JUNE 2023

Climate Central Solutions Brief: Ocean Carbon

PART OF THE CLIMATE SOLUTIONS SERIES

CLIMATE CENTRAL

Oceans regulate global climate and keep heat-trapping gases out of the atmosphere. But human-caused warming and continued carbon pollution put tremendous pressure on marine ecosystems and natural processes that move carbon from the air to the depths of the ocean for long-term storage.

Humans can support and protect marine ecosystems that pull heat-trapping carbon dioxide from the air and store it in the ocean. Emerging technologies could enhance or modify the ocean's capacity for carbon capture.

Restoring and protecting our oceans is not only a climate solution—it can also build climate resilience, support coastal economies, and preserve biodiversity. But these solutions are not enough to slow global warming on their own; they must be paired with deep and rapid cuts to carbon pollution.

This research brief explains the ocean carbon cycle and summarizes some of the ways humans can bolster the ocean's capacity as a climate solution.

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Carbon storage in the ocean

Carbon is continually moving between the atmosphere, ecosystems on land, and the ocean. The ocean carbon cycle is sustained by both the living and nonliving factors that comprise marine ecosystems.

Oceans **sequester** (or remove) roughly 26% of the CO$_2$ humans release into the air each year, primarily by burning coal, oil, and natural gas. Oceans store around 45 times more carbon than the atmosphere and 12 times more than ecosystems on land, making them the planet's largest **carbon sink**—where large amounts of carbon are captured and held for long periods of time. Most ocean carbon is stored in the water as a dissolved gas.

How long carbon is stored in the ocean depends primarily on how deep it sinks. Shallower waters serve as short-term (in terms of months or years) carbon storage. But some carbon is transported to the deep ocean, where it will be out of touch with the atmosphere for decades to centuries. Carbon that makes it to the seafloor can be locked away in sediments and rock formations for millennia, or longer—potentially the most important carbon reservoir on the planet.

Ocean carbon: from the surface to the seafloor

The ocean carbon cycle begins at the sea surface, where atmospheric CO_2 diffuses into the water through physical mixing and chemical reactions. Tiny plant-like organisms called phytoplankton convert CO_2 into **organic carbon** (carbon incorporated into life forms) through photosynthesis.

The organic carbon in phytoplankton and the animals that consume phytoplankton is called **biomass**. The organic carbon that doesn't end up in biomass is used by phytoplankton and animals for energy, and returned back to the water as CO_2.

In addition to being stored in living marine organisms, carbon in the ocean can take another pathway: it can sink. Sinking biomass in the ocean ranges from microscopic phytoplankton cells to the carcasses of large whales. This sinking transfers carbon from the atmosphere, through the food web, and to the deep ocean. Oceanographers call it the **biological carbon pump**.

Box 1. Ocean carbon cycle in a warming world

The ocean carbon cycle has been disrupted as humans pump more carbon pollution into the atmosphere, primarily through burning fossil fuels. The latest Intergovernmental Panel on Climate Change reports assert that the ocean carbon process is beginning to change in response to warming.

Atmospheric concentrations of CO_2 are at record levels and increasing each year. Higher concentrations of CO_2 in the air mean that more is absorbed into the ocean, causing ocean acidification—a fundamental change in seawater chemistry. Since the Industrial Revolution, CO_2 moving from the atmosphere into the ocean has increased the ocean's acidity by around 30%. Acidification will continue as long as humans continue to emit carbon pollution. This disruption to ocean chemistry, including increased acidity, makes it harder for marine animals such as snails, oysters, corals, and some phytoplankton to build their shells and skeletons.

Oceans have also absorbed 90% of the extra heat caused by carbon pollution, and 2022 was the warmest year on record for oceans. Warm water does not absorb carbon as well as cold water. If less CO_2 is absorbed by oceans, then more is left in the atmosphere to continue warming (and damaging) the planet.

Box 2. Pressure from human activity

In addition to warming, oceans face other pressures from human activity that impact their health, biodiversity, and ability to store and sequester carbon. Reducing these pressures can help marine ecosystems weather some of the effects of climate change (up to a point).

Unsustainable fishing and harvesting practices have diminished or depleted marine resources in places across the globe. Techniques like bottom trawling damage habitat (such as deepwater coral reefs), catch marine life other than the targeted fish (including mammals, sea turtles, and fish), and release potentially huge stores of carbon on the seafloor by dredging up sediments. Miles of rope used to catch lobster and crabs as well as large commercial ships can injure and kill whales.

Human activity on land also affects the ocean. Coastal development can introduce pollutants into the water and affect the function of nearshore ecosystems (such as wetlands and mangroves). According to NOAA, 80% of pollution in the marine environment originates on land, from sources such as leaking septic tanks, motor vehicles, and runoff from agricultural activities. Debris and pollutants make their way into the water through both legal and illegal ocean dumping practices.

CARBON IN THE MARINE FOOD WEB

Phytoplankton are the base of a vast marine food web. Zooplankton (animals that drift with the currents) graze on phytoplankton. Small fish and many other kinds of sea life feed on plankton near the ocean surface. These organisms are in turn consumed by bigger predatory fish (e.g., tuna or sharks) and large marine mammals (whales), building carbon into bigger animals along the food chain.

