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Blue Carbon in Marine Protected Areas: Part 2

A Blue Carbon Assessment of Greater Farallones National Marine Sanctuary

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Office of National Marine Sanctuaries
John Armor, Director

Report Authors: Sara Hutto[1], Rietta Hohman[1], Sage Tezak[1]
[1]Greater Farallones Association

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Cover photos: (clockwise from top left) A breaching humpback whale, bull kelp, a salt marsh, and an eelgrass meadow. Photos: (clockwise from top left) Abe Borker, Kevin Joe/California Department of Fish and Wildlife, Kate Bimrose/Greater Farallones Association, Melissa Ward

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Contact

Sara Hutto
Conservation and Climate Program Coordinator
Greater Farallones Association for NOAA's Greater Farallones National Marine Sanctuary
991 Marine Drive, The Presidio
San Francisco, CA 94129
Sara.hutto@noaa.gov

Table of Contents

Abstract

Coastal and marine ecosystems play a significant role in the global carbon cycle, sequestering and storing carbon over long timescales. These "blue carbon" ecosystems help mitigate climate change and its impacts by facilitating the uptake of atmospheric carbon dioxide (CO_2) into the ocean and transporting carbon into sediments or deep waters where it can remain indefinitely if undisturbed. Inclusion of these coastal and ocean processes as part of the solution to global climate change is essential in achieving global carbon mitigation and emission reduction goals; however, blue carbon is often overlooked in climate mitigation policies. Further, resource managers of the largest network of U.S. marine protected areas (MPAs), the Office of National Marine Sanctuaries, have not incorporated assessments of blue carbon extent and functionality into their management plans, policies, or decisions, which can result in unintentional carbon emissions and lost opportunities to further protect and enhance carbon sequestration in MPAs.

Though blue carbon is a rapidly growing area of research, guidance for how to apply blue carbon information in MPA management is lacking, and for some sequestration processes, completely absent. As requested by Greater Farallones National Marine Sanctuary (GFNMS) in response to Part 1 of this series, the Greater Farallones Association conducted a blue carbon assessment for the sanctuary. This is the first assessment of multiple blue carbon sequestration processes in a U.S. federal MPA, with the primary purpose of informing one of the nation's largest MPAs in its management decision-making. The carbon storage and annual sequestration for two coastal blue carbon habitats, seagrass and salt marsh, and two oceanic carbon sequestration processes, kelp export and dead whale falls, were assessed within the boundaries of the sanctuary using regional and site-specific data. These processes have the potential to sequester 4,950 megagrams of carbon (MgC) each year (or 18,150 metric tons CO_2 equivalent), which is valued at $925,650 in societal benefit annually and is 140 times the amount of CO_2 that is emitted from annual site operations. Whale falls account for roughly 60% of this annual sequestration; salt marsh, seagrass, and kelp account for roughly equal parts of the remaining 40%, though annual sequestration by the region's kelp forests have declined by 99.7% from 2008 to 2019. Sanctuary coastal blue carbon habitats currently hold approximately 175,000 MgC in their sediments, which, if destroyed, could release approximately 643,000 metric tons of CO_2, or the equivalent of adding 140,000 vehicles to the road for one year. Understanding carbon sequestration within national marine sanctuaries is key for managing changes to stored carbon, which has national and global climate relevance. While these estimates are an incomplete characterization of carbon services provided by GFNMS, this report nonetheless serves as a preliminary step in guiding sanctuary management to protect and enhance the critical climate mitigation services of its coast and ocean resources.

Key Words

blue carbon, carbon storage, carbon sequestration, Greater Farallones National Marine Sanctuary, carbon stock, marine protected area, climate change, mitigation, kelp, whale, seagrass, salt marsh

Executive Summary

The coastline of GFNMS, looking out to the open ocean. Photo: NOAA

The ocean is the largest carbon sink in the world, accumulating 20–35% of atmospheric carbon dioxide (CO_2) (Sabine et al., 2004), and it plays a significant role in the global carbon cycle by storing and cycling 93% of Earth's CO_2 and holding over half the world's biological carbon in living marine organisms (Nellemann et al., 2009). Blue carbon, the carbon that is captured and stored by marine and coastal vegetation and organisms, is increasingly recognized as a critical component of climate mitigation and therefore should be better understood and protected. Advancing the effective management of blue carbon must begin with baseline knowledge of the marine and coastal resources providing sequestration services. Very few studies demonstrate how to assess sequestration processes beyond the traditional coastal marshes, seagrasses, and mangroves that dominate the blue carbon literature, and there is very little guidance for resource managers to understand how they should apply blue carbon information to ongoing management decisions, marine spatial planning, and project prioritization. Further, resource managers of the largest network of federal marine protected areas (MPAs) in the United States, the Office of National Marine Sanctuaries, have not incorporated calculations of blue carbon into their management plans, policies, or decisions. The omission of blue carbon assessments in MPA management can result in unintentional carbon emissions due to uninformed management decisions (e.g., permitting an activity that may disturb carbon stores) and lost opportunities to further protect and enhance carbon sequestration in MPAs. Though blue carbon is a rapidly growing area of research, guidance for how to apply blue carbon information in marine and coastal management is lacking, and for some sequestration processes, completely absent.

Carbon sequestration: the process of capturing and storing atmospheric CO_2

Carbon capture: the absorption of dissolved inorganic CO_2 and fixation of carbon into living tissues

Carbon storage: the long-term removal of carbon from the atmospheric carbon cycle on the scale of centuries to millennia

Figure 1. The National Marine Sanctuary System includes 17 protected areas administered by NOAA. GFNMS is shown in the red box. Image: NOAA

Greater Farallones National Marine Sanctuary (GFNMS), one of 17 protected areas administered by NOAA through the National Marine Sanctuary System (Figure 1), seeks to better understand its blue carbon resources to inform restoration, protection, and other management activities. GFNMS protects 3,295 square miles along the coast of north-central California (Figure 2), supporting an array of habitats and marine and estuarine species. Seasonal upwelling provides essential nutrients from the deep ocean to the surface, while surface winds transport the nutrient-rich waters along the coast. The circulation of nutrients provides the foundation for a rich and thriving ecosystem that ranges from plankton to apex predators. The sanctuary supports foraging areas for annual whale migrations, coastal and pelagic fisheries, and kelp beds that provide essential habitat for a diversity of species. The healthy function of these ecosystems provides many benefits to local communities and economies. Given the great diversity and complexity of the sanctuary's ecosystems, understanding the various processes that result in carbon capture and storage will both inform sanctuary management and demonstrate more broadly the role that MPAs can play in reaching carbon mitigation goals in the United States and around the world. This report aims to advance the understanding of coastal and oceanic blue carbon and to inform future management decisions in GFNMS.

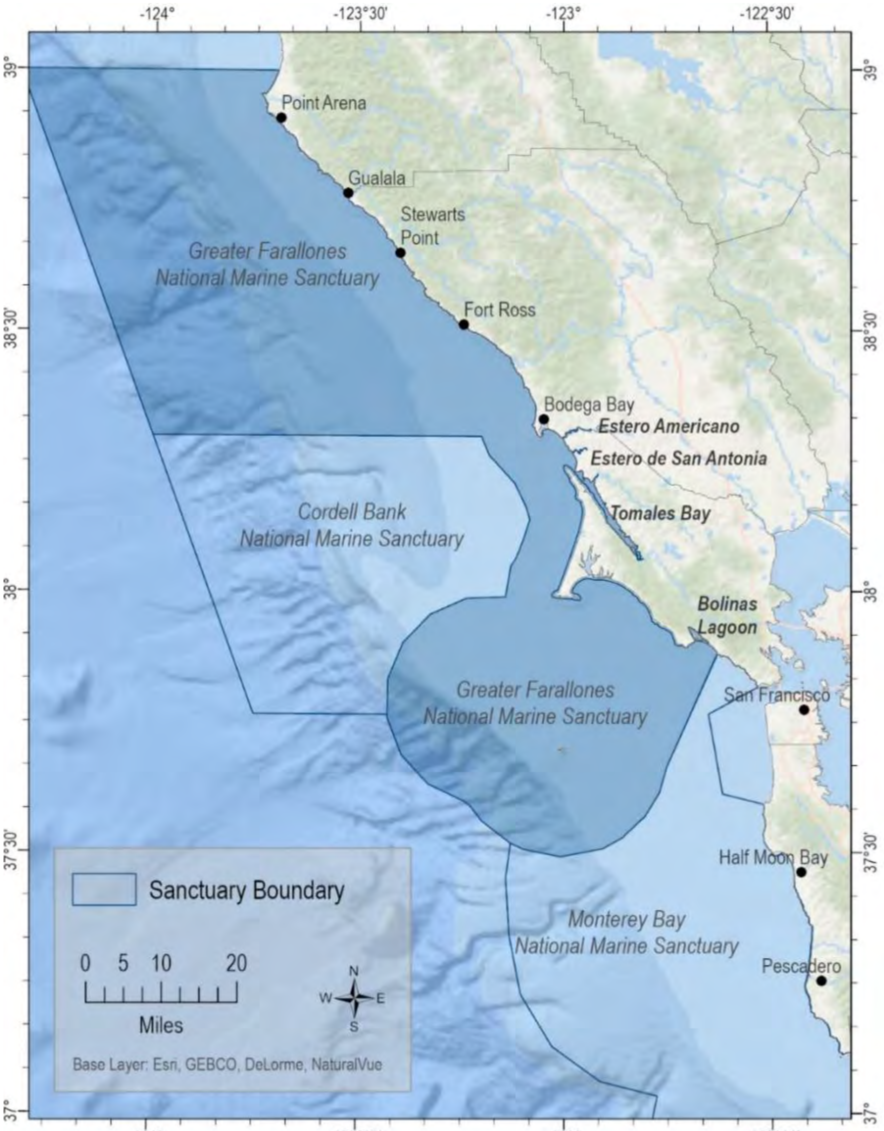

Figure 2. Map of GFNMS, located along the north-central coast of California, shaded in blue. Locations included in the seagrass and salt marsh assessment are identified in bold italics. Image: Sage Tezak

