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Blue Carbon in Marine Protected Areas: Part 1

A Guide to Understanding and Increasing Protection of Blue Carbon

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U.S. Department of Commerce
Gina M. 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

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

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 600,000 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 research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and cultural 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 (sanctuaries.noaa.gov).

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Contact

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

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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 to 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 (ONMS), 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. Led by Greater Farallones National Marine Sanctuary (GFNMS), with support from the Greater Farallones Association, this review is Part 1 of a series to inform and guide MPA managers in the assessment, protection, and management of blue carbon habitats and processes. The purpose of this first report is to serve as an informational, guiding document to aid ONMS and MPA managers worldwide in considering and including blue carbon processes within management decision-making. This includes a review of blue carbon potential in MPAs, the role MPAs play in protecting and restoring blue carbon, potential future funding mechanisms to support blue carbon management, guiding principles for advancing blue carbon inclusion in MPA management, and a path forward for national marine sanctuaries. Guiding principles include:

- Ecosystem-based management is blue carbon management.
- With small initial investments, MPA managers can vastly increase their knowledge of blue carbon at their site.
- Blue carbon should be incorporated into marine spatial planning and considered in MPA designation and management.
- Managers should understand how to leverage blue carbon to finance MPAs.
- Certain management actions produce greater sequestration gains.
- Blue carbon management is not just coastal.
- Climate policies must include blue carbon.

To assist ONMS in implementing the above principles, *Blue Carbon in Marine Protected Areas: Part 2; A Case Study* provides an assessment of select blue carbon habitats and processes for GFNMS, and can serve as a model assessment for other sites in the National Marine Sanctuary System. As sites assess blue carbon sequestration potential, these assessments can build upon the body of knowledge in this series. The reports can serve as a preliminary step in ensuring that national marine sanctuary management protects and enhances the critical climate mitigation services of its coastal and ocean resources.

Key Words

blue carbon, carbon storage, carbon sequestration, carbon export, marine protected area, climate change, mitigation, seagrass, salt marsh, mangrove, phytoplankton, kelp, fish, whale

Introduction

A school of fish swim above an eelgrass bed in Channel Islands National Marine Sanctuary. Photo: NOAA

The global rise of atmospheric CO_2 concentrations as a result of anthropogenic activities and the resulting warming of the Earth's surface have led many scientists and politicians to look for natural ways to store and sequester carbon over long timescales. The ocean is the largest carbon sink in the world, accumulating 20–35% of atmospheric CO_2 (Sabine et al., 2004), and plays a significant role in the global carbon cycle by storing and cycling 93% of Earth's CO_2 and storing over half of the world's biological carbon in living marine organisms (Nellemann et al., 2009). First coined in a 2009 United Nations Environment Programme report (Nellemann et al., 2009), "blue" carbon refers to carbon stored in coastal and open ocean ecosystems, and includes those habitats, species, and processes that facilitate the uptake of atmospheric carbon into the ocean and transport that carbon into sediments or deep waters (Lutz & Martin, 2014).

Coastal blue carbon ecosystems (seagrass, salt marsh, and mangrove) are well recognized as globally significant carbon sinks, storing three to five times more carbon per unit area than tropical forests, and sequestering carbon at a rate ten times greater than tropical forests (National Oceanic and Atmospheric Administration [NOAA], 2021). These vegetated coastal habitats remove carbon dioxide from the atmosphere (carbon capture, Figure 1) and fix it into organic carbon in the stems, branches, leaves, and roots of the plant for years to decades. Dead plant material eventually accumulates in the oxygen-free sediments stabilized by the plants' roots or rhizomes, accumulating considerable amounts of carbon over time (carbon storage, Figure 1).

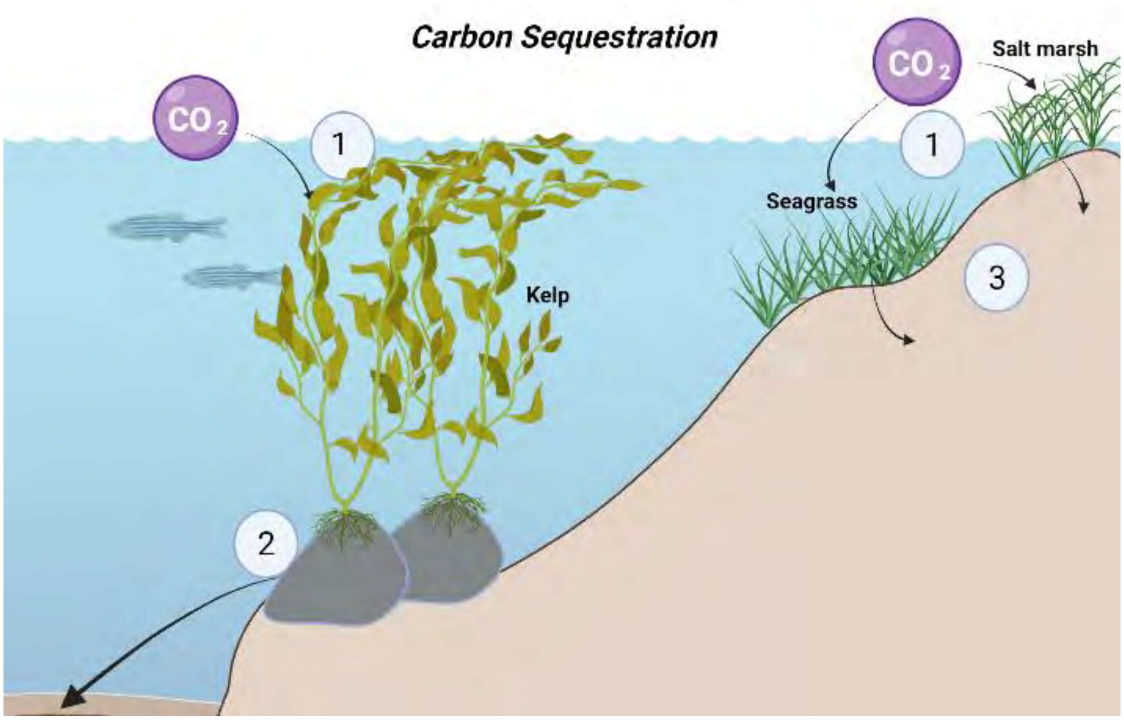


Figure 1. Diagram indicating pathways for carbon sequestration by kelp, seagrass, and salt marsh. (1) Carbon capture is the absorption of dissolved inorganic CO_2 and fixation of carbon into the tissues of kelp, seagrasses, and salt marsh. (2) Carbon storage occurs when kelp material is exported from the subtidal rocky reefs to deep-sea environments, where it may be buried in sediments. (3) Carbon storage occurs when dead seagrass and salt marsh plants get trapped *in situ* in the oxygen-free sediment, stabilized by roots and rhizomes. For both (2) and (3), carbon can remain captured indefinitely if undisturbed. Image: biorender.com

Blue carbon sequestration is not limited to coastal vegetated habitats. Increasingly, research indicates that oceanic carbon capture and storage, via the sinking of marine animals and vegetation to the deep sea (see kelp in Figure 1), is likely far more significant than previously estimated. There is some debate around whether these processes should be considered blue carbon in the traditional sense because sequestration is not occurring *in situ* where the carbon is first fixed and initially stored (Howard et al., 2017a; Smale et al., 2018). However, Smale et al. (2018) argued it is critical for scientists and managers to look beyond traditional carbon sink habitats to also include the movement of carbon across habitats and the critical role that marine macroalgae and marine vertebrates play in transferring vast amounts of carbon from surface waters to the deep sea, where the carbon may be immobilized for thousands to millions of years (Ducklow et al., 2001). Developing carbon budgets for habitats in isolation, excluding carbon connectivity and habitats that function as carbon "donors," is "neither representative of marine ecosystems, nor a useful approach for prioritizing management" (Smale et al., 2018). Limiting blue carbon policy and management to the thin margin of coastal vegetated habitats will not be enough to demonstrate the role of marine systems in climate mitigation (S.Lutz, personal communication, January 21, 2021), and thus acknowledging the role of carbon donors to deep-sea sequestration is critical for accurate and comprehensive blue carbon valuation and management (Smale et al., 2018). Therefore, this review of blue carbon is an attempt to be inclusive of oceanic sequestration processes—recognizing that this field of research is nascent but advancing rapidly—to ensure the importance of all marine systems in natural carbon sequestration is acknowledged. 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, and international bodies are increasingly recognizing the critical role the world's ocean plays.

