. O., Parma, A.M., Suuronen, P., & Kaiser, M. J. (2017). Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(31), 8301–8306. https://doi.org/10.1073/pnas.1618858114

Hiddink, J. G., van de Velde, S. J., McConnaughey, R. A., De Borger, E., Tiano, J., Kaiser, M. J., Sweetman, A. K., & Sciberras, M. (2023). Quantifying the carbon benefits of ending bottom trawling. *Nature*, *617*, E1–E2. https://doi.org/10.1038/s41586-023-06014-7

Hunt, C., Demšar, U., Dove, D., Smeaton, C., Cooper, R., & Austin, W. E. N. (2020). Quantifying marine sedimentary carbon: A new spatial analysis approach using seafloor acoustics, imagery, and groundtruthing data in Scotland. *Frontiers in Marine Science*, *7*, 588. https://doi.org/10.3389/fmars.2020.00588

Hutto, S. H., Hohman, R., & Tezak, S. (2021). *Blue carbon in marine protected areas: Part 2; A blue carbon assessment of Greater Farallones National Marine Sanctuary*. National Marine Sanctuaries Conservation Series ONMS-21-10. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries.

Interstate Technology and Regulatory Council. (2016). *Geospatial analysis for optimization at environmental sites*. www.itrcweb.org/gro-1

Jacquemont, J., Blasiak, R., Le Cam., C., Le Gouellec, M., & Claudet, J. (2022). Ocean conservation boosts climate change mitigation and adaptation. *One Earth*, *5*(10), 1126–1138. https://doi.org/10.1016/j.oneear.2022.09.002

Jenkins, C. (2005). *Summary of the onCALCULATION methods used in dbSEABED*. University of Colorado at Boulder, Institute of Arctic and Alpine Research (INSTAAR). http://pubs.usgs.gov/ds/2006/146/docs/onCALCULATION.pdf

Karl, H. A., Chin, J. L., Ueber, E., Stauffer, P. H., & Hendley, J. W., II (Eds.). (2001). *Beyond the Golden Gate—Oceanography, geology, biology, and environmental issues in the Gulf of the Farallones*. U. S. Department of the Interior and U. S. Geological Survey. https://pubs.usgs.gov/circ/c1198/

Keil, R., & Hedges, J. (1993). Sorption of organic matter to mineral surfaces and the preservation of organic matter in coastal marine sediments. *Chemical Geology*, *107*(3–4), 385–388. https://doi.org/10.1016/0009-2541(93)90215-5

Keil, R. G., Montluçon, D. B., Prahl, F. G., & Hedges, J. I. (1994). Sorptive preservation of labile organic matter in marine sediments. *Nature*, *370*, 549–552. https://doi.org/10.1038/370549a0

Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J., Andrews, J., Artioli, Y., Bakker, D. C. E., Burrows, M. T., Carr, N., Cripps, G., Felgate, S. L., Fernand, L., Greenwood, N., Hartman, S., Kröger, S., Lessin, G., Mahaffey, C.,...& Williamson, P. (2020). Carbon on the northwest European shelf: Contemporary budget and future influences. *Frontiers in Marine Science*, *7*, 143. https://doi.org/10.3389/fmars.2020.00143

National Centers for Coastal Ocean Science. (2020). *Vessel monitoring system data* [Unpublished data set]. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service.

Nellemann, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L., & Grimsditch, G. (Eds.). (2009). *Blue carbon: The role of health oceans in binding carbon; A rapid response assessment*. United Nations Environment Programme, GRID-Arendal. https://www.grida.no/publications/145

Oberle, F. K. J., Storlazzi, C. D., & Hanebuth, T. J. J. (2016). What a drag: Quantifying the global impact of chronic bottom trawling on continental shelf sediment. *Journal of Marine Systems*, *159*, 109– 119. https://doi.org/10.1016/j.jmarsys.2015.12.007

Ocean Exploration Trust. (2017). *E/V* Nautilus *exploration program: Cruise NA080* [Unpublished data set].