This Tier 2 (Intergovernmental Panel on Climate Change [IPCC], 2014) assessment, using site-specific carbon stock values and sequestration rates, provides an estimate of the amount of carbon currently stored in the sediments underlying two coastal habitats, seagrass and salt marsh, as well as the annual sequestration occurring in those sediments. Additionally, recognizing the critical role of carbon "donors" (i.e., species that export carbon to long-term carbon sinks rather than contributing to *in situ* storage within the habitat) in deep-sea sequestration (Smale et al., 2018), this assessment also quantifies the export of carbon to the deep sea via bull kelp within sanctuary boundaries and dead whale falls for five baleen whale species in the Northeast Pacific. These processes together have the potential to sequester 4,950 megagrams of carbon (MgC) each year (or 18,150 metric tons CO_2 equivalent), which is valued at $925,650 in societal benefit annually and is 140 times the amount of carbon emitted from annual sanctuary operations. Dead whale falls account for roughly 60% of this annual sequestration; salt marsh, seagrass, and kelp account for roughly equal parts of the remaining 40%, though annual sequestration by the region's kelp forests have declined by 99.7% from 2008 to 2019. Coastal blue carbon habitats in the sanctuary currently hold approximately 175,000 MgC in their sediments, which, if destroyed, could release approximately 643,000 metric tons of CO_2, or the equivalent of adding 140,000 vehicles to the road for one year[1]. The purpose of this assessment is to acknowledge the importance of both oceanic and coastal sequestration, while generating a baseline understanding of how much carbon is stored and annually sequestered by select blue carbon processes within the sanctuary.

Based on this preliminary assessment, it is recommended that GFNMS work with partners to fill identified data gaps and scale up the scope of the assessment to be more comprehensive. Notably, carbon stored and immobilized in coastal sediments adjacent to seagrass and salt marsh habitats, as well as seafloor sediments along the continental shelf and slope, are not considered in this assessment and should be prioritized for future work. GFNMS should continue collaborations with state-wide blue carbon organizations and international partners to advance understanding of blue carbon science and assessment, and work with the Office of National Marine Sanctuaries to mainstream blue carbon assessments in sanctuary planning processes. Most importantly, the information presented in this assessment could and should be used now to inform management activities, permitting and policy decisions, and staffing and funding priorities. Though this assessment is preliminary, the results indicate that the sanctuary contains vast carbon stores, and there is great opportunity to not only provide additional protections for the critical living marine resources in this biodiverse region, but to advance the restoration of blue carbon habitats and processes.

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[1] Calculated using the EPA Greenhouse Gas Equivalencies Calculator, which assumes vehicles emit 4.6 metric tons of CO_2 per year, with an average fuel economy of 22 miles per gallon and 11,500 miles driven per year.

Chapter 1: Coastal Blue Carbon Assessment

Introduction

Coastal blue carbon ecosystems (seagrass, salt marsh, and mangrove) are well recognized as globally significant carbon sinks; these vegetated coastal habitats remove CO_2 from the atmosphere and store it in the stems, branches, leaves, and roots of the plant, with long-term carbon accumulation occurring in the sediments they hold in place. Two coastal blue carbon ecosystems are present in GFNMS: tidal salt marsh, characterized by salt-resistant grasses, herbs, and shrubs and the mixing of fresh and salt water caused by tidal fluctuations (Commission for Environmental Cooperation, 2016), and seagrass, which forms extensive underwater meadows with dense belowground networks of rhizomes that hold sediment in place.

Coastal blue carbon habitats in GFNMS: salt marsh in Bolinas Lagoon (left) and seagrass in Tomales Bay (right). Photos: Bob Lewis (left), Melissa Ward (right)

In GFNMS, salt marsh habitat is found in protected embayments, including Bolinas Lagoon, Tomales Bay, Estero de San Antonio, and Estero Americano (Office of National Marine Sanctuaries, 2014; Figure 2). Marsh vegetation in this region is characterized by pickleweed (*Salicornia pacifica*) and saltgrass (*Distichlis spicata*) (AECOM, 2016), with Pacific cordgrass and alkali bulrush lining the more shallowly sloped edges. Salt marshes offer food and shelter for many coastal species during vulnerable lifecycle stages. For example, some flounders breed near salt marshes to allow juveniles to develop in the marsh system. Herons, sandpipers, ducks, rails, and geese are also dependent upon the marsh for feeding and breeding (NOAA, 2014).

Two seagrasses are found in GFNMS: coastal fringing surfgrass (genus *Phyllospadix*) and inshore eelgrass (*Zostera marina*). Eelgrass is the focus of this assessment, as this species forms extensive underwater meadows with dense belowground networks of rhizomes that stabilize carbon-rich sediments. Eelgrass beds occur on the extensive mudflats in Tomales Bay, and within Estero de San Antonio and Estero Americano in GFNMS. Historically, eelgrass was present in Bolinas Lagoon, and it is not known why the species has largely disappeared (GFNMS, 2008). Seagrass beds provide important breeding and nursery habitat for organisms such as herring, which attach their eggs to eelgrass. Seagrass supports a unique and diverse assemblage of invertebrates, including snails, shrimp, nudibranchs, and sea hares. The structure of seagrass beds provides protection from predation, especially for juvenile invertebrates and fishes. Pacific herring, invertebrates, and birds depend on seagrass beds in Tomales Bay to spawn and feed (NOAA, 2014).

Taylor's sea hare crawling on a blade of seagrass. Photo: NOAA

Methods

Geographic Extent

For all coastal habitats, geographic extent data within sanctuary boundaries are required to determine how much carbon is sequestered and stored in the underlying sediments. Seagrass meadow extents shift from year to year and are highly dynamic; the underlying sediments, however, do not exhibit significant variability in carbon content when compared with nearby bare sediments (Ward et al., 2021). As this assessment focuses on the underlying sediments rather than plant photosynthesis as a proxy for sequestration, maximum extent data were used to estimate the carbon stored in estuarine sediments. Seagrass extent data were collected from the California Department of Fish and Wildlife for the years 1992, 2000–2002, and 2013 and Merkel and Associates, Inc. for 2015 and 2017 using side-scan sonar. Data were mapped in ArcGIS and clipped to sanctuary boundaries for analysis.

Tidal marsh extent data were sourced from the Marin Countywide Fine Scale Vegetation Map, which includes tidal wetlands mapped in 2019 using light detection and ranging (LiDAR, a remote sensing method) to a 0.1 hectare minimum mapping unit. The tidal wetlands map should be considered an approximation of tidal wetland extent due to the wide spectral variation within species groups, the influence of substrate on spectral signature, and other factors. Maximum extent data were not used because tidal salt marshes are less prone to drastic range shifts and therefore recent survey data present the most accurate representation of current distribution.

Carbon Stock and Sequestration

A Tier 2 assessment for salt marsh and seagrass extents in GFNMS requires region-specific carbon stock values to estimate carbon storage (the amount of carbon present in the sediment within the vegetated habitat, typically to a depth of one meter) and sediment accumulation rates to estimate annual sediment carbon sequestration (the amount of carbon that accumulates in the sediment on an annual basis). As discussed in Part 1 of this series, a Tier 2 assessment is more accurate than a Tier 1 assessment, which uses global means for these data. Additionally, carbon stock and sequestration were calculated solely for sediments underlying these biogenic habitats; carbon storage in the above-ground vegetation is not included in this assessment. Carbon stock data for sediments underlying both habitats were calculated specifically for Tomales Bay as part of a larger California-wide study of carbon stock values (Ward et al., 2021). To ensure the most accurate estimate for GFNMS, only values from Tomales Bay were used in this study, as 99% of the mapped seagrass and a significant portion of mapped salt marsh in GFNMS is in Tomales Bay. Using local values increases the accuracy of the assessment, as sequestration and storage rates can vary widely from location to location, resulting in a large margin of error (Table 1). Ward et al. (2021) calculated salt marsh carbon stock in Tomales Bay as 279 (±41.4 SE) MgC/hectare to 1-m depth, based on six 20-cm depth cores taken in Walker Marsh (Figure 3). This is similar to other estimates from the literature (Table 1). Ward et al. (2021) calculated seagrass carbon stock in Tomales Bay as 106 (±17.6) MgC/hectare to 1-m depth, based on 15 20-cm depth cores from three seagrass meadows in Tomales Bay: Tom's Point, Cypress Grove, and Chicken Ranch (Figure 3). This is similar to California-wide and global estimates, but higher than U.S. West Coast estimates (Table 1).