Since 1995, government representatives have gathered annually for the United Nations Climate Change Conference (Conference of the Parties or COP). In 2005, at COP11, world leaders set out to limit the rise of global warming to 2 °C, in part by conserving and enhancing natural ecosystems that store and sequester carbon. The parties established the program on reducing emissions from deforestation and forest degradation (also referred to as REDD+) to enhance carbon stored in forests (Sanz-Sanchez et al., 2013). In 2019, Chile hosted the first "blue" COP in Madrid, Spain (COP25) to elevate the conversation about the role the ocean plays in mitigating climate change impacts. Led by the United Kingdom, Chile, France, Costa Rica and the United States, panelists discussed the role of MPAs in climate mitigation, the importance of including blue carbon in countries' nationally determined contributions to global emissions reductions, and the need to study, monitor, protect, and restore blue carbon ecosystems. As a direct result of these conversations, the International Partnership on MPAs, Biodiversity and Climate Change was launched in 2021 to advance consideration of MPAs as nature-based solutions to climate change. This partnership will inform conversations to advance the inclusion of the ocean, and MPAs in particular, in international climate agreements. This "sea change" in support of ocean-based climate action has been supported by a myriad of scientific studies and publications. Most notably, *The Ocean as a Solution To Climate Change: Five Opportunities for Action*, a report commissioned by the High Level Panel for a Sustainable Ocean Economy, found that ocean-based climate action could deliver up to a fifth (21%, or 11 gigatons of CO_2 equivalent) of the annual emission cuts needed in 2050 to limit global temperature rise to 1.5° C (Hoegh-Guldberg et al., 2019). This report did not consider the sequestration services of oceanic blue carbon, so the contribution of the world's coasts and ocean to climate mitigation are likely much higher, and must be part of the global solution.

Panel presentation at COP25: global climate action in marine protected areas. Photo: Joint Nature Conservation Committee

From these high-level initiatives and reports, marine protected area agencies and environmental organizations are recognizing the importance of blue carbon through increased research and policy considerations. This work is fundamental to grow awareness of the value of blue carbon to climate change mitigation strategies and to advance blue carbon science and policy. However, unlike managers of terrestrial forests under the REDD+ program, no international program exists that incentivizes the enhancement of blue carbon (Alongi et al., 2016; Howard et al., 2017b). For MPA managers trying to assess and communicate the sequestration potential of blue carbon, very few studies demonstrate how to incorporate sequestration processes beyond the traditional coastal marshes, seagrasses, and mangroves that dominate the blue carbon literature. Similarly, while some of these studies demonstrate how to apply blue carbon assessments to monetize the value of coastal habitats and finance further protection, there is very little guidance for resource managers to understand how they should apply this information to ongoing management decisions, marine spatial planning, and project prioritization. Further, resource managers of the largest network of U.S. federal marine protected areas, the Office of National Marine Sanctuaries (ONMS), have not incorporated calculations of blue carbon into 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., focusing on restoration rather than preventing erosion of coastal salt marshes) 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.

A recreational diver swims through a school of fish in Flower Garden Banks National Marine Sanctuary. Fish are an often overlooked contributor to global carbon storage and eventual immobilization in deep-sea environments. Fish also support local economies throughout ONMS. Photo: NOAA

The healthy function of these ecosystems is invaluable to local communities and economies. Given the great diversity and complexity of sanctuary ecosystems, understanding the various processes that result in carbon sequestration 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 how it might influence MPA management. Sanctuary staff are committed to advancing blue carbon science and assessment, and hope this report serves as a preliminary step in ensuring sanctuary management protects and enhances the critical climate mitigation services of its coastal and ocean resources.

Standard Units of Carbon Sequestration

There are many different units used in blue carbon assessments to quantify carbon sequestration. Results of blue carbon studies are presented in this review largely using megagrams, though occasionally teragrams and petagrams are reported. To provide ease of understanding regarding the unit equivalencies throughout this paper, unit types are provided in Table 1, along with greenhouse gas equivalence in terms of passenger vehicles driven for one year[1]. Megagram is the most frequently used unit throughout blue carbon literature and is equivalent to one metric ton. Petagrams are the largest unit of measurement and represent large-scale sequestration. Additionally, it is important to note that sequestration of 1 ton of carbon represents 3.67 tons of CO_2, so 3 tons of carbon represents 11 tons of CO_2 (Romm, 2008). Carbon is more frequently reported by scientists, while CO_2 is a term that is more easily understood by the general public and is therefore used more frequently in policy and public discussions (Romm, 2008). Because different greenhouse gases, including CO_2, methane, nitrous oxide, and others, have varying global warming potentials (the amount of warming a gas causes over 100 years), CO_2 equivalent, also written as CO_2e, is used to convert those warming potentials into one common unit and signifies the amount of CO_2 that would have the equivalent global warming impact of the various gases emitted (Brander, 2012).

Table 1. Conversion of carbon quantification units into grams and metric tons.

Unit	**Gram Equivalent**	**Metric Ton Equivalent**	**Greenhouse Gas Equivalent** (# cars driven for 1 year)
Megagram (Mg)	1,000,000	1	0.2
Teragram (Tg), Megaton (Mt)	$1x10^{12}$	1,000,000	217,480
Petagram (Pg)	$1x10^{15}$	$1.102x10^{9}$	217,000,000

[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 Carbon Sequestration

Coastal blue carbon ecosystems are regularly saturated with saltwater and tend to have stagnant depositional areas with anoxic conditions created by very high levels of microbial respiration. This allows for the steady accumulation of carbon over time (Chmura et al., 2003). Given the constant buildup of organic matter and sediments within vegetated habitats, coastal blue carbon ecosystems are capable of accreting meters of soil carbon over thousands of years (Howard et al., 2014). In terrestrial ecosystems, that same buildup of carbon in soil is limited by the availability of oxygen, which allows for microbial oxidation of the soil, releasing CO_2 into the atmosphere. Blue carbon ecosystems not only have a greater tendency to sequester carbon than terrestrial ecosystems, but also provide greater longevity in the storage of captured carbon, thus validating the necessity to account for coastal blue carbon in climate mitigation goals.

Salt Marsh

Salt marsh in Bolinas Lagoon, GFNMS. Photo: Bob Lewis

Tidal salt marshes are found along coastlines from the Arctic to the tropics and are characterized by the mixing of fresh and salt water caused by tidal fluctuations (Commission for Environmental Cooperation [CEC], 2016). As tides flood the marsh, they saturate the soil and promote anoxic conditions, which lead to the trapping of carbon in the sediments (Laffoley & Grimsditch, 2009). Aboveground plant assemblages in the marsh require exposure to the atmosphere and photosynthesize above the flood level (CEC, 2016). This aboveground assemblage is the smallest portion of salt marsh biomass contributing to carbon storage. Most stored carbon is found in belowground living biomass and organic matter in soil, facilitated by frequent anoxic conditions (Howard et al., 2014). Carbon storage is higher in salt marshes dominated by fine-grain sediments (Kelleway et al., 2016) and salt marshes that receive fluvial input (Macreadie et al., 2017). Salt marshes are the largest coastal blue carbon storage ecosystem in the United States, occupying over 19,000 km^2 (Field et al., 1991) and comprising 1–

2% of the total estimated yearly carbon sink in the U.S. (Chmura et al., 2003). It is unknown how much salt marsh habitat is currently protected within MPAs, but this should be a priority for assessment, as threats to remaining salt marsh include habitat conversion, poor water quality, and erosion from sea level rise and increasing storm activity (Laffoley & Grimsditch, 2009). Since the early 1600s, the United States has lost more than half of its wetlands (more than 110 million acres), and from 2004–2009, this loss has occurred at an average rate of 80,000 acres per year (NOAA, n.d.). The West Coast of the United States alone has lost up to 90% of its salt marshes since the 1900s (Barbier et al., 2011; Gedan et al., 2009). MPAs can ensure that remaining salt marshes are protected from development and disturbance and have adequate sediment supply to keep pace with sea level rise, which is critical for maintaining the carbon sequestration benefits provided by this coastal habitat (Laffoley & Grimsditch, 2009).

Seagrass

A scorpionfish hides in the seagrass beds in Florida Keys National Marine Sanctuary. Photo: NOAA

Seagrasses form extensive underwater meadows that include dense belowground networks of rhizomes, which hold sediment in place (CEC, 2016). The greatest share of long-term carbon storage in seagrass beds occurs within the sediments; however, carbon capture occurs in the leaves, rhizome tissue, and flowers (CEC, 2016). Carbon storage is higher in systems associated with larger, more persistent, and more structurally complex seagrass species, and at shallower and less turbid sites (Howard et al., 2017a). Global estimates of carbon sequestration (19.9 Pg carbon/year; Fourqurean et al., 2012) and storage (15% of global blue carbon storage; Laffoley & Grimsditch, 2009) by seagrasses are significant; however, data gaps exist for U.S. MPAs, and until site-specific carbon sampling is conducted, global estimates are the only data available.

The ability of seagrass habitats to support carbon sequestration is under threat in the U.S. and globally by anthropogenic impacts that limit the extent and health of seagrasses. Threats include turbidity that blocks access to sunlight, eutrophication, increased water temperatures, pollution, and physical damage from moorings and boats (CEC, 2016). Approximately 20% of the United States' seagrass extent is protected in national marine sanctuaries (estimated from United Nations Environment Programme World Conservation Monitoring Centre & Short [2018]). The majority of seagrass meadows in the U.S. have experienced rapid decline since 1980 (Waycott et al., 2009), including losses of 50% in Tampa Bay, 76% in the Mississippi Sound, 90% in Galveston Bay, and 46% in Chesapeake Bay (NOAA, n.d.). Recent significant seagrass losses (58% since 2009) in Florida's Indian River Lagoon have led to an Unusual Mortality Event for the Florida manatee (Florida Fish and Wildlife Conservation Commission, 2021). Protection of remaining seagrass beds and restoration of damaged or lost beds is imperative to not only increase carbon sequestration and storage, but also to maintain important direct and indirect benefits for society, such as coastal protection, water purification, maintenance of fisheries, tourism, recreation, research, and education (Barbier et al., 2011). Additionally, recent work by Ricart et al. (2021) indicates seagrasses along California's coast (including four sites within GFNMS and one site within Monterey Bay National Marine Sanctuary) provide localized protection from ocean acidification by ameliorating low-pH conditions for extended periods of time, possibly providing refugia to vulnerable species like Dungeness crab and Olympia oyster.