Palanques, A., Puig, P., Guillén, J., Demestre, M., & Martín, J. (2014). Effects of bottom trawling on the Ebro continental shelf sedimentary system (NW Mediterranean). *Continental Shelf Research*, *72*, 83–98. https://doi.org/10.1016/j.csr.2013.10.008

Paradis, S., Goñi, M., Masqué, P., Durán, R., Arjona-Camas, M., Palanques, A., & Puig, P. (2021). Persistence of biogeochemical alterations of deep-sea sediments by bottom trawling. *Geophysical Research Letters*, *48*(2), e2020GL091279. https://doi.org/10.1029/2020GL091279

Patsch, K., & Griggs, G. (2006). *Littoral cells, sand budgets, and beaches: Understanding California's shoreline*. University of California, Institute of Marine Sciences and California Department of Boating and Waterways, California Coastal Sediment Management Workgroup. https://www.coastal.ca.gov/coastalvoices/resources/2006-LittoralCells.pdf

Pusceddu, A., Bianchelli, S., Martín, J., Puig, P., Palanques, A., Masqué, P., & Danovaro, R. (2014). Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(24), 8861– 8866. https://doi.org/10.1073/pnas.1405454111

Sala, E., Mayorga, J., Bradley, D. Cabral, R. B., Atwood, T. B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A. M., Gaines, S. D., Garilao, C., Goodell, W., Halpern, B. S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J.,…& Lubchenco, J. (2021). Protecting the global ocean for biodiversity, food and climate. *Nature*, *592*, 397–402. https://doi.org/10.1038/s41586-021-03371-z

Serrano, O., Lavery, P. S., Duarte, C. M., Kendrick, G. A., Calafat, A., York, P. H., Steven, A., & Macreadie, P. I. (2016). Can mud (silt and clay) concentration be used to predict soil organic carbon content within seagrass ecosystems? *Biogeosciences*, *13*, 4915–4926. https://doi.org/10.5194/bg-13-4915-2016

Sliter, R. W., Conrad, J. E., Lorenson, T. D., Papesh, A. G., Balster-Gee, A. F., Watt, J. T., & Warrick, J. A. (2021). *Geophysical and core sample data collected offshore San Francisco, California, during field activity 2019-649-FA from 2019-10-11 to 2019-10-18* [Data set]. U.S. Geological Survey, Pacific Coastal and Marine Science Center. https://doi.org/10.5066/P9LBG9H5

Smeaton, C., Austin, W., & Turrell, W. R. (2020). Re-evaluating Scotland's sedimentary carbon stocks. *Scottish Marine and Freshwater Science*, *11*(2). https://doi.org/10.7489/12267-1

Smeaton, C., Hunt, C. A., Turrell, W. R., & Austin, W. E. N. (2021). Marine sedimentary carbon stocks of the United Kingdom's Exclusive Economic Zone. *Frontiers in Earth Science*, *9*, 593324. https://doi.org/10.3389/feart.2021.593324

Storlazzi, C. D., & Jaffe, B. E. (2002). Flow and sediment suspension events on the inner shelf of central California. *Marine Geology*, *181*(1–3), 195–213. https://doi.org/10.1016/S0025-3227(01)00267-5

Storlazzi, C. D., & Reid, J. A. (2010). The influence of El Niño-Southern Oscillation (ENSO) cycles on wave-driven sea-floor sediment mobility along the central California continental margin. *Continental Shelf Research*, *30*(14), 1582–1599. https://doi.org/10.1016/j.csr.2010.06.004

Storlazzi, C. D., McManus, M. A., & Figurski, J. D. (2003). Long-term, high-frequency current and temperature measurements along central California: Insights into upwelling/relaxation on the inner shelf. *Continental Shelf Research*, *23*(9), 901–918. https://doi.org/10.1016/S0278-4343(03)00045-1

Trimmer, M., Petersen, J., Sivyer, D. B., Mills, C., Young, E., & Parker, E. R. (2005). Impact of long-term benthic trawl disturbance on sediment sorting and biogeochemistry in the southern North Sea. *Marine Ecology Progress Series*, *298*, 79–94. https://doi.org/10.3354/meps298079

Valentine, P. C. (2019). *Sediment classification and the characterization, identification, and mapping of geologic substrates for the glaciated Gulf of Maine seabed and other terrains, providing a physical framework for ecological research and seabed management*. Scientific Investigations Report 2019–5073. U.S. Department of the Interior, U.S. Geological Survey. https://doi.org/10.3133/sir20195073

NATIONAL MARINE
SANCTUARIES

AMERICA'S UNDERWATER TREASURES