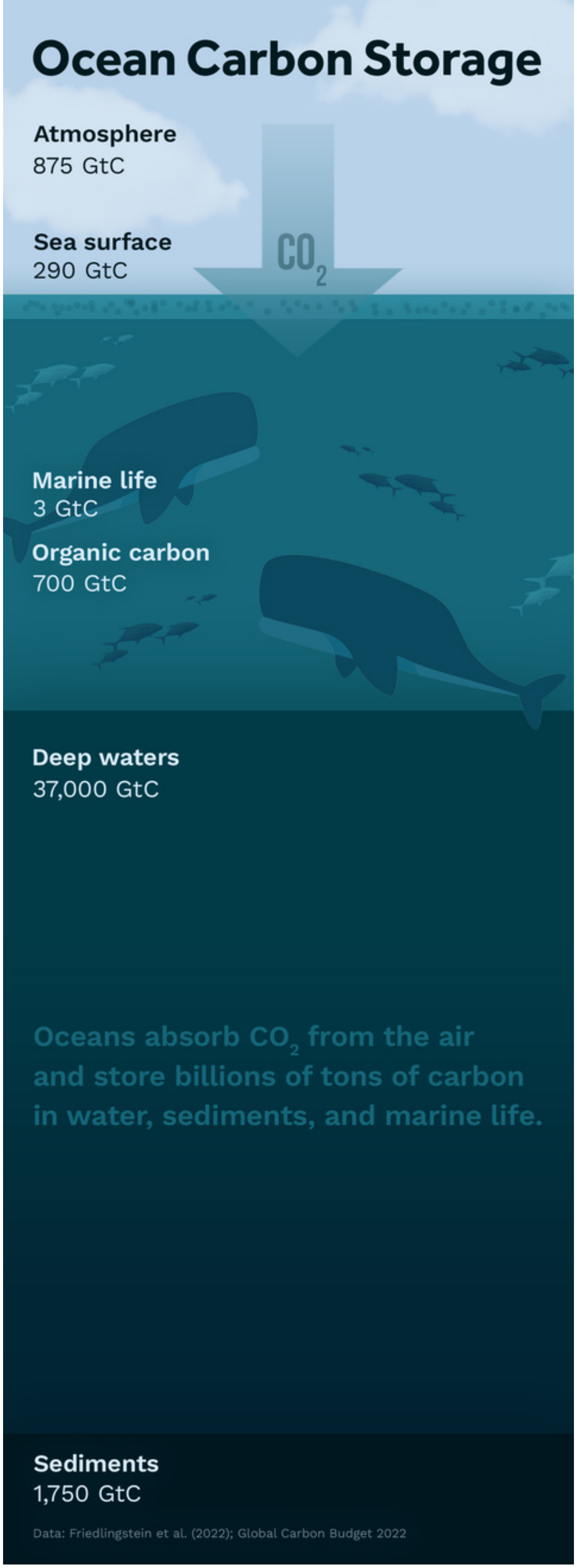
Plants and animals store carbon in their bodies or structures, increasing the amount as they feed and grow, and serving as temporary carbon storage during their lifetime. Marine organisms collectively contain around 3 gigatonnes of carbon (GtC) in their biomass.

Marine plants and animals release some CO_2 through respiration, which returns to the atmosphere to begin the cycle again. Organisms also release carbon through their waste and decay. Much of the waste is decomposed by microbes, and the carbon is dissolved back into the water, where it once again feeds phytoplankton at the surface.

The rest of the waste material rains down from shallow waters into the deep ocean. This material is sometimes referred to as "marine snow" for its pale, fluffy appearance as it drifts. Along the way, many flakes are consumed by detritivores (animals that feed on decaying organic material), and the remainder sinks to the seafloor.

TWILIGHT ZONE CARBON

Each night, a massive migration of marine organisms takes place between the sea surface and the mesopelagic depths—also known as the ocean's "twilight zone."



Oceans absorb CO_2 from the air and store billions of tons of carbon in water, sediments, and marine life.

Data: Friedlingstein et al. (2022); Global Carbon Budget 2022

Source: Global Carbon Budget 2022

Trillions of fish and invertebrates live in this zone, which extends between 660 to 3,300 feet below the sunlit surface.

During this daily journey to the upper ocean, known as **diel vertical migration**, these organisms feed on plankton before retreating back to the depths. This vertical food web is another pathway that brings surface carbon to the deep ocean, as part of the biological carbon pump. Vertical migration by fish, as well as their sinking feces, could contribute around 16% of the total carbon transferred to the deep sea each year.

The twilight zone is big, deep, and dark—and much about this extreme environment and its inhabitants remains a mystery. Researchers are developing specialized tools and technology to explore the twilight zone, with the aim of better understanding how it functions and, perhaps, how it can be leveraged for more carbon storage.