Mangrove

A mangrove forest in Florida Keys National Marine Sanctuary, showing both aboveground and belowground biomass. Photo: NOAA

Mangroves are salt-tolerant viviparous shrubs and trees that grow in coastal, brackish waters. They are a diverse group of plants, with 80 different species worldwide (three in the U.S.), and share differing morphological and physiological adaptations to their environment (Laffoley & Grimsditch, 2009). Mangroves are a critical blue carbon habitat present in some U.S. MPAs (e.g., mangroves line over 1,800 miles of coastline in Florida Keys National Marine Sanctuary) and other sub-tropical and tropical MPAs worldwide. In mangrove systems, carbon is sequestered through the entrapment and burial of sediments from local or adjacent systems by roots and pneumatophores and through the net growth of forest biomass (Laffoley & Grimsditch, 2009; Howard et al., 2014). For every hectare of mangrove forest, 0.129–23.98 Mg of carbon is sequestered every year (Chmura et al., 2003; Donato et al., 2011; Sifleet et al., 2011), and mangroves store more carbon than any other vegetated habitat, per unit area. A variety of factors influence sequestration potentials, such as latitude (Laffoley & Grimsditch, 2009) and the age of the forest (Sifleet et al., 2011).

Mangroves are in decline globally, and forests in the United States are currently most impacted by erosion and extreme weather events (e.g., hurricanes), and, to a lesser extent, habitat conversion via coastal construction (Goldberg et al., 2020). The U.S. saw a 30% decline in mangrove extent from the 1950s to 1990, primarily due to habitat conversion (Valiela et al., 2001). Since 2000, however, the primary driver of mangrove loss in the U.S. has been erosion from extreme events and sea level rise, with a decline just over 9.5 km^2, or a 0.3% loss (Goldberg et al., 2020). Though mangrove conservation has made great strides in the U.S., and mangrove loss has declined substantially, climate-related stressors will continue to increase. Just 10% of U.S. mangrove extent is protected by the National Marine Sanctuary System (estimated from The Global Mangrove Watch; Bunting et al., 2018). Evaluating and mitigating climate-driven impacts to protected mangroves is vital for U.S. MPA managers to ensure the vast carbon stores within mangrove ecosystems stay in place and that mangroves can continue to sequester carbon from the atmosphere.

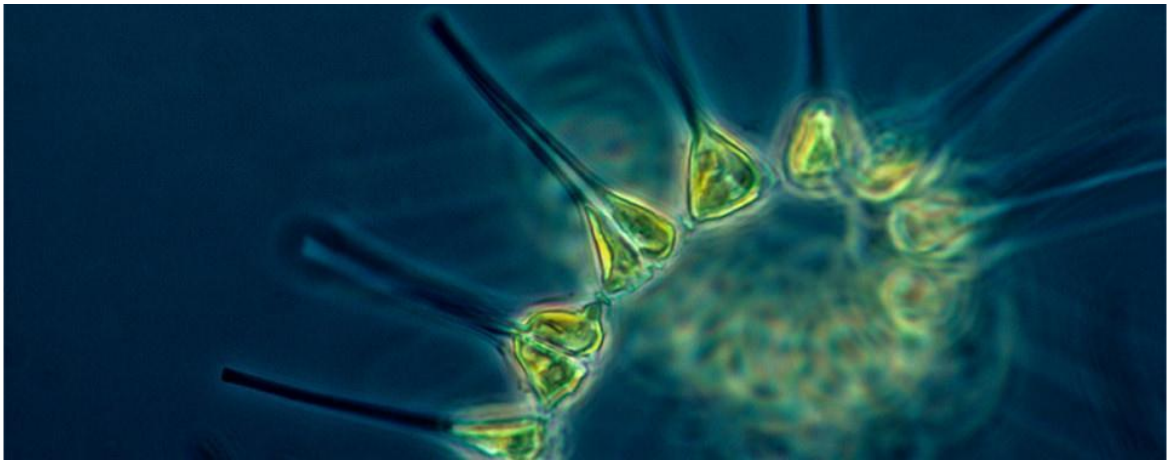
Chapter 2: Oceanic Blue Carbon

Introduction

Octopus resting on the carbon-rich seafloor in Cordell Bank National Marine Sanctuary. Photo: NOAA

Ocean-based carbon sequestration (marine blue carbon), which depends on contributions from such processes as kelp biomass export to the deep-sea and marine vertebrate "deadfalls," is increasingly recognized as a critical carbon removal and storage service. For all oceanic carbon sequestration (described in detail by Lutz & Martin [2014]), seafloor sediments are often the final destination for carbon immobilization. These sediments hold vast amounts of carbon on geologic timescales, from thousands to millions of years, if left undisturbed (Estes et al., 2019) and are the largest non-fossil pool of organic carbon on the planet. Globally, seafloor sediments store 3,117 Pg of carbon in the top meter, which is more than two times the carbon stocks in the top meter of terrestrial soils (Atwood et al., 2020). Continental shelf sediments store the most carbon per unit area; important drivers in the supply of carbon to shelf sediments include proximity to river discharge and upwelling areas that result in highly productive waters (Atwood et al., 2020). If disturbed, the top layers of sediment become suspended, exposing organic carbon to remineralization into the water column, potentially further acidifying coastal waters and reducing the ocean's capacity to absorb atmospheric CO_2 (Sala et al., 2021). A likely major cause of disturbance to seafloor sediments is bottom-trawl fishing, which is ubiquitous across continental shelves, releasing as much carbon globally as the aviation and agriculture sectors. (Sala et al., 2021). Along the U.S. West Coast alone, approximately 119,000 km^2 are trawled annually (Amoroso et al., 2018), releasing approximately 36 million Mg of carbon. The descriptions below highlight just a few ocean-based processes that are likely significant contributors to carbon immobilization within seafloor sediments.

Phytoplankton

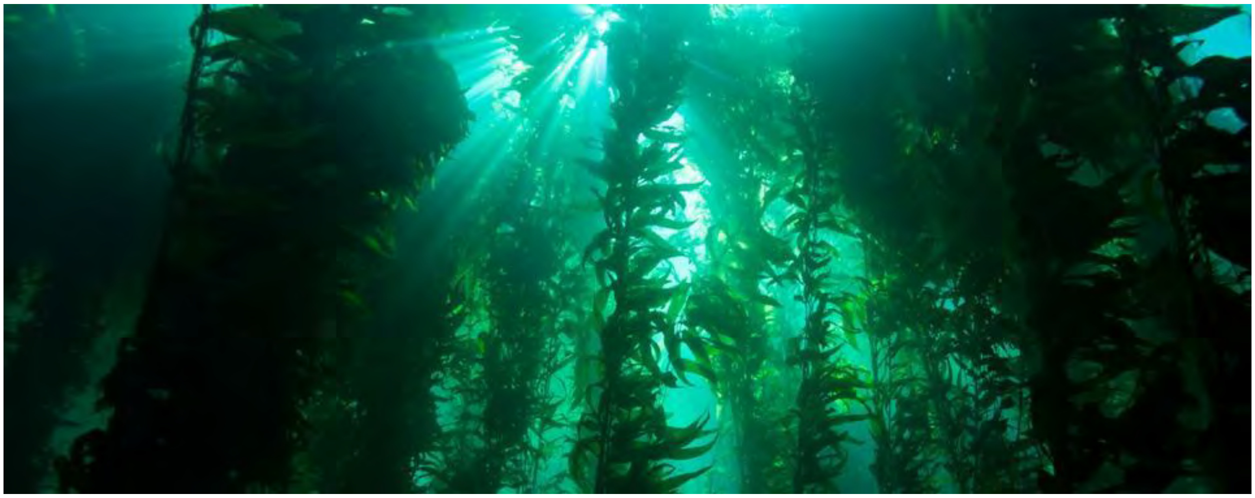


Phytoplankton are microalgae that photosynthesize and convert atmospheric CO_2 to organic carbon. Photo: NOAA

Quantifying open-ocean carbon sequestration poses considerable difficulties due to its complexity and gaps in research. Within the open ocean, phytoplankton have garnered particular interest because of their high net primary productivity. On average, global phytoplankton populations capture 37 billion metric tons of CO_2 from the atmosphere annually, equivalent to 40% of annual global emissions, or the amount of CO_2 captured by four Amazon Rainforests (Chami et al., 2019; Nellemann et al., 2009). Phytoplankton absorb dissolved CO_2, convert it to biomass, and then facilitate deep-sea carbon transport through two main mechanisms: 1) phytoplankton that are not consumed die and sink to the seafloor, and 2) phytoplankton that are grazed upon can be secreted in zooplankton fecal pellets, which can sink to the seafloor (Laffoley et al., 2014). Larger phytoplankton, like diatoms and coccolithophores, have higher sinking velocities and accelerate carbon export (Passow & Carlson, 2012). About 1–2% of global diatom production, or approximately 1 million Mg of carbon (equivalent to 1.7% of annual global CO_2 emissions [Laffoley et al., 2014]), is exported to the deep sea and immobilized annually (Ragueneau et al., 2006). Zooplankton that feed on phytoplankton also contribute significantly to deep-sea carbon flux; these include foraminifera (Schiebel, 2002); pteropods (Bednaršek et al., 2012; Berner & Honjo, 1981; Fabry, 1990); and salps, which are planktonic tunicates and were recently found to contribute approximately 45% of carbon flux to the deep sea in the Northeast Pacific (Huffard et al., 2020).