The carbon sequestration rate for sediments underlying GFNMS seagrass was calculated in this study by multiplying the carbon stock estimate for Tomales Bay seagrass (106 MgC/hectare; Ward et al., 2021) by sediment accumulation rates (SAR; 0.12–0.98 cm/year) from Capece (2019). These rates were determined from one 20-cm core taken in Cypress Grove, Tomales Bay, using Pb210 dating. The high variability in SAR is likely due to temporal changes in runoff, storm-driven sediment deposition or loss, and tidal flows, and is likely a reflection of true variability in sedimentation (M. Ward, personal communication, July 7, 2021). The Capece (2019) range encompasses SAR reported in three other studies from Tomales Bay (O'Donnell, 2017; Flores, 2011; Rooney, 1995) and is used in this assessment to accurately capture the variance in sediment sequestration. The carbon sequestration rate, therefore, is estimated to be between 12.7–103.9 $gC/m^2/yr$, compared to the global average estimate of 83 $gC/m^2/yr$ (Laffoley & Grimsditch, 2009). Because the sequestration rate varies so widely, a lower and upper estimate are provided in the calculations of annual carbon sequestration. The lower estimate calculation is shown here as an example:

$$Sediment\ accumulation\ rate\ x\ carbon\ stock = annual\ sequestration\ rate$$

$$0.12\frac{cm}{year} * 0.0106\frac{gC}{cm^3} = 0.001272\frac{gC}{\frac{cm^2}{yr}} = 12.72\frac{gC}{m^2/yr}$$

The carbon sequestration rate for sediments underlying GFNMS salt marshes was calculated in this study in the same manner as seagrass, by multiplying the carbon stock estimate for Tomales

Bay salt marsh (279 MgC/hectare; Ward et al., 2021) by the average SAR (0.7 cm/yr) obtained from Byrne et al. (2005). This average rate was taken from 20 cores using Pb210 dating in Bolinas Lagoon, and is the best available SAR for salt marshes in the GFNMS region. The carbon sequestration rate, therefore, is estimated to be 195.3 gC/m^2/yr, which is similar to the average global estimate of 210 gC/m^2/yr (Laffoley & Grimsditch, 2009; Chmura et al., 2003).

Table 1. Published salt marsh and seagrass carbon stocks and sequestration rates. Local rates were used for this assessment; regional, national, and global average rates are shown for comparison and context.

Scale of study	**Salt marsh carbon stock** (MgC/hectare)	**Salt marsh sequestration** (gC/m^2/year)	**Seagrass Carbon Stock** (MgC/hectare)	**Seagrass Sequestration** (gC/m^2/year)
Local	279 (±41.4) (Tomales Bay; Ward et al,. 2021)	195 (Tomales Bay/Bolinas Lagoon; present study)	106 (±17.6) (Tomales Bay; Ward et al., 2021)	12.7–103.9 (Tomales Bay; present study)
California	235 (Ward et al., 2021)	NA	110 (Ward et al., 2021)	NA
U.S.	270 (Holmquist et al., 2018)	NA	65–92 (West Coast only; Kauffman et al., 2020; Prentice et al., 2019)	NA
Global	255 (IPCC, 2014)	210 (Laffoley & Grimsditch, 2009; Chmura et al., 2003)	108 -139 (IPCC, 2014; Fourqurean et al., 2012)	83 (Laffoley & Grimsditch, 2009)

Total carbon stock and annual sequestration were calculated as described by Howard et al. (2014) for both seagrass and salt marsh in the sanctuary (salt marsh shown as an example):

$$\text{area (ha)} * \text{carbon stock (MgC/ha)} = \text{carbon stock for the sanctuary}$$
$$355.8\ \text{ha} * 279\ (\pm 41.4)\ \text{MgC/ha} = 99{,}268\ \text{MgC}$$

$$\text{area } (m^2) * \text{annual sequestration rate} = \text{annual sequestration rate for salt marsh sediments}$$
$$3,557{,}904\ m^2 * 195\ (\pm 29.0)\ \text{gC}/m^2/\text{yr} = 693.8\ \text{MgC /year}$$

Results

Seagrass meadows, composed of eelgrass (*Zostera marina)*, cover an area of 7,158,514 m^2 in GFNMS, with 99% of the extent solely located in Tomales Bay (Figure 3), with patchy extent in Estero Americano and Estero de San Antonio (Figure 4). Eelgrass sediments are estimated to currently store 75,880 MgC, which, if released via habitat destruction, would be the equivalent of adding, on average, 60,509 passenger vehicles[2] to the road for one year or burning 31 million gallons of gasoline (Table 2). In addition to the carbon already stored in seagrass sediments, every year 91–743 MgC accumulates in the sediments, which is equivalent to removing up to 593 passenger vehicles from the road or preventing the burning of 219,000 gallons of gasoline each year. The benefit of this carbon sequestration service can be valued in terms of the cost to society if the service were no longer provided (referred to as the social cost of carbon[3], which is

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[2] Calculated using the EPA Greenhouse Gas Equivalencies Calculator, which assumes vehicles emit 4.6 metric tons of CO_2 per year, with an average fuel economy of 22 miles per gallon and 11,500 miles driven per year.

[3] Climate change causes far-reaching impacts to society, including increased prevalence of damaging storms, food insecurity, and drought. To account for these damages to society and the economy, the social cost of carbon places a dollar value on one metric ton of CO_2 released into the atmosphere. In effect, the

currently set at $51 per metric ton of CO_2; Boushey et al., 2021); eelgrass meadows in the sanctuary provide up to $139,000 per year[4] in carbon sequestration benefits to society by continuously removing and slowing accumulation rates of atmospheric CO_2.

Salt marsh in GFNMS covers an area of 3,557,904 square meters within Tomales Bay (Figure 3), Estero Americano, Estero de San Antonio (Figure 4), and Bolinas Lagoon (Figure 5). Dominant species include: *Distichlis spicata* (44% cover), *Sarconia pacifica* (36% cover), and *Spartina foliosa* (9% cover). Salt marsh sediments in GFNMS are estimated to currently store 99,268 MgC, which, if released via habitat destruction, would be the equivalent of adding, on average, 79,159 passenger vehicles to the road for one year or burning 41 million gallons of gasoline (Table 2). In addition, salt marsh sediments in the sanctuary annually accumulate an additional 693.8 MgC, which is equivalent to removing 553 passenger vehicles from the road each year or preventing the burning of 250,000 gallons of gasoline each year. Using the social cost of carbon (the cost to society from the release of one metric ton of CO_2), salt marsh in GFNMS provides $129,859 in societal benefits every year.

Table 2. Carbon storage and sequestration for seagrass and salt marsh habitats in GFNMS.

Habitat Type	**Extent** (m2)	**Carbon Storage** (MgC)	**Annual Sequestration** (MgC/yr)	**Passenger Vehicle equivalence**	**Societal Benefit** ($51/Mg CO_2)
Seagrass	7,158,514	75,880	91–743	60,509 for one year; 73-593 per year	$17,000–139,000
Salt Marsh	3,557,904	99,268	693.8	79,159 for one year; 553 per year	$129,859

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dollar value represents the cost to society through medical expenditures, physical damage to property, and loss of resources.

[4] Societal benefit is calculated as annual sequestration (MgC/year) x CO_2 conversion factor (3.67) x $51.