Harnessing the potential of phytoplankton to sequester carbon and offset the impacts of climate change has been a topic of scientific debate for years. Introducing iron—a limiting nutrient for phytoplankton growth—into the water column can allow plankton populations to grow larger and sequester more carbon (Righetti et al., 2019). Known as iron fertilization, this strategy has generated significant debate because of the potential unforeseen consequences of artificially increased phytoplankton production, including hypoxia, harmful algal blooms, biotoxins, changes in biochemistry, and changes in food web structure (Cullen & Boyd, 2008). Due to these likely consequences, an international moratorium on iron fertilization was established in 2007 to deter future projects; however, nonprofits and governments are still interested in this approach (Schiermeier, 2007; Tollefson, 2008). Research has increasingly focused on natural processes that enhance phytoplankton production to increase carbon sequestration while avoiding negative consequences associated with artificial nutrient fertilization. Natural solutions include restoring whale populations and reducing anthropogenic stressors, including nutrient loading, heavy metal runoff, and oil spills (Lavery et al., 2012; Häder & Gao, 2015).

Kelp



An underwater forest of giant kelp in Monterey Bay National Marine Sanctuary. Photo: NOAA

Kelp, large brown algae in the order Laminariales, are commonly found attached to rocky substrates and form dense forests in temperate zones worldwide. These macroalgae have remarkably high productivity, and they fix carbon much more rapidly than terrestrial plants, with growth rates reaching up to 2 feet in a 24-hour period. Rapid biomass turnover occurs through the detachment of stipes and blades by tides, wave action, and herbivory, dispersing pieces of kelp throughout the surrounding environment (Laffoley & Grimsditch, 2009). Kelp communities are increasingly recognized as significant contributors to global carbon sequestration, acting as "carbon donors" to "receiver sites" by exporting carbon to deep-sea environments (Hill et al., 2015). Kelp carbon export can occur in the form of particulate organic carbon, via blade erosion or detachment of entire plants, and dissolved organic carbon. Dissolved organic carbon is an important but poorly understood part of carbon cycling and export (Watanabe, 2020) due to a lack of information on how much is produced and the fraction of production that is recalcitrant and avoids consumption by microorganisms (Frigstad et al., 2020). The export of kelp carbon to deep-sea sinks is influenced by buoyancy and oceanographic conditions (Dugan et al., 2018), and subsequent burial and sequestration is influenced by decay and microbial activity (Hill et al., 2015).

Three major avenues for kelp particulate organic carbon sequestration include direct deep-sea carbon export of kelp biomass, export through herbivory, and *in situ* sequestration in depositional environments where kelp beds are surrounded by soft sediments. While kelp requires a hard substrate to attach and grow, some kelp beds are surrounded by mudflats and sediments that allow for *in situ* carbon sequestration and storage at rates of up to 6.2 Tg of carbon per year (Krause-Jensen & Duarte, 2016). For example, some kelp beds in Alaska are attached to tubeworms that allow the kelp to grow in an otherwise inhospitable environment of mud (Bracken, 2018). The soft sediments surrounding the tubeworms create ideal conditions for carbon burial and storage that do not exist in kelp forests found on rocky substrates.

An underwater forest of bull kelp in GFNMS. Photo: Keith Johnson

However, carbon export of kelp biomass to the deep sea is likely a more globally significant component of long-term carbon storage. To understand deep-sea carbon export, Krause-Jensen and Duarte (2016) generated a rough estimate of macroalgae carbon storage potential in the deep sea, the continental shelf, and kelp beds. The study combined previous studies on deep-sea export for different macroalgae species across the globe to calculate avenues of sequestration. They estimated that 173 Tg of carbon are sequestered per year globally, which is equivalent to over 600 million metric tons of CO_2, with 90% sequestered through deep-sea export and the remaining 10% buried in coastal sediments. DNA analysis by Ortega et al. (2019) indicates that carbon originating from macroalgae, including kelp species, is found far (up to 5,000 km) from its coastline of origin, with 69% of macroalgae at the ocean surface expected to reach depths greater than 1,000 m and 24% of macroalgae at the ocean surface expected to reach depths greater than 4,000 m. Kelp are dispersed throughout the environment through fragmentation, tattering, and shredding by herbivores; in Norway, herbivory accounts for 22% of kelp-derived carbon that could reach the seafloor, as animals such as sea urchins do not fully digest the kelp, allowing the small particles to sink (Wernberg & Filbee-Dexter, 2018). Though kelp biomass dispersion and export undoubtedly varies between kelp species and across regions as a result of variable oceanographic processes, numerous studies from across the globe, including Norway, the Falkland Islands, the U.K., and Australia, have documented a similar trend: kelp storage and export is a significant contributor to global carbon sequestration and is a critical component of global climate mitigation (Frigstad et al., 2020; Bayley et al., 2017; Burrows et al., 2014; Queirós et al., 2019; Filbee-Dexter and Wernberg, 2020).

Fish

The lanternfish is a common mesopelagic fish that vertically migrates to the euphotic zone to feed. Photo: SEFSC Pascagoula Laboratory; Collection of Brandi Noble/NOAA

Though multiple mechanisms for fish-mediated carbon storage and immobilization have been described in the literature (see Lutz & Martin [2014] for a comprehensive review), the process of carbon transport by mesopelagic fishes to the deep sea is of particular interest, not only because it is a more direct route of carbon transfer, but because it may be the most intact biological mechanism for oceanic carbon cycling by marine vertebrates (Irigoien et al., 2014). Mesopelagic fishes inhabit intermediate depths of the ocean between approximately 200 and 1,000 m and are characterized by vertical movement at night into the euphotic zone in search of food. Here, they feed on zooplankton, whose carbon is derived from phytoplankton that have fixed CO_2 into organic carbon. Mesopelagic fishes mediate carbon export from the euphotic zone via physical movement to the deep sea during vertical migration, where carbon is then released at depth via defecation, respiration, excretion, and mortality. This effectively removes it from the atmospheric carbon cycle, and some of it can become immobilized through deposition and burial (Davison et al., 2013). This active, or fish-mediated, export was found to account for 15–17% of all carbon export from the euphotic zone off the U.S. West Coast (Davison et al., 2013). This estimate was corroborated in a recent global synthesis that found fishes mediate an average of 16% of the carbon exported from the euphotic zone (Saba et al., 2021). Despite these promising results, the high variability in estimations of fish-mediated carbon export signifies there are considerable knowledge gaps and may also reflect methodological differences (Saba et al., 2021). Improved measurements of active and passive carbon export, standardized methodology, and a stronger relationship between observations and models will improve the estimation of fish-mediated flux and provide a foundation for possible policy recommendations to enhance this sequestration process (Saba et al., 2021).

Black sea bass, an important species for both commercial and recreational fisheries, finds refuge among sponges in Gray's Reef National Marine Sanctuary. Photo: NOAA

Another process by which fishes store and immobilize carbon is growth. If left in the ocean, fish biomass will eventually sink in the carcass or be consumed and maintained within the ocean food web. Fisheries extract a large amount of biomass carbon, much of which is eventually released back into the atmosphere (Mariani et al., 2020). Rebuilding fish stocks in marine protected areas increases the amount of carbon in the biosphere rather than the atmosphere, enhancing long-term carbon sequestration through active carbon transport and carcass deadfalls (Mariani et al., 2020; Wright et al., 2020). Policymakers and resource managers are beginning to understand the importance of fishes to the global carbon cycle, making further scientific study and assessment of their inclusion in carbon budgeting essential.

Whales

Humpback whales traveling through Hawaiian Island Humpback Whale National Marine Sanctuary. Photo: NOAA

Since the onset of industrial whaling in the 17th century, global whale populations have decreased to less than one fourth of pre-industrial abundances (Chami et al., 2019; Duarte, 2021). Uncontrolled and unregulated whaling brought global populations to near extinction by the 18th century, and they remained low until the emergence of global conservation efforts (Baker & Clapham, 2004; Whitehead, 2002). The whale conservation movement has since led to population recovery through international regulations and cooperation; however, whale populations are still significantly lower than pre-whaling baselines around the world (Whitehead, 2002). A growing body of evidence suggests whales play a significant role in global carbon storage, and this ecosystem service must be taken into account in the conservation and restoration of whale populations.

Marine vertebrates facilitate uptake of atmospheric carbon into the ocean and transport carbon from the ocean surface to deep waters and sediment, thus providing a vital link in the process of long-term carbon sequestration (Lutz et al., 2014).

Research regarding whale carbon storage demonstrates three mechanisms by which whales facilitate carbon sequestration: the “whale pump,” the “whale conveyor belt,” and “whale falls” (Lutz & Martin, 2014). The whale pump and conveyor belt are indirect processes that result in carbon sequestration. Driven by whale defecation at the surface, nutrients such as iron, phosphorus, and nitrogen are released into the water column at concentrations up to 10 million times greater than background levels, stimulating local phytoplankton growth on levels that rival artificial iron fertilization projects (Chami et al., 2019; Lavery et al., 2012). The whale pump is characterized by the vertical movement of whales, such as sperm whales, from deep-sea feeding grounds to surface waters. Because of physiological adaptations to deep-sea diving, whales are unable to defecate at depth and therefore must do so at the surface. This biological response ensures that nutrients from defecation are dispersed at the surface, where light is available for phytoplankton growth. Research conducted by Lavery et al. (2010) shows that an estimated 240,000 tons of CO_2 removal is facilitated by sperm whales every year in the Southern Ocean through the promotion of phytoplankton growth. The authors estimated that due to historic whaling of sperm whales, 2 million tons of carbon that otherwise may have been fixed remained in the atmosphere (Lavery et al., 2010). The whale conveyor belt also functions to sequester carbon via nutrient dispersion from defecation; however, this process describes the latitudinal movement of whales from nutrient-rich feeding grounds, often in temperate and polar waters, to nutrient-poor calving grounds, often in the tropics (Roman et al., 2014; Roman & McCarthy, 2010). Defecation in nutrient-poor waters allows for phytoplankton growth, which was previously inhibited by a lack of nutrient availability. In both cases, defecation provides nutrients for phytoplankton blooms, which enhance carbon sequestration and storage through the processes described above for phytoplankton.

A whale dives, exposing its tail above the water in the National Marine Sanctuary of American Samoa. Whales use 11 national marine sanctuaries for either feeding or breeding. Photo: NOAA

Direct carbon sequestration via whale falls occurs when whales die and sink to the ocean floor, where some carbon stored in their tissues can be immobilized in the deep sea for millennia. Also referred to as “marine vertebrate” or “fish” carbon, large whales are especially efficient at fixing and storing vast amounts of carbon due to their relatively high metabolic efficiency (Pershing et al., 2010). Further, their large size, long lives, and limited predation results in significant storage of carbon during the life of the whale, which can then be moved from surface waters to the deep sea following a whale fall. Globally, whale populations store vast amounts of carbon; an estimated 33 tons of CO_2 equivalent is stored in each great whale (Chami et al., 2019). Just one century of whaling resulted in the removal of 23 million tons of carbon from the marine system (Pershing et al., 2010); much of this carbon was burned in oil lamps to light the streets of major cities, releasing it directly into the atmosphere (Duarte, 2021). Pershing et al. (2010) estimate that globally, great whales store just 15% of the carbon they did before the onset of industrial whaling due to population and size reductions. Numerous additional studies demonstrate the difference in carbon sequestration and storage potential from pre-whaling to current whale populations; for example, carbon sequestration via humpback whale fecal plumes in the Gulf of Maine is estimated to have been orders of magnitude greater prior to whaling (Roman & McCarthy, 2010) and carbon storage by five whale species in the Southern Ocean is estimated to have declined by 83% due to population reductions from commercial whaling (Dufort et al., 2020).

A whale fall in Monterey Bay National Marine Sanctuary, with many scavengers feeding on the carcass. The carbon stored in whale remains can become immobilized in deep-sea sediments. Photo: NOAA

Through these indirect and direct mechanisms, whales have enormous potential to store and sequester carbon over long timescales, and more whales in the ocean means increased carbon storage and immobilization, as well as increased fertilization of surface waters. If global whale populations are fully restored to historic levels, an additional 160,000 tons of carbon could be sequestered each year just through increased whale falls, which would be equivalent to preserving over 2,000 acres of forest annually (Pershing et al., 2010). Additionally, carbon exported by recovered whale populations is likely more efficient than artificial carbon dioxide removal methods that are currently being explored. Even the most successful iron fertilization experiment managed to export just 900 tons of carbon, suggesting it would take 200 such events to match the export potential of fully restored whale populations (Pershing et al., 2010).

Carbon removal is not the only benefit whales provide to society. The International Monetary Fund valued the average great whale at $2 million, including benefits such as whale watching and contribution to the marine food web, and estimated the current global whale population to be worth at least $1 trillion (Chami et al., 2019). Chami et al. (2019) estimated that it would cost $13 USD per person on Earth to rebuild global whale populations to historic levels, an investment that could ultimately sequester up to 1.7 billion tons of CO_2 equivalents per year. Researchers are advocating for new market mechanisms that incentivize whale protections, including ship speed reductions and the development of carbon market methodologies (MPA News, 2020a).

Chapter 3: Blue Carbon Assessment and Financing

In order to maintain and potentially restore blue carbon services in marine protected areas, it is critical to understand the extent of blue carbon habitats and processes and their associated levels of carbon sequestration. Blue carbon assessments enable managers to inventory blue carbon services, track changes, determine protective measures for habitats and/or ecosystem functions, and predict the measures' effects on carbon sequestration in established or proposed MPAs. Managers may also calculate the economic value of the ecosystem service provided by their blue carbon resources to help justify restoration or protection projects, prioritize associated actions, or participate in the carbon market. Regardless of the reason, being able to communicate a monetary value for the habitats and species that store and sequester carbon to the public, partners, and potential funders is of increasing importance. Demonstrating the value of MPAs through a climate mitigation lens can be a powerful tool for increasing financing options. This chapter reviews the basics of blue carbon assessment and valuation, as well as mechanisms for financing blue carbon protection.

Assessment and Valuation

To participate in carbon markets, create meaningful policies, or communicate the value of blue carbon, one must quantify carbon stocks (how much carbon is currently stored in the system), annual sequestration potential, and emissions resulting from change to the system. This process is known as creating a carbon inventory or assessment, and it can be conducted at various scales (Ocean Science Trust [OST], 2020). The Intergovernmental Panel on Climate Change (IPCC) has proposed an international standardization of carbon inventories through a three-tiered method to quantify existing and future carbon stocks in coastal ecosystems (Howard et al., 2014; Table 2). Each tier provides differing levels of clarity and certainty of assessment in addition to varying levels of expense. The most accurate assessment is a Tier 3 assessment, which is the most costly and resource intensive. For projects to enter into the carbon market, a Tier 3 analysis must accurately measure existing and future carbon sequestration rates.

Table 2. Tiers for developing a carbon inventory (adapted from Howard et al. [2014]).

Tier	Data Requirements	Description	Purpose
1	IPCC default values	Tier 1 assessments are the least accurate and have minimal levels of certainty. They are based on default activity data and emissions factors from the IPCC. The range of error is +/-50% for aboveground pools and +/-90% for belowground pools.	To gain a rough estimate of the amount of carbon stored and annually sequestered for a given site or region; for raising awareness of blue carbon and creating foundational knowledge.
2	Country-specific data for key factors	Tier 2 assessments include aspects of site-specific or country-specific data and have increased accuracy and resolution from Tier 1 assessments.	To provide increased clarity on the amount of carbon stored and sequestered for a given area; to lend support to ongoing restoration and conservation projects.

Tier	Data Requirements	Description	Purpose
3	Site-specific carbon stock inventory, repeated measurements of key stocks over time, or modelling	Tier 3 assessments require direct, site-specific data for carbon stocks in each component of the ecosystem or land use. Repeated measurements of carbon stocks are required over time to estimate change in carbon in or out of the system. Tier 3 assessments can be provided through direct measurements or modelling.	To enter into the carbon market or to gain highly accurate information on the amount of carbon stored and sequestered for a given site.

A Tier 1 analysis is a "back of the envelope" assessment to calculate the extent of blue carbon habitats, the amount of carbon currently stored in those habitats, and the amount of carbon annually sequestered by those habitats. It is the least expensive method of evaluation and provides estimates that can be used to communicate the value of blue carbon services to the public to further MPA conservation goals and lay the groundwork for future assessments. Tier 1 estimates are a simple calculation: multiply the area of the ecosystem by the global mean carbon stock value (Table 3). Tier 2 assessments are similar, but use carbon stock and sequestration values that are specific to the region, and are therefore more accurate, as global averages have a significant range of values and therefore higher uncertainty. Managers around the globe are currently using Tier 1 and 2 assessments to describe the amount of carbon currently stored in their protected areas, as well as potential emissions from ecosystem disturbance. Tier 3 assessments require more resources, time, and planning, as well as direct, repeated field measurements at the site of interest. While this method is more accurate, it is considerably more costly and requires scientific equipment and measurements that are collected at regular intervals, including carbon pool sampling and emissions measurements. For data requirements and detailed methods for Tier 3 assessments, see Howard et al. (2014).