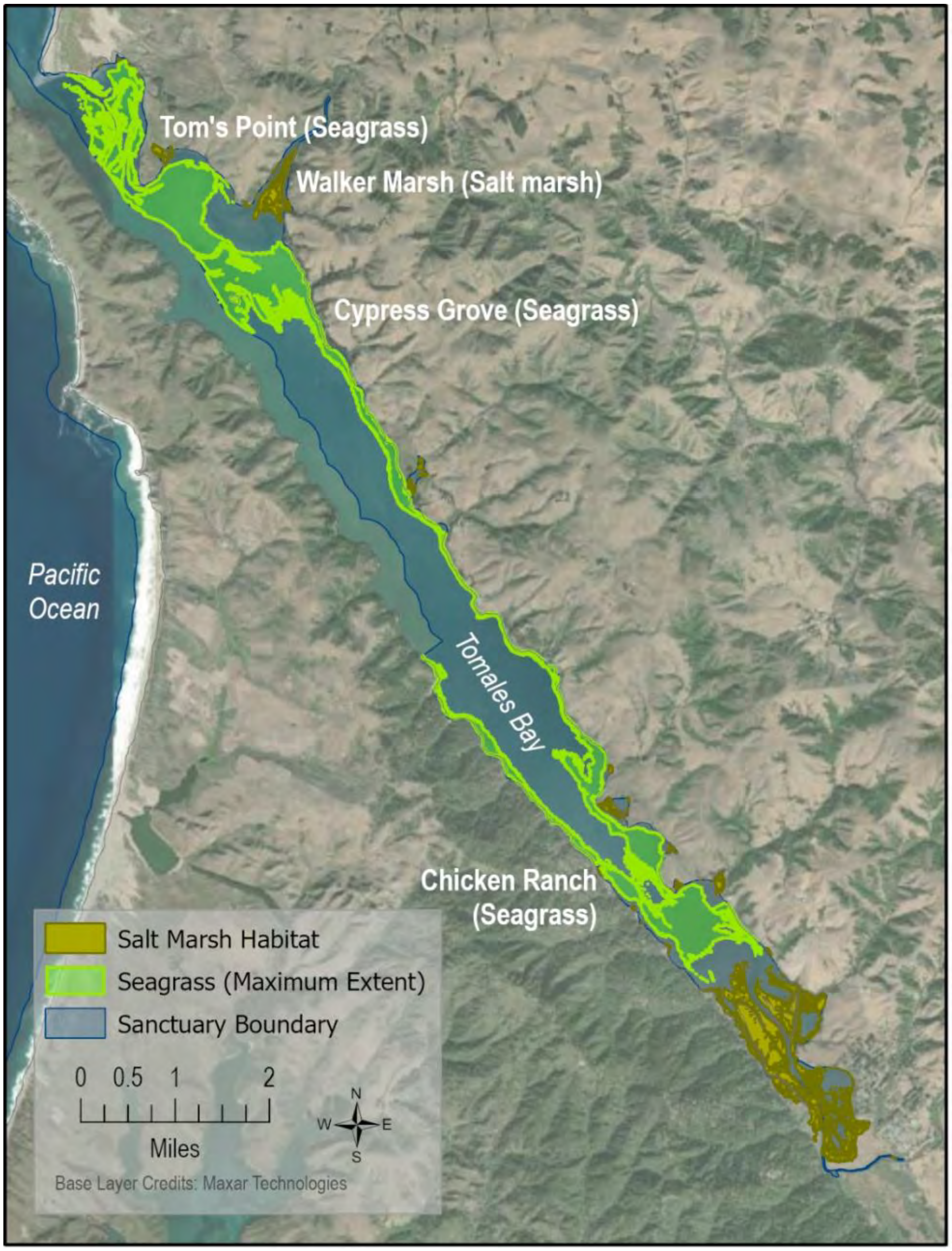

Figure 3. Map of Tomales Bay, showing salt marsh and seagrass extent. Names indicate data collection locations; seagrass carbon stock data were collected from Chicken Ranch, Cypress Grove, and Tom's Point (Ward et al., 2021); seagrass SAR data were collected from Cypress Grove (Capece, 2019); salt marsh carbon stock data were collected from Walker Marsh (Ward et al., 2021). Image: Sage Tezak

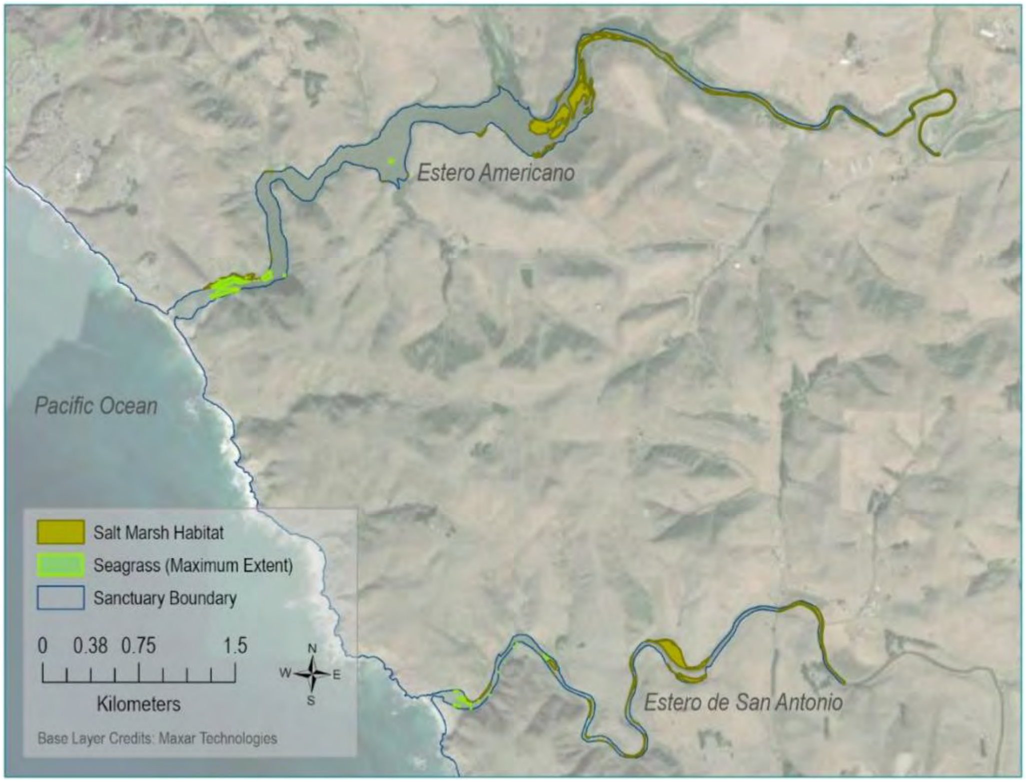

Figure 4. Map of Estero Americano and Estero de San Antonio showing salt marsh and seagrass extent. Image: Sage Tezak

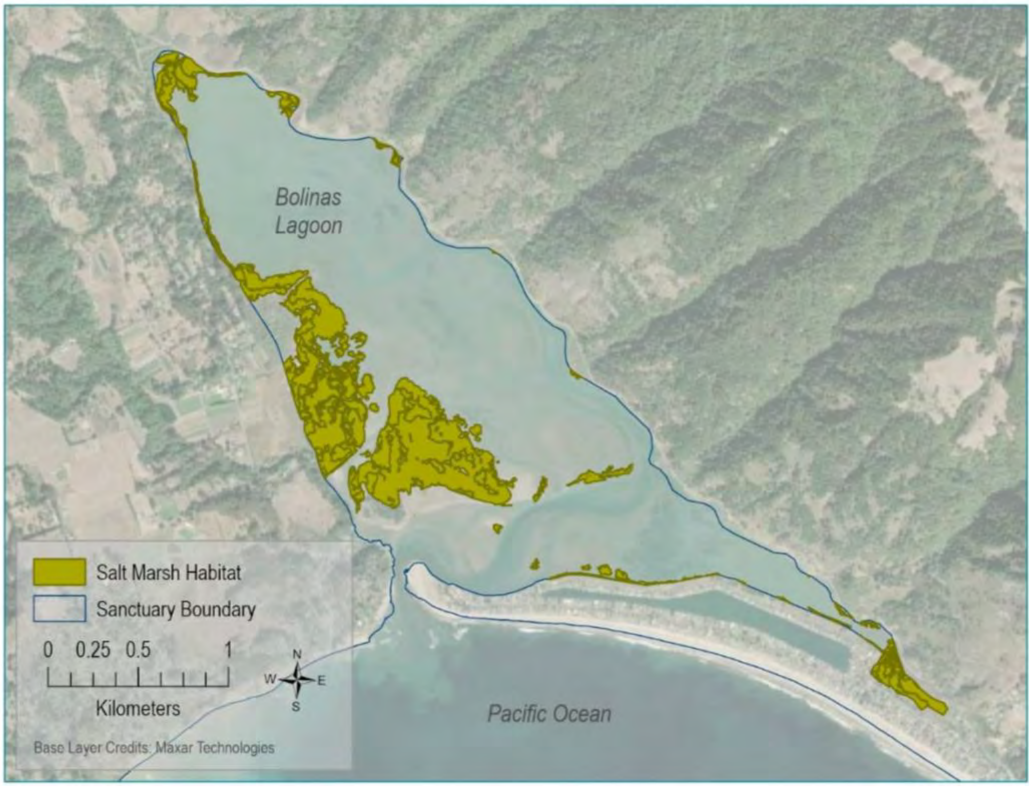

Figure 5. Map of Bolinas Lagoon showing salt marsh extent. Image: Sage Tezak

Chapter 2: Marine Blue Carbon Assessment

Introduction

Carbon sequestration is not limited to coastal vegetated habitats, and increasingly, research indicates that oceanic carbon sequestration via the sinking of marine animals and vegetation to the deep sea is likely far more significant than previously estimated. Though numerous sequestration processes occur within the marine environment of GFNMS (see Part 1 for a more complete review), the lack of robust data and methodology to estimate these processes greatly limits the scope of their assessment. Therefore, this assessment focuses on two processes for which data were available or novel methods could be developed: the export of carbon to the deep sea via bull kelp and dead whale falls.

A bull kelp forest underwater in GFNMS. Photo: Keith Johnson

Kelp is commonly found attached to rocky substrates in the form of dense forests in temperate regions such as California. The GFNMS rocky nearshore environment is characterized by dense forests of kelp growing at depths from 2 meters to more than 30 meters (Foster & Schiel, 1985). Bull kelp (*Nereocystis luetkeana*) is the dominant canopy-forming kelp in the sanctuary, and extensive kelp forests occur along the Sonoma and Mendocino County coasts (NOAA, 2014). Due to compounding environmental factors, kelp forests throughout GFNMS have drastically decreased since 2014, with an estimated decline of 90% in bull kelp extent during that time (Rogers-Bennett & Catton, 2019). Kelp forests remain an integral part of the GFNMS marine environment, and efforts are underway to restore this critical ecosystem (Hohman et al., 2019). Bull kelp in the sanctuary grows in rocky reef habitat that prevents burial of plant material; thus, carbon is not sequestered locally, as it is in some coastal blue carbon habitats, including seagrasses and salt marshes. Rather, kelp are considered blue carbon "donors" to deep-sea environments. As kelp is detached from the subtidal rocky substrate it grows on, a portion of that biomass is exported offshore and sinks to the seafloor. Because it is stored far offshore and in deep water, this carbon is effectively isolated from atmospheric influences and other disturbances (Krause-Jensen & Duarte, 2016).

A humpback whale and its calf. Humpback whales are one of five baleen whales included in this assessment. Photo: NOAA

Though there are multiple avenues through which whales contribute to carbon storage and export (see Part 1 for a complete review), this assessment focuses on the most readily estimated process: direct carbon export when whales die and sink to the seafloor (whale falls), where the carbon stored in their tissues can remain in the deep sea for millennia. Abundant baleen whale populations, including blue, gray, humpback, and fin whales, feed in and migrate through GFNMS waters. Blue whales respond to the seasonal patterns in productivity in foraging areas along the west coast of North America and exhibit strong seasonal migration to primarily feed on euphausiids in the Gulf of the Farallones before migrating to breeding and calving grounds in lower latitudes (Lockyer, 1981). Humpback whales follow similar migration patterns and primarily feed on small schooling fish and euphausiid prey in the Gulf of the Farallones before migrating to breeding and calving grounds in Mexican and Central American waters (Kieckhefer, 1992). While migrating through the sanctuary, commercial vessel traffic and fishing gear can negatively impact large whales. They can experience chronic exposure to engine and propeller noise, collisions with ships, and entanglement in fishing gear. GFNMS seeks to reduce these impacts by working with commercial vessel operators to reduce their speed when in the vicinity of large whales and with local fishers to collect lost fishing gear (GFNMS, 2021).

Methods

Bull Kelp

Geographic Extent

To calculate carbon capture and export to deep-sea environments, the amount of bull kelp within GFNMS was first calculated. Bull kelp canopy can be identified by several remote sensing platforms because their floating surface canopies have strong reflectance in the near-infrared and are optically distinct from the surrounding ocean water (McPherson et al., 2021). Kelp canopy in northern California has been surveyed using three methods: aerial plane-based surveys (inconsistently from 1999–2016), Landsat (continuously from 1985–2020), and uncrewed aerial vehicle (UAV) surveys (2019 and 2020). Landsat imagery provides the longest, most consistent and complete historical data set and was identified to be the most appropriate data source to determine bull kelp canopy in the sanctuary. Bull kelp exhibits great temporal and spatial variability, with shifting beds from year to year, including a significant loss of kelp in 2014 that persisted in subsequent years. To accurately capture this variance and provide meaningful information for sanctuary managers, this analysis compares the carbon capture and export by sanctuary kelp beds in a relatively high kelp growth year (2008), prior to the 2014 decline, with a low kelp growth year (2019), following the decline.

Biomass

From the canopy extent data, partners at UC Santa Cruz and UC Santa Barbara were consulted to develop novel methodology to estimate bull kelp biomass from kelp canopy cover in GFNMS. Prior to this assessment, a biomass conversion for bull kelp canopy from remote sensing data did not exist. Drone imagery, stipe density from subtidal surveys, and kelp bulb weight from three sites in Mendocino County were examined to develop a numerical relationship between kelp fraction (the amount of kelp per pixel) in remote sensing imagery and total kelp biomass (including stipe, bulb, and canopy). The resulting linear model was developed based on the assumption that a kelp fraction of zero is equivalent to zero stipe count, and the maximum kelp fraction observed (0.785) is equivalent to the maximum observed stipe density (20/m^2), with a slope of 94.8 kg/m^2. This method has not been validated, but the resulting estimates are likely to be within an order of magnitude of true biomass and are likely to be conservative, as the method excludes biomass from kelp that has not grown to the surface (T. Bell, personal communication, May 4, 2021).

Using cloud-free Landsat 5, 7, and 8 imagery, the spectral signature of kelp was identified during the peak growth period in 2008 and 2019. Layers for kelp cover for each of these years were clipped to the borders of GFNMS. Kelp area was determined at a resolution of 30 x 30 m, and kelp fraction per pixel was identified using multiple endmember spectral mixture analysis. The biomass conversion formula was then applied to estimate the total kelp canopy biomass for each year.

Carbon Stock and Sequestration

Given that kelp is approximately 90% water, dry weight is calculated as 10% of the total biomass, and 30% of the dry weight is carbon (Rosell & Srivastava, 1985; Ahn et al., 1998).

Therefore, total wet biomass (kg) is converted to total carbon standing stock (kg C) by multiplying by 0.03. Total carbon standing stock represents the amount of carbon temporarily stored in the sanctuary's kelp beds in a given year.

*total wet biomass * 0.03 = total carbon standing stock*

Given that bull kelp is an annual species, it is assumed that the total carbon standing stock, once divided by the total canopy area (m^2), is the net primary productivity (NPP) rate for the region. However, this rate does not account for primary productivity losses via dissolved organic carbon (DOC) and erosion of particulates from the end of kelp blades (particulate organic carbon [POC]). To apply the model of kelp carbon export developed by Krause-Jensen and Duarte (2016), both POC and DOC must be accounted for in the total NPP. Therefore, an additional 15% was added to the NPP rate to account for DOC (based on estimates by Reed et al. [2015] for giant kelp), and 15% was added to account for blade erosion (conservative estimate; T. Bell, personal communication, April 29, 2021). To add 15% for DOC and 15% for blade erosion (a total of 30%), the NPP is multiplied by 1.3.

$$total\ carbon\ standing\ stock\ (\frac{MgC}{year}) * 1.3 = total\ NPP\ (\frac{MgC}{year})$$

A global model of kelp carbon export developed by Krause-Jensen and Duarte (2016) estimated that 43% of the carbon from the NPP is exported from the algal bed, with 52% of that as DOC and 48% as POC. Of the DOC that is exported, 67% remineralizes and 33% is further exported below the mixed layer, where it is assumed to be sequestered indefinitely. Of the POC that is exported, 85% remineralizes and 15% is buried in shelf sediments or exported to the deep sea. The authors ultimately identify the percentage of NPP that is sequestered long term via four processes: POC buried *in situ* in kelp bed sediments (0.39%), DOC exported below the mixed layer (7.70%), POC exported to the deep sea (2.30%), and POC buried in continental shelf sediments (0.92%). Excluding the *in situ* estimate (because kelp grows solely on rocky reefs in the sanctuary), this resulted in an estimate of 10.92% of the NPP ultimately being sequestered. The total NPP, therefore, was multiplied by 0.11 to estimate the portion that is sequestered in any given year via kelp carbon export from the sanctuary.

$$total\ NPP\ \left(\frac{MgC}{year}\right) * 0.11 = annual\ carbon\ sequestration\ \left(\frac{MgC}{year}\right)$$

Baleen Whales

As large baleen whales die, the vast majority of carcasses sink to the seabed (up to 90%; Smith & Baco, 2003), taking the carbon they have stored with them and immobilizing that carbon indefinitely in the deep sea. As it is not possible to draw sanctuary boundaries around such mobile species, the next best estimate is to use populations that reside in the Eastern North Pacific (ENP) and are known to feed in the highly productive waters of the sanctuary. To calculate the amount of carbon that is currently exported from the euphotic zone to the deep sea every year via whale falls, NOAA Fisheries ENP population estimates for five baleen whales were multiplied by published global carbon export estimates (metric tons C per individual per year; Pershing et al., 2010) for each species and divided by two, assuming a conservative estimate that 50% of dead whales reach the deep sea (Smith & Baco, 2003).

$$\frac{number\ of\ whales\ *\ gross\ carbon\ flux\ (\frac{tons\ C}{whale/yr})}{2} = annual\ carbon\ export\ (\frac{MgC}{yr})$$

The five species in this assessment include humpback, gray, fin, blue, and minke whales. Where pre-whaling population estimates were available, the pre-whaling carbon export was also calculated. Toothed whales exhibit different behavior and feeding patterns, and are therefore not included in this assessment. It should be noted, however, that a growing body of evidence indicates that "fish carbon," carbon stored in the biomass of all marine megafauna, makes a significant contribution to carbon flux to the deep sea but inclusion of this "fish carbon" was beyond the scope of this assessment.