Table 3. Global means for soil organic carbon stocks up to one-meter depth and annual sequestration rates for mangrove, tidal salt marsh, and seagrass ecosystems (modified from Howard et al. [2014]).

Ecosystem Type	Carbon Stock (Mg/ha)	Range (Mg/ha)	Annual Sequestration (g C/m^2/yr)
Mangrove	386	55–1378	174[2]
Tidal salt marsh	255 (270[3] for U.S.)	16–623	151[4]
Seagrass	108 (65–92[5] for U.S. West Coast)	10–829	83[3]

Selecting the appropriate level of assessment will depend on the resources available and the goals of the project. A Tier 1 or 2 analysis (depending on data availability) is recommended for all managers interested in blue carbon assessment, as these provide baseline information on the amount of carbon stored and sequestered; can inform managers where to spend limited restoration funds to meet climate change goals, especially if considered alongside other habitat co-benefits; and can contribute to a total economic valuation of all ecosystem benefits generated by an MPA. Simply understanding the carbon stock and sequestration rates of a particular area enables managers to communicate the blue carbon "potential" or overall carbon value of that

[2] Alongi, 2012; range of 10–920 g C/m^2/year
[3] Holmquist et al., 2018
[4] Duarte et al., 2005
[5] Kaufman et al., 2020; Prentice et al., 2020

area. The margins of error, however, are large, and management decisions based on these numbers should be considered carefully. Despite this uncertainty, a Tier 1 or 2 assessment can be very useful for informing policy and planning and creating a foundation for advanced academic study. The government of Scotland, for example, commissioned comprehensive blue carbon inventories for both coastal and oceanic sequestration, and has demonstrated great success with modest initial investment in blue carbon characterizations (Burrows et al., 2014, 2017). As a part of this effort, in 2014, Scotland conducted an assessment of blue carbon for its entire exclusive economic zone, including tidal marsh, seagrass, kelp, phytoplankton, and offshore sediments, and annual sequestration was found to equal roughly half of Scotland's annual emissions (Burrows et al,. 2014). A follow-up study (Burrows et al., 2017) analyzed the amount of carbon currently stored in Scotland's system of MPAs, both inshore and offshore, and it was found to equal roughly four years' worth of emissions. Though these inventories were not, in every case, verified by field measurements and would not be eligible for carbon market participation, numerous policy decisions have been influenced by these data, including increased protections for significant blue carbon habitats and the consideration of blue carbon as a criterion for the designation of new MPAs (J. Baxter, personal communication, July 27, 2020). Additionally, the first known marine spatial planning project that used blue carbon information in its analysis was just completed for the Orkney Islands. The results of that project also detail the activities that should be avoided in order to prevent the destruction of blue carbon sinks, which would result in significant carbon emissions (J. Baxter, personal communication, July 27, 2020).

The social cost of carbon (SCC) is a valuable tool that can be used, along with a Tier 1 or 2 analysis, to communicate the value of blue carbon habitats to stakeholders, partners, and funders. 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 SCC places a dollar value on one metric ton of CO_2 released into the atmosphere. In effect, the dollar value represents the cost to society through medical expenditures, physical damage to property, and loss of resources. Currently, the estimation is around $51 per metric ton of CO_2, although experts agree that the price should be significantly higher (Ricke et al., 2018), and the Biden Administration recognizes it will likely increase following more thorough analysis (Boushey, 2021). The SCC is typically used in policymaking decisions such as pollution standards and transportation rulemaking, but it can also enable MPA managers to communicate the importance of blue carbon ecosystems without entering the voluntary market system. The SCC also provides an opportunity to quantify a monetary value of non-traditional blue carbon sinks within an MPA, such as kelp and large marine vertebrates that lack a carbon market methodology.

Financing Blue Carbon Protection

A growing number of finance mechanisms are increasingly available to managers of blue carbon in protected areas. Because protected areas are often accompanied by commitments or mandates to protect resources in perpetuity, investing in blue carbon protection and restoration in protected areas is low risk, with a high return on investment (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2021). While it is out of the scope of this review to address all possible finance options for MPAs (for a more exhaustive review, see Herr et al. [2014]), a few mechanisms are briefly described below.

Blue Bonds

Blue bonds, essentially loans made by investors to borrowers with fixed interest rates and schedules, are an increasingly popular way to finance projects and activities with environmental benefit, focused on achieving the United Nations Sustainable Development Goals related to the ocean (Mathew & Robinson, 2021). The first blue bond, issued in 2018, raised USD $15 million from international investors for the Republic of the Seychelles to support the expansion of MPAs, improve fisheries management, and develop the Seychelles' "blue economy" (Mathew & Robinson, 2021). In 2019, the Nordic Investment Bank followed suit, issuing a bond for USD $200 million to protect and rehabilitate the Baltic Sea (Roth et al., 2019). The Nature Conservancy is using blue bonds to refinance the national debt of 20 island nations, using the savings to support MPAs through a trust fund that holds governments accountable. There is high demand in the market for such bonds (Yu, 2020); the global "green" bond (similar to blue bonds but used for land-based conservation) market has grown from $11 billion issued in 2013 to $269.5 billion in 2020 (Jones, 2021). In an effort to encourage blue bond issuance in the financial markets as a tool for improving ocean health, the United Nations Global Compact released *Practical Guidance to Issue a Blue Bond* in 2020. This guidance recommends alignment with existing global standards, clear and measurable targets to achieve objectives of the Sustainable Development Goals, external reviews of the bond and its sustainability targets, and listing the bond on a security exchange.

Mitigation Banking

Compensatory mitigation is required under the Clean Water Act in the event that wetland or aquatic resources are adversely and unavoidably impacted by permitted discharge. Mitigation banking refers to the practice of setting aside restored or enhanced wetland or coastal areas from which future permittees can purchase credits if unavoidable damage is projected to occur within the service area of the mitigation bank, thus satisfying the requirements of compensatory mitigation for the project (OST, 2020). Mitigation banking enables the consolidation of multiple, small-scale restoration or enhancement projects, and because they are implemented before any actual damage occurs, these sites are more likely to succeed than permittee-responsible mitigation projects (U.S. Environmental Protection Agency [EPA], 2019). Other benefits of mitigation banking include a more efficient and cost-effective permitting process, ecological benefits, reduced uncertainty in mitigation success, and economic incentive for protecting and restoring coastal and wetland habitats (EPA, 2019). Through the Smith Cove Blue Carbon Pilot Project, the Port of Seattle is piloting the use of mitigation banking as a mechanism for advancing blue carbon goals (OST, 2020). By planting/installing kelp, eelgrass, salt marsh, and shellfish beds over 25 acres and then evaluating the sequestration and pH amelioration benefits, the port will be able to generate credits to offset future negative impacts; they also plan to sell additional credits beyond regulatory requirements to generate income to fund restoration into the future (OST, 2020).

Carbon Markets

The ability of blue carbon ecosystems to store and sequester carbon over geological timescales has garnered interest in entering mangroves, tidal marshes, and seagrasses into carbon markets as a strategy to generate funds for their protection and restoration. Carbon markets are based on the "right to pollute" and can be either voluntary or compliance based. In compliance-based markets, emission reductions are achieved through mandated greenhouse gas (GHG) emission caps, which are implemented alongside the distribution of emission permits. They allow for the emission of a specific amount of a pollutant and can be freely bought and sold among individuals and businesses. Over time, the emissions cap decreases, thereby decreasing overall emissions. In the United States, no federal compliance market exists. However, California implemented a compliance market via cap-and-trade in 2012, targeting the emissions of 450 businesses that are responsible for 85% of the state's overall emissions (California Environmental Protection Agency, 2015). Offset projects must show verified and quantifiable units of GHG emissions to be eligible for generating offset credits used for compliance. Currently, four protocols are approved under California's cap-and-trade program: urban forestry, forestry, livestock digesters, and destruction of ozone-depleting substances (California Air Resources Board, 2012). Though blue carbon habitats are not included, the state's portion of cap-and-trade proceeds are deposited in the Greenhouse Gas Reduction Fund, where they can be appropriated by the state legislature to state agencies for projects that reduce emissions (OST, 2020). To date, $11 billion has been appropriated: $47 million to the California Department of Fish and Wildlife for the Wetlands and Watershed Program, $7 million to the State Coastal Conservancy for the Climate Ready grant program, and $5 million to the Coastal Commission for coastal resilience planning (OST, 2020). Projects in California sanctuaries may be eligible for some of these funds.

Alternatively, a voluntary carbon market allows entities to offset their own emissions by purchasing carbon offsets that finance carbon reduction projects such as forest restoration, salt marsh restoration, and renewable energy. The voluntary market permits more flexibility in offset choices and is used primarily by private sector companies to reduce their carbon footprint, demonstrate corporate environmental responsibility, and enhance public relations (Mack et al., 2015). In addition to wetland restoration, blue carbon enhancement projects that could demonstrate GHG reductions include: enhancing sediment supply (beneficial reuse of dredged sediment), restoring hydrology (removing tidal barriers, restoring tidal flow), reducing nutrient input, reducing sediment disturbance (limiting dredging, boat anchoring, and trawling), and improving ecosystem function (reintroducing or restoring depleted native species). A critical requirement of these projects is to prove additionality; that is, the carbon captured and stored through proposed activities would be additional to what would have been captured and stored if the project were not to take place or without the sale of carbon credits (MPA News, 2020a). The voluntary market offers a way for MPAs to gain extra revenue while also investing in future blue carbon projects. For example, in Madagascar, the Tahiry Honko project is restoring 1,200 hectares of mangrove forests, generating 1,300 carbon credits per year on the voluntary market, with demand from buyers for these credits about 1,000 times higher than current supply (MPA News, 2020b).

To be eligible to trade carbon offsets on either compliance-based or voluntary carbon markets, projects must demonstrate a quantifiable net greenhouse gas reduction that persists over a certain time period (often 50–100 years), requiring a Tier 3 analysis (see above). For example, if a manager is interested in salt marsh restoration, with the goal of generating emissions offsets in the voluntary carbon market, it is necessary to conduct rigorous and extensive data collection and multiyear monitoring that can verify a persistent emissions benefit (as well as verification by a third party like Verified Carbon Standard or American Carbon Registry). Project costs are high (market readiness alone costs approximately $150,000 up front and $75,000 to monitor every 5 years) and only make financial sense if the projected restoration area is greater than 1,000 acres (OST, 2020). Therefore, a feasibility study should first be completed to understand the financial viability of carbon market participation. For example, the Ballona Wetlands Restoration Project in Southern California used a Tier 3 analysis to assess the feasibility of carbon market participation and quantify the benefits of restoration in terms of carbon sequestration. Restoring 600 degraded acres of the wetland would generate $2,538 per year in California's voluntary carbon market, which would not cover the annual monitoring and reporting costs associated with participation in the carbon market (Bear, 2017). Because of its small area, high construction costs, and the low cost of carbon, this project was not financially viable for market participation, which is likely also the case for most U.S. West Coast estuaries. However, larger estuaries have significantly greater area from which a network of proposed restoration projects could be pooled into one proposal for carbon market participation (e.g., Snohomish Estuary in Puget Sound, Washington; Crooks et al., 2014), especially if monitoring and administrative costs can be shared.

We need to be able to speak the language of the markets to ensure our resources are valued in a financial way (Chami, 2020).

There will likely be increasing opportunities for MPA managers to advance blue carbon offset trading in the future. In California, businesses will need to increase their carbon offsets as emissions allowances continue to decrease via the cap-and-trade program and/or seek to further reduce their carbon footprint through voluntary markets as the public demand for carbon offsets increases (OST, 2020). Additionally, the price of carbon ($15.25 in early 2019; Sapkota & White, 2020) will likely increase. Though entering the carbon market may not be financially viable now, MPA managers should be knowledgeable of carbon market processes and understand future opportunities, as MPAs could benefit greatly from participation once these processes are further formalized and become financially viable. Even beyond coastal blue carbon habitats, there is increasing focus from scientists, economists, and managers on developing market methodologies for ocean-based carbon sequestration processes (MPA News, 2020a). This could make the carbon market a viable future option for creating additional revenue for MPA management, expanding existing projects, or acquiring funds for restoration that are otherwise not available. Blue carbon has been widely overlooked in international and national discussions of GHG abatement, but ONMS can help elevate blue carbon as a critical contributor to climate mitigation by conducting assessments and communicating results. As more MPAs communicate the value of their blue carbon resources, it incentivizes others to do the same and grows awareness of the importance of blue carbon as a form of abatement. This will promote the development and implementation of new market methodologies.

Chapter 4: Guiding Principles for Marine Protected Area Managers

Well-managed marine protected areas are a critical component of global and national mitigation and adaptation responses to climate change. The following guiding principles are critical to advance the assessment, protection, and restoration of blue carbon habitats and processes in MPAs.

With small initial investments, MPA managers can vastly increase their knowledge of blue carbon at their site. Managers can't protect what they don't know is there. Conducting a Tier 1 analysis for coastal blue carbon is a quick calculation, requiring only spatial data, and can provide a rough estimate of the climate mitigation services provided by the coastal habitats in an MPA. Communicated using the SCC, along with other benefits to society, this easy initial assessment can provide a compelling case for further protection and restoration. In many cases, site-specific or regional data are available from research partners, vastly improving the accuracy of these estimates and providing a foundation for management and funding priorities. Part 2 of this series provides an example of a Tier 2 analysis completed for a subset of habitats and species in GFNMS, a large MPA along the West Coast of the United States.

Ecosystem-based management is blue carbon management. Carbon sequestration can be enhanced through ecosystem-based management that targets preservation or restoration of food web dynamics and ecosystem functionality (Howard et al., 2017b). Within MPA networks, predator-prey interactions are inherently protected, which helps control herbivore populations. Decreased grazing allows plants and algae to continue to grow, increasing their carbon sequestration capacities and the preservation of carbon stocks. For example, presence of sea otters along the Alaskan and Canadian coasts increased carbon cycling and carbon storage in kelp forests by an order of magnitude when compared to areas with no sea otters (Wilmers et al., 2012). This dynamic of predators leading to increased carbon sequestration and storage has been documented across habitats worldwide, including blue crabs in New England salt marshes, predatory fish in Australian mangroves, and tiger sharks in Australian seagrasses (Atwood et al., 2015).

The presence of predators, like sea otters and blue crabs, contributes to enhanced carbon cycling, accumulation, and storage. Left: A sea otter mother with pup floats on its back at the surface in Olympic Coast National Marine Sanctuary. Right: A blue crab on the sand within a seagrass meadow. Photos: NOAA

Blue carbon should be incorporated into marine spatial planning and considered in MPA designation and management. To ensure that nationally significant blue carbon habitats and processes continue to sequester carbon rather than become sources of emissions, it is critical that marine spatial planning and the designation of new MPAs consider the presence of blue carbon (Howard et al., 2017b). By mapping blue carbon habitat, nationally significant areas and processes can be identified and assessed for potential designation as new MPAs. The Orkney Islands blue carbon audit demonstrates this novel approach to MPA designation by prioritizing carbon-rich areas, like maerl beds, kelp forests, and seagrass, for protection (Porter et al., 2020). Once protected, either in an existing MPA or through the designation of a new MPA, blue carbon conservation measures must be included in MPA management plans (Herr et al., 2017; Moraes, 2019). Specific actions include: identify and manage for threats to blue carbon systems; include carbon sequestration as a primary goal of MPA designation and management; create MPA boundaries based on "long-term permanence of carbon stocks and sink capacity"; prioritize areas with high carbon sequestration potential; and identify and implement management actions that increase carbon sequestration (Howard et al., 2017b).

Reducing impacts leads to significant sequestration gains. Managers often consider restoration to be the single greatest management action to increase blue carbon sequestration. However, Moritsch (2021) found that reducing erosion of existing blue carbon habitats produces sequestration benefits that far exceed those resulting from restoration alone. In the continental U.S., annual emissions from salt marsh erosion are estimated at 62,900 Mg of carbon, which is equivalent to approximately 50,000 cars driven for one year (McTigue et al., 2021). Removing levees and other structures that exacerbate erosion, moving structures away from the shoreline, and implementing wide-scale use of a living shoreline provides substantial carbon sequestration benefits (Moritsch, 2021; Davis et al., 2015). Such coastal resilience measures have already garnered great interest and support for the many other benefits they provide (Kordesch et al., 2019); climate mitigation is yet another reason to support resilient coastlines. Much of the work MPAs are already doing to reduce impacts and increase climate resilience likely has sequestration benefits, and management activities should be assessed for such benefits as part of the planning process.

Erosion rates of 1–2 feet per year have been documented in Elkhorn Slough in Monterey Bay National Marine Sanctuary, resulting in carbon emissions. Efforts are underway to reduce erosion and restore the salt marsh. Photo: Becky Stamski/NOAA

Managers should understand how to leverage blue carbon to finance MPAs. As described in Chapter 3, for an MPA to finance coastal protections via carbon markets at the current market price of carbon, the proposed project must be at least 1,000 square meters and must provide additionality (the carbon captured and stored through proposed activities would be additional to what would have been captured and stored if the project were not to take place or without the sale of carbon credits). Though this is a serious impediment for most MPAs at this time, MPA managers should continue tracking blue carbon market development, as this could change rapidly. Other financing mechanisms, such as blue bonds and mitigation banking, may be viable options depending on the governance, scale, and scope of restoration and protection measures.

Blue carbon management is not just coastal. Currently, restoration and protection of blue carbon is fairly limited to coastal blue carbon—seagrasses, salt marshes, and mangroves—but the largest carbon reserves on Earth are found in the open ocean and within seafloor sediments, an enormous area with massive carbon sequestration potential. These globally significant carbon stores must be recognized by managers and policymakers, and the field of blue carbon as a whole must expand its scope to recognize the important mitigation potential of oceanic blue carbon. Rebuilding whale stocks to historic levels (Pershing et al., 2010), reducing disturbance to continental shelf sediments (Sala et al., 2021), restoring healthy, functioning marine food webs (Wilmers et al., 2012), and rebuilding fish populations (Mariani et al., 2020) will "recarbonize the biosphere" and help "decarbonize the atmosphere" (Duarte, 2021).