Population Estimates

Pre-whaling and current population numbers were sourced from NOAA Fisheries marine mammal stock assessments for either California/Oregon/Washington or ENP stocks of five baleen whale species (Table 7).

The California/Oregon/Washington humpback whale stock is defined as individuals that feed off the west coast of the United States, including animals from both the California-Oregon and Washington-southern British Columbia feeding groups (Calambokidis et al., 1996, 2008; Barlow et al., 2011). Current population estimates for the entire North Pacific range from 18,000 to 20,000 (Calambokidis et al., 2008). However, the California/Oregon/Washington population was targeted most heavily for whaling, with shore-based whaling depleting the stock twice (1925 and 1956–1965), and is considered endangered and depleted (NOAA Fisheries, 2020a).

For gray whales, there is greater uncertainty around different populations of whales within the ENP. There is a Pacific Coast Feeding Group (PCFG), defined as individuals that spend the summer and autumn feeding in coastal waters of the Pacific coast of North America from California to southeast Alaska (International Whaling Commission, 2012). While likely relevant for this assessment, it remains unresolved whether this feeding group is a distinct stock (Weller et al., 2013), making population estimates difficult. Therefore, both a PCFG and an ENP population estimate were used in this assessment. A steady increase has been observed in both the PCFG and the greater ENP population (Calambokidis et al., 2017), and neither stock is endangered or depleted (NOAA Fisheries, 2019a). However, since the beginning of 2019 and as of May 2021, an unusual mortality event is ongoing. Elevated gray whale strandings are occurring along the entire west coast of North America, with some whales showing signs of starvation (NOAA Fisheries, 2021). The most recent population estimate indicates a decline of 23.7%, coinciding with this unusual mortality event. However, the population fully rebounded from a decline of similar magnitude in the early 2000s, suggesting that short-term declines are not uncommon and may not have long-term impacts on the population (Stewart & Weller, 2021). This assessment uses the 2017 stock assessment for consistency with other species assessments.

The California/Oregon/Washington fin whale stock is one of three recognized stocks of the North Pacific population of fin whales. The pre-whaling population in the North Pacific was estimated to be 42,000–45,000, reduced to 13,620–18,680 by 1973 (Ohsumi & Wada, 1974). However, there are clear indications of recovery in the California/Oregon/Washington stock, with a 5-fold increase in abundance from 1991 to 2014, which has largely been driven by increases in Northern California, Oregon, and Washington, with stable populations in Central and Southern California (Nadeem et al., 2016). The species is still formally listed as endangered, and consequently, this stock is officially considered depleted (NOAA Fisheries, 2019b).

The ENP blue whale stock may range as far west as Wake Island (2,000 miles west of Hawai‘i) and as far south as the equator (Stafford et al., 1999, 2001), but primarily uses nine important feeding areas along the U.S. west coast in summer and fall (NOAA Fisheries, 2020b). One of these biologically important feeding areas is in the sanctuary (Calambokidis et al., 2015). There is no pre-whaling estimate for blue whales, though Monnahan et al. (2014) estimated that 3,411 blue whales were removed from the eastern North Pacific between 1905 and 1971 via commercial whaling. There is no evidence of population growth of the ENP stock since the 1990s; however, Monnahan et al. (2015) estimate that the population was at 97% of carrying capacity in 2013. Regardless, the ENP stock of blue whales is considered depleted and the species is listed as endangered (NOAA Fisheries, 2020b).

Minke whales residing in the waters off California, Oregon, and Washington appear behaviorally distinct from those found in Alaska, and are therefore considered a separate stock (NOAA Fisheries, 2016). No estimates are available for the pre-whaling population of minke whales, and the current population estimate for the California/Oregon/Washington stock is 636 individuals (Barlow, 2016). There are no data on population trends for this stock and the population status is unknown (NOAA Fisheries, 2016).

Results

Bull Kelp

Prior to the significant kelp loss that first occurred in 2014, bull kelp covered an area of nearly 2.5 million square meters in GFNMS in a typical year of highly productive growth. Data from 2008 were used to represent a high-growth year for this analysis (Table 3). With an estimated total wet biomass of 143 million kg, sanctuary kelp beds temporarily stored 4,289 Mg of carbon. Adding 30% to account for losses via DOC and POC, NPP was estimated to be 5,577 MgC/year. With approximately 11% of bull kelp NPP exported to the deep-sea environment, 613 Mg carbon were removed from the carbon cycle, which is similar to the average annual sequestration via salt marsh sediments and the high end estimate for seagrass sediments in the sanctuary. This annual sequestration is equivalent to removing 489 passenger vehicles from the road for one year or preventing the burning of 253,000 gallons of gasoline. Using the social cost of carbon to provide an economic value of this carbon sequestration service ($51/metric ton CO_2), bull kelp in the sanctuary can provide $115,000 annually in added benefits to society in a year of highly productive growth. Alternatively, following the massive kelp loss event of 2014, kelp growth has been very low in subsequent years, represented in this analysis by data from 2019 (Table 3). In that year, bull kelp covered an area of 6,483 square meters in GFNMS, with an estimated total wet biomass of 411,403 kg, which temporarily stored 12 Mg of carbon. NPP was estimated to be 16 MgC/year, with approximately 1.8 MgC exported to deep-sea environments. This is just 0.3% the annual sequestration provided by the sanctuary’s kelp beds in 2008, and is equivalent to removing 1.4 passenger vehicles from the road for one year, providing $337 in sequestration services to society.

Table 3. Carbon storage and sequestration for bull kelp habitat in GFNMS in 2008 and 2019.

Year	**Extent** (m^2)	**Total Wet Biomass** (kg)	**Carbon Standing Stock** (MgC)	**Net Primary Productivity** (MgC/year)	**Annual Sequestration** (MgC/year)	**Passenger Vehicle Equivalence**	**Societal Benefit**
2008	2,480,714	142,969,202	4,289	5,577	613	489	$114,735
2019	6,483	411,403	12	16	1.8	1.4	$337

Baleen Whales

Table 4 provides gross carbon flux for each of the five whale species included in this assessment, along with pre-whaling (if available) and current population estimates. Carbon export from the euphotic zone to the deep sea was calculated for each current population and ranged from just over 11 MgC per year for minke whales to 1,415 MgC per year for ENP gray whales. The estimated total annual carbon export for baleen whales in the ENP may be as high as 2,899 MgC/year, which is more than the combined annual sequestration via seagrass, salt marsh, and kelp export in the sanctuary. This amount of carbon export and immobilization is equivalent to removing 2,312 passenger vehicles from the road or preventing the burning of over 1 million gallons of gasoline each year. Using the social cost of carbon, baleen whales that likely feed in sanctuary waters provide up to $542,689 in added benefit to society per year through the carbon immobilization potential of whale falls. Incorporating the pre-whaling estimates for the North Pacific stocks of humpback and fin whales brings the annual carbon export to 7,366 MgC/year.

Table 4. Carbon flux and export for ENP populations of five great whale species.

Whale Species	**Population Status**	**Population Size**		**Gross Flux** (tons C /individual/year; Pershing et al., 2010)	**Annual Carbon Export** (MgC/year)	
		Pre-Whaling	Current		Pre-Whaling	Current
Humpback (CA/ OR/WA)	Depleted; endangered	15,000 (entire N. Pacific; Rice, 1978)	2,900 (NOAA Fisheries, 2020a)	0.103	773	149
Gray (ENP and PCFG)	Recovered (ENP); no formal status (PCFG)	N/A; likely less than current population	26,960 (ENP; Durban et al., 2017), 243 (PCFG; Calambokidis et al., 2017)	0.105	N/A	1,415 (ENP); 13 (PCFG)
Fin (CA/OR/ WA)	Depleted; endangered	42–45,000 (entire N. Pacific; Ohsumi & Wada, 1974)	9,029 (Nadeem et al., 2016)	0.223	4,850	1,007
Blue (ENP)	Depleted; endangered	N/A	1,496 (Barlow, 2016)	0.424	N/A	317

Whale Species	**Population Status**	**Population Size**		**Gross Flux** (tons C /individual/year; Pershing et al., 2010)	**Annual Carbon Export** (MgC/year)	
		Pre-Whaling	Current		Pre-Whaling	Current
Minke (CA/OR/WA)	Unknown	N/A	636 (Barlow, 2016)	0.018	N/A	11
TOTAL						2,899

Chapter 3: Discussion

Based on this assessment, the amount of carbon currently stored in the sediments underlying coastal, vegetated habitats (seagrass and salt marsh) in GFNMS is approximately 175,148 Mg carbon. If destroyed, these sediments could release over 642,000 metric tons of CO_2, or the equivalent of adding approximately 140,000 vehicles to the road for one year. Alternatively, if these biogenic habitats are protected, the carbon in the underlying sediments will remain immobilized indefinitely. Annually, these sediments, along with deep-sea carbon export via bull kelp (in a highly productive year) and dead whale falls, sequester approximately 4,950 Mg carbon; if deep-sea and coastal sediments are protected from disturbance, this carbon will remain out of the atmosphere indefinitely. Additionally, if these habitats and living marine resources are protected and restored, carbon sequestration and immobilization can be expected to increase. For perspective, gross emissions from sanctuary operations were 128.5 metric tons CO_2 equivalent, or 35 Mg of carbon[5] in 2019, the most recent year analyzed (Johnson, 2020). This includes all transportation (car, air, boat), electricity, waste, and natural gas consumption. Annual sequestration provided by just two coastal habitats and two ocean processes, an admittedly limited analysis, is 140 times greater than annual emissions produced by the sanctuary in protecting these habitats and species. This sequestration is equivalent to 3,947 passenger vehicles driven for one year or the burning of over 2 million gallons of gasoline, and provides approximately $925,650 in societal benefit every year. This analysis highlights the value of MPAs, where efforts to protect water, habitat, living, and maritime heritage resources also maintain carbon sequestration processes and ensure that stored carbon stays where it is, namely in the habitats and animals the MPA protects.

Aerial view of Estero de San Antonio, an important estuary in GFNMS. Photo: Kenneth and Gabrielle Adelman/California Coastal Records Project (copyright 2002–2021)

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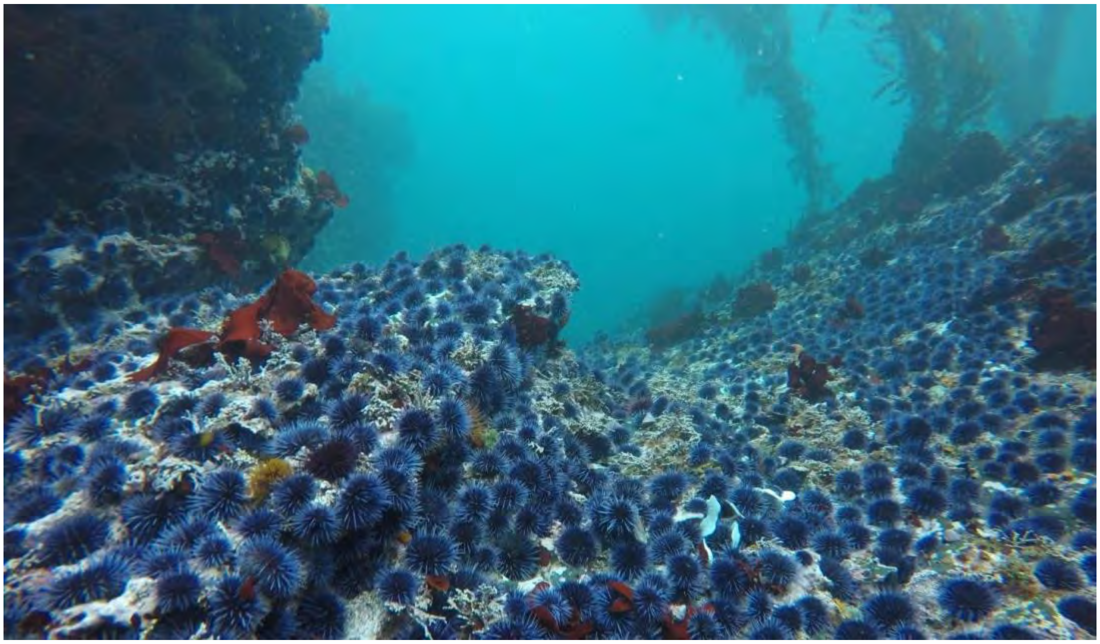
[5] 1 ton of carbon is equivalent to 3.67 tons of CO_2, and 1 Mg of carbon is equivalent to 1 metric ton of CO_2.

There are several limitations of this assessment that render it a conservative estimate of the sanctuary's contribution to carbon sequestration and storage. First, carbon sequestration is occurring in the marine environment through a number of processes (see Part 1 for a more complete review); this assessment is limited to two coastal habitats and two oceanic processes and is by no means comprehensive. Future assessments should attempt to quantify additional sequestration processes. Second, as mapping efforts have not been conducted extensively throughout the sanctuary, there are uncertainties in the spatial extent of both seagrass and salt marsh habitats. Seagrass meadow extents are difficult to confidently estimate because of their ephemeral nature and frequent range shifts, and because aerial surveys along the coastline may not accurately identify seagrass meadows in turbid conditions (McKenzie et al., 2020). This assessment only considers the carbon stored in sediments underlying seagrass and salt marsh, but there are also separate depositional areas in these estuaries that store similar amounts of carbon (Ward et al., 2021). For these reasons, the estimates here probably underestimate the amount of carbon sequestered by coastal habitats in the sanctuary.

The estimate of kelp-derived carbon sequestration is based on novel methodology and presents multiple sources of uncertainty, including the development of a new biomass-from-canopy-cover relationship, as well as the estimation of NPP based on studies of related species. Nevertheless, it is critical to build upon the growing body of knowledge and attempt to quantify the carbon benefit that kelp provides. This assessment found the annual sequestration potential of sanctuary bull kelp forests to be quite significant in a year of high kelp growth. However, this region has not experienced high productivity since 2013. Due to compounding stressors of water temperature and increased grazing pressure from purple sea urchins, carbon storage and export from kelp forests has been a tiny fraction (0.3% in 2019) of its maximum potential for the last seven years. The carbon sequestration benefit of kelp restoration, when considered alongside additional economic and social benefits, has led sanctuary managers to prioritize efforts to protect and actively restore kelp forests.



Purple urchin "barren" showing near-complete loss of a kelp forest. Photo: Steve Lonhart/NOAA

The estimate of whale carbon export via whale falls accounts for approximately 60% of the annual carbon sequestration among the four processes considered here. This is likely an overestimate, as it was necessary to examine populations distributed over a much wider area than the sanctuary due to their highly mobile nature. This highlights the difficulty MPAs may have in accurately characterizing the role protected areas play in supporting and protecting some of the more significant ocean-based sequestration processes. In the calculation of whale carbon export, a direct comparison between pre-whaling and present-day populations is not possible due to lack of accurate historic population estimates for the Northeastern Pacific region. However, humpback, blue, and fin whales are considered to be depleted (and the status of minke whales is unknown), so it is reasonable to assume that carbon export was higher prior to the 1900s. Since the onset of industrial whaling in the 17th century, global whale populations have decreased to less than 25% what they once were (Chami et al., 2019, Duarte, 2021), and several large whale species in the North Pacific are listed as endangered under the Endangered Species Act and depleted under the Marine Mammal Protection Act. Though whaling has not occurred within these waters since the 1970s, populations have not fully rebounded, in part due to the current leading causes of mortality: ship strikes and entanglement with fishing gear (NOAA Fisheries 2019a, 2019b, 2020a, 2020b). For example, between 2001 and 2010, 44 whale deaths were reported in Central California, with 23% from suspected or verified vessel strikes (NOAA, 2014).

Using pre-whaling estimates for the entire Eastern North Pacific for fin and humpback whales more than doubles the total carbon export estimate. Even so, this pre-whaling carbon flux is likely an underestimate due to the documented decrease in body size of whale species that were extensively hunted and the impact of that smaller size on carbon export (Pershing et al., 2010). In the case of blue whales, a decrease in body length of 2 meters was documented by analyzing historical whaling records (Gilpatrick & Perryman, 2008). Larger animals require less food per unit mass and, thus, are more efficient at storing carbon than smaller animals (Pershing et al., 2010). Therefore, our estimates of carbon export prior to whaling are likely underestimates, both due to lack of accurate population estimates and the modern decrease in body sizes. Additionally, for both humpback and blue whales, annual take from entanglements and ship strikes exceeds the potential biological removal (defined as the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population), indicating that removing these pressures would result in population growth. Finally, recognizing that this assessment examines just one of many whale-mediated carbon export processes (see Part 1 for a more complete review), the estimate of carbon sequestration services by the sanctuary's whale populations is a gross underestimate, though a critical first step in building a more complete understanding of the full value of protecting these and other processes known to reduce atmospheric carbon dioxide.

Chapter 4: Recommendations for Greater Farallones National Marine Sanctuary

Future Assessments

There are several actions that could be undertaken by GFNMS and its partners to improve the estimates provided in this assessment, including filling existing data gaps and expanding the scope of this assessment. For kelp spatial data, orthomosaics from UAV surveys will yield much finer resolution and better capture the subtle dynamics and patchy nature of kelp forests. Once full UAV surveys are completed for key sites within the sanctuary, these can be used as a proxy for comparison with satellite data. This will enable quantification of the decline in annual sequestration potential since the onset of kelp loss, as well as the potential for increased sequestration potential resulting from restoration efforts. To obtain a more accurate biomass conversion formula, it is recommended that at least one consistent survey site be established where a small sample of bull kelp bulbs can be taken and weighed and stipe density can be counted, concurrent with UAV surveys. This will provide a validated conversion formula to estimate bull kelp biomass to better understand carbon stock in kelp forests in the sanctuary. To better quantify kelp carbon export, the main sources of uncertainty include the rate of kelp carbon export to offshore sediments and the production and portion of DOC exported from kelp forests.