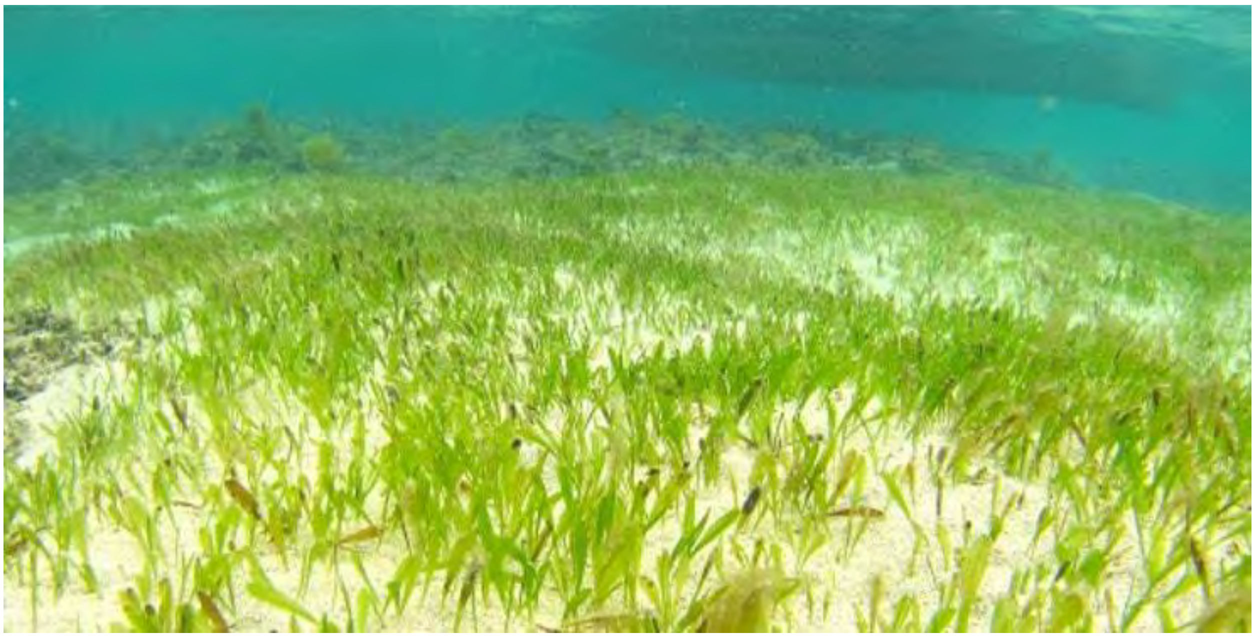
Recarbonize the biosphere to decarbonize the atmosphere by restoring the abundance of life on land and in the ocean (Duarte, 2021).

Conservation measures taken by Stellwagen Bank National Marine Sanctuary are directed at rebuilding stocks of the North Atlantic right whale, with lasting climate mitigation benefit. Photo: NOAA

Climate policies must include blue carbon. From sub-national management to international climate policies and agreements, blue carbon as a mitigation tool has not yet been fully realized. That is certainly changing, especially in light of recent international climate talks and reports (see Introduction for more information). MPA managers play an important role in protecting and restoring blue carbon. In 2017, coastal wetlands were included in the U.S. GHG emissions inventory for the first time, and NOAA is currently partnering with the U.S. Department of State to support other countries in including coastal blue carbon in their GHG inventories. On a sub-national scale (e.g., California), there are also opportunities to incorporate blue carbon into coastal planning and climate mitigation policies (Moritsch et al., 2021), and MPA managers certainly have a role to play in informing these policy changes.

Conclusion: A Path Forward for National Marine Sanctuaries

Well-managed marine protected areas are a critical component of global and national mitigation and adaptation responses to climate change. Quantifying and protecting blue carbon sequestration processes should be an essential component of achieving the Biden Administration's climate mitigation goal of a 50% reduction of GHGs from 2005 levels by 2030. In addition, protecting valuable blue carbon habitat and processes has a clear nexus with the administration's adaptation goal of conserving 30% of the nation's lands and waters by 2030 (Executive Order 14008, 2021). MPAs protect valuable blue carbon habitats and processes, and must be part of the climate solution.



Hawaiian seagrass, found in Papahānaumokuākea Marine National Monument, a UNESCO World Heritage site. Photo: Russell Amimoto

An assessment of carbon stock in the 50 marine sites on UNESCO's World Heritage List (including Papahānaumokuākea Marine National Monument) found these sites' protected carbon stores were equivalent to 10% of global GHG emissions (UNESCO, 2020). Continued protections via MPA designations and management are critical to ensuring that stored carbon stays where it is, and that sequestration processes can continue to draw down atmospheric carbon. Additionally, carbon mitigation services provided by MPAs may qualify for new sources of funding through the carbon market in the future, and blue carbon financing may be able to support the creation of new MPAs that restore or protect nationally significant blue carbon resources (Herr et al., 2015).

It is clear that MPA programs globally should play a role in advancing the inclusion of blue carbon science and protection into policy and management. ONMS has an opportunity to demonstrate national and global leadership by leveraging staff expertise, synthesizing available data, and developing guidance to protect and restore blue carbon habitats and processes within MPAs. It is recommended that ONMS implement the following actions:

1. Map and conduct an analysis of the extent of U.S. coastal blue carbon habitats and processes currently protected by the National Marine Sanctuary System;
2. Conduct a Tier 1 or Tier 2 analysis (depending on data availability) of key blue carbon habitats and processes protected by ONMS;
3. Determine whether additional protections are warranted in existing sanctuaries or through the expansion or designation of new sanctuaries;
4. Develop an approach for considering blue carbon during the designation process;
5. Develop a system-wide approach to blue carbon management to ensure sanctuaries are maximizing their climate mitigation potential, including guidelines for incorporating blue carbon into condition reports, vulnerability assessments, management plans, permitting processes, and environmental compliance documents; and
6. Develop strategies to effectively maintain and potentially increase blue carbon sequestration across the National Marine Sanctuary System.

The wreck of USS *Monitor* at the bottom of the sea in Monitor National Marine Sanctuary, where the surrounding sediments likely hold vast carbon stores. Photo: NOAA

To assist ONMS in implementing the above recommendations, “Part 2: A Case Study” provides an assessment of select blue carbon habitats and processes for GFNMS and can serve as a model assessment for other sites in the system. As sites across the National Marine Sanctuary System assess blue carbon sequestration potential, these assessments can build upon the body of knowledge in this series of documents. These reports can serve as a preliminary step in ensuring national marine sanctuary management protects and enhances the critical climate mitigation services of its coastal and ocean resources.

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Glossary

Blue carbon – Carbon that is sequestered and stored in oceanic and coastal systems.

Carbon donor – Habitats or species that sequester carbon that is then exported to long-term carbon sinks rather than remaining stored *in situ*.

Carbon inventory – An account of the net loss and gain of emissions from terrestrial ecosystems or the ocean. The account is used to establish emissions trends over a period of time.

Carbon market – A trading system for the right to emit greenhouse gases.

Carbon sink – An environment that absorbs more atmospheric CO_2 equivalents than it releases.

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.

Deep-sea carbon flux – The carbon exchanged between the upper boundaries of the ocean and the deep sea; most often refers to the amount of carbon sinking out of the euphotic zone.

Ecosystem-based management – Management practice that recognizes complex ecosystem and ecological dynamics and linkages, including human impacts.

Kelp forest – A dense growth of large, brown algae in cool, relatively shallow waters close to shore.

Mangrove – Salt-tolerant, viviparous shrub or tree that grows in brackish waters along the coastline.

Marine protected area (MPA) – A clearly defined geographical space in the ocean, coast, or Laurentian Great Lakes that is recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.

Nationally determined contributions – Non-binding national plans that highlight climate actions, including climate-related targets, policies, and measures, governments aim to implement in response to climate change and as a contribution to achieve the global targets set out in the 2015 Paris Agreement.

Mesopelagic zone – Ocean depth between 200–1,000 meters that is often characterized as having little to no light.

Ocean acidification – The increased acidity of the ocean caused by absorption of atmospheric CO_2 into the water column.

Phytoplankton – Microscopic photosynthetic organisms in a lake or ocean that form the base of the food web in an ecosystem.

Seagrasses –Vascular flowering plants that form extensive underwater meadows with dense belowground networks of rhizomes that hold sediment in place.

Sequestration rate – The amount of carbon accumulated in the sediment on an annual basis.

Social cost of carbon (SCC) – The economic harm from increased flooding, food security issues, sea level rise, and weather disasters caused by emitting one metric ton of CO_2 into the atmosphere. This metric is expressed as a dollar value.

Tidal salt marsh – Coastal wetlands characterized by salt-resistant grasses, herbs, and shrubs and the mixing of fresh and salt water caused by tidal fluctuations.

NATIONAL MARINE SANCTUARIES

AMERICA'S UNDERWATER TREASURES