Operator prepares to launch a UAV to survey kelp canopy in GFNMS. Photo: Abby Nickels

Though beyond the scope of this assessment, there are many sequestration processes not considered here that should be considered for future assessments. This includes phytoplankton production and deep-sea export, assessing biomass carbon for major vertebrate species (in addition to the five whales included in this assessment), and assessment of the carbon stored within depositional areas outside seagrass and salt marsh within estuaries, as well as continental shelf and slope sediments. Ward et al. (2021) found that seagrass-adjacent bare sediments contained similar amounts of organic carbon as sediments within seagrass meadows; this contribution, therefore, could be significant and should be quantified. Future research could develop a model that predicts estuarine carbon stock based on sediment type, as data indicate grain size is a good predictor of carbon sequestration rates, with finer sediments associated with higher sequestration (M. Ward, personal communication, March 1, 2021). Ideally, both SAR and carbon stock data would be collected from the same site; this assessment was limited in the availability of this site-specific data, and for sanctuary salt marshes, rates from different locations had to be used (SAR from Bolinas Lagoon and carbon stock from Tomales Bay). The sequestration rate, based on sediment accumulation studies, should be improved with further sampling in Tomales Bay to better understand temporal and spatial variability in annual sequestration. Seafloor sediments should also be considered for future assessment. Six 1-meter sediment cores taken in or very near the sanctuary along the continental shelf and slope had carbon stock values that ranged from 890,000 to 1.5 million MgC/hectare (Cartapanis et al., 2016), which is roughly 5,000 times more carbon than the data presented here for estuarine sediments in the sanctuary. It is very likely that the bulk of carbon protected in national marine sanctuaries lies offshore in continental shelf sediments, and further analysis of these stores, including a depth profile of organic and inorganic carbon content and carbon dating of the sediments, where they are located, and how well they are currently being protected will be critical to ensure sanctuaries continue to contribute to the climate solution.

A mudflat adjacent to salt marsh in Bolinas Lagoon (top) and an octopus resting on the seafloor (bottom). Both estuarine mudflat and seafloor sediment carbon should be included in future assessments. Photos: (top) Kate Bimrose, (bottom) NOAA

In partnership with academic institutions, additional research priorities include: determining site-specific carbon export pathways of bull kelp based on oceanographic and bathymetric characteristics, identifying the location of carbon "sinks" for bull kelp export and burial rate at those sinks, exploring the carbon sequestration potential of fringing coastal surfgrasses (outside of estuaries), and determining the lateral fluxes of carbon exported from seagrass and salt marsh habitats. Regional advancement of blue carbon science and expansion of the evidence base for blue carbon protection will benefit sanctuary managers. Thus, an effort should be made to advance the work of the newly formed California Blue Carbon Collaborative. Similar to the Pacific Northwest Blue Carbon Working Group, the California collaborative could create a comprehensive blue carbon assessment for the state, focusing first on state and federal MPAs. This group can also support research priorities that advance protection of blue carbon processes in state and federal MPAs, including research to determine species- and site-specific sequestration and storage and advance discussions around how to make carbon markets more accessible for blue carbon managers.

Valuation

As discussed in Part 1 of this series, the only blue carbon system found in GFNMS that is currently eligible for carbon offset trading on the voluntary market is tidal wetlands. At current carbon prices, the acreage of restoration activity must be greater than 1,000 acres to be financially viable. While there are no direct links to carbon market viability for GFNMS at this time, this assessment provides quantitative information to demonstrate the benefit of coastal blue carbon habitats and oceanic blue carbon processes. The social cost of carbon is a useful and effective tool to communicate this benefit for climate regulation, water purification, coastal protection, and mitigating climate change. In lieu of participation in the carbon offset trading market, the sanctuary should utilize this information to engage stakeholders, the public, scientists, funders, and other MPA managers, and should incorporate this information into economic valuations of sanctuary resources and ecosystem services. Combined with other ecosystem services and social benefits (e.g., fishing, ecotourism), a valuation for carbon sequestration services can be a compelling reason to support the protection and restoration that sanctuaries provide for coastal and marine ecosystems. A future path to carbon market participation that could be considered by sanctuary managers is to combine restoration efforts with other MPAs in the West Coast region to meet the minimum acreage required for market viability; a carbon market feasibility analysis may help inform such efforts.

Management

First and foremost, sanctuaries must take blue carbon into account in regular sanctuary assessment and planning. This is critical in communicating the value of sanctuaries in a changing climate and in ensuring sanctuary management is part of national and international efforts to meet climate mitigation goals. The GFNMS ten-year condition report, which characterizes the status and trends of sanctuary resources, should include an economic valuation for carbon sequestration and storage services and a characterization of blue carbon habitats and processes. In addition, the site’s climate vulnerability assessment should also incorporate blue carbon habitats and processes to inform protection and restoration priorities, and its management plan should include strategies and activities that ensure blue carbon is well managed within the sanctuary. Ideally, a blue carbon assessment should precede the condition report process to ensure this information is available and used throughout the management planning cycle to fully inform management decisions and policies. The site manager should use blue carbon information to inform the prioritization of management activities that demonstrate benefit to both living resources and climate mitigation (e.g., prioritizing the recovery of bull kelp forests or the protection of seafloor sediments), as well as in decision-making (e.g., in assessing how different management alternatives in a proposed project may impact carbon sequestration and storage). Permitting processes should also consider the carbon consequence of proposed activities in addition to other impacts.

Managers may immediately think of coastal restoration as an obvious management action to increase blue carbon sequestration and storage. However, Moritsch et al. (2021) found that the sequestration benefits of reducing erosion of existing blue carbon habitat far exceed those of restoring habitat. In the continental U.S., annual emissions from salt marsh erosion are estimated at 62,900 ± 2,810 MgC, which is equivalent to approximately 50,000 vehicles driven for one year (McTigue et al., 2021), and modeling suggests that management responses like managed retreat and levee removal significantly increase sequestration (Moritsch et al., 2021). Wide-scale use of a living shoreline approach to coastal protection (as opposed to coastal armoring) will also provide substantial carbon sequestration benefit (Davis et al., 2015). Much of the work GFNMS is already doing, like reducing human impacts (e.g., removing moorings from seagrass beds), protecting living resources (e.g., slowing ships), and providing space for habitat migration (e.g., restoration in Bolinas Lagoon), has sequestration benefits that should be assessed during the management planning process.

Removing moorings from Tomales Bay reduces physical impacts to seagrass meadows (left). Slowing ships reduces collisions with whales, helping populations rebound (right). Both are effective tools to protect carbon-sequestering habitats and processes in the sanctuary. Photos: (left) NOAA, (right) John Calambokidis/Cascadia Research Collective

Multi-benefit management actions should be prioritized by sanctuary managers. For all five whale species included in this assessment, ship strikes are either the leading cause of death (Laist et al., 2001) or second only to entanglement in fishing gear. Current management efforts to slow ship speeds in both the San Francisco Bay region and Southern California via the voluntary incentive program called "Protecting Blue Whales and Blue Skies" has demonstrated a two-fold climate benefit: in 2020 alone, slowing ships resulted in a decrease of 24,258 metric tons of CO_2 from exhaust emissions and a 35% decrease in ship strike risk for whales (Santa Barbara County Air Pollution Control District, 2021). Slower ships contribute significantly to a local reduction in atmospheric CO_2, both directly by reducing emissions and indirectly by increasing the sequestration potential of whale populations. This is an example of a management action that has multiple benefits and should be considered a priority for GFNMS and other West Coast sanctuaries. In addition, the spatial range of baleen whales indicates a need for coordinated management across national marine sanctuaries and other U.S. jurisdictions. A blue carbon policy assessment could detail the full range of options for managers, including cost, ease of implementation, and impact.

In conclusion, this first step towards a Tier 2 blue carbon assessment for GFNMS provides foundational information to improve climate-informed decision-making and illustrates to other MPAs that with modest time and resource investments, blue carbon resources can be more fully understood and protected. MPAs are a critical tool for reaching global climate mitigation goals (Hoegh-Guldberg et al., 2019; Simard et al., 2016); therefore, the assessment and consideration of blue carbon in MPA management is of great importance.

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Glossary of Acronyms

CO_2	carbon dioxide
DOC	dissolved organic carbon
ENP	Eastern North Pacific
GFNMS	Greater Farallones National Marine Sanctuary
MgC	megagrams of carbon
MPA	marine protected area
NPP	net primary productivity
PCFG	Pacific Coast Feeding Group
POC	particulate organic carbon
SAR	sediment accumulation rate
UAV	uncrewed aerial vehicle

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