CARBON IN LARGE MARINE LIFE: WHALES

Big marine animals (namely whales) are unique links in the ocean carbon cycle because they move nutrients vast distances and contain huge amounts of carbon in their bodies over a lifespan of many decades.

Whales dive underwater to feed and return to the sea surface to breathe, where they release nutrient-rich fecal plumes that feed plankton. Whales also migrate long distances between feeding and breeding grounds. During this journey the "great whale conveyor belt" releases tons of waste (fecal matter and urea) and circulates nutrients to different parts of the ocean, further stimulating phytoplankton growth.

When whales or other large marine animals die, their carcasses sink to the sea floor (known as deadfall carbon), where they feed deep-sea organisms and are eventually incorporated into sediments.

CARBON SINKING DEEP

Carbon that makes its way to depths of the ocean is pulled from the biological carbon pump and can potentially be locked away for millennia—making the seafloor one of the most critical carbon reservoirs on the planet. Seafloor surface sediments store about 1,750 Gt of carbon. Over millions of years, these deposits are compressed into seafloor and sub-seafloor rock formations for carbon storage on geologic timescales.

THE PHYSICAL CARBON PUMP

Ocean circulation and currents affect the absorption and movement of gases (including CO_2 and oxygen) between the atmosphere and layers of the ocean.

Warm surface water flows from the tropics towards the poles. As the water moves and cools, it absorbs CO_2 from the atmosphere. In a few places around Greenland and Antarctica, the water becomes dense enough to sink thousands of feet below the surface, taking the dissolved carbon away from the atmosphere and into the deep ocean. This deep water flows around the world as part of the "global ocean conveyor belt." These deep waters are hugely important carbon stores.

While sinking seawater stores carbon, places where seawater rises to the surface (a process called upwelling), can release CO_2 back to the atmosphere. These places include the band of currents around Antarctica and the equatorial Pacific.

Blue carbon solutions

Blue carbon is the term for carbon captured by marine and coastal ecosystems. There are many ways that humans can restore, protect, or better manage the marine ecosystems that capture and store CO_2. When paired with deep cuts to emissions, solutions that focus on conservation and restoration can bolster the ocean's capacity for carbon storage.

Protecting and enhancing blue carbon has many co-benefits and few potential risks compared to other methods for ocean-based CO_2 removal that rely on ecosystem manipulations. (Note: These approaches are further discussed in the section entitled "*Emerging approaches for ocean* CO_2 *removal.*")

Overall, ocean organisms sequester a relatively small amount of carbon, but increased biodiversity builds resilience in a changing climate and supports more robust fisheries—which provide food for billions of people and support the livelihoods of millions across the globe. In addition to storing carbon, intact coastal ecosystems offer wildlife habitat, natural barriers against storm surges, and recreation opportunities.

The Blue Carbon National Working Group coordinates and supports blue carbon conservation work in the U.S. and internationally. The group includes dozens of governmental and nongovernmental agencies and organizations.

SUSTAINABLE MANAGEMENT OF FISHERIES

Overfishing (catching fish faster than they are able to reproduce) can cause population declines that harm ecosystems and reduce long-term harvests that provide food and income. Maintaining healthy fisheries is one way to conserve marine life and sustain the temporary pool of ocean carbon stored in marine food webs.

The National Oceanic and Atmospheric Administration (NOAA) is the federal agency that implements and enforces commercial and recreational fisheries laws and regulations in the U.S. Laws regarding fisheries activities are primarily driven by the Magnuson-Stevens Fishery Conservation and Management Act. One such mechanism is setting and monitoring annual catch limits to reduce overfishing and sustainably manage fish populations. These approaches have allowed the U.S. to maintain most stocks at healthy levels and rebuild 49 stocks that were once overfished. Warming ocean temperatures, however, are a growing threat to fisheries on both coasts.

LETTING BIG FISH SINK

Big fish, sharks, and whales have the capacity to store large amounts of carbon in their bodies during long life spans. When they die, their sinking carcasses move that carbon to the seafloor, keeping it from returning to the atmosphere.

Studies suggest that commercial fisheries management could potentially be optimized for better carbon storage by limiting the extraction of blue carbon (i.e., fish) to support rebuilding stock and increasing the amount of deadfall carbon, particularly in areas where such extractions are unprofitable without subsidies.

RESTORATION OF WHALE POPULATIONS

Humans have reduced global whale populations during the past 150 years through whaling and fishing operations. The U.S. ended commercial whaling in 1972 with the Marine Mammal Protection Act. Ten years later, the International Whaling Commission followed suit. Present-day whale populations face pressures from climate change and human activities in feeding grounds and migration routes (e.g., boat collisions in shipping lanes, entanglement in commercial fishing nets).

A study in 2010 compared pre-whaling abundance of eight baleen whale species in the North Atlantic (roughly 2.6 million individuals) to levels in 2001 (around 880,000 individuals). This decline in whale populations resulted in a loss of nearly 164,000 tons of carbon per year that could be moved to the deep ocean. Restoring blue whales (*Balaenoptera musculus*) to pre-whaling populations could result in 200,000 tons of carbon storage annually.

Although these large animals make up a small portion of the overall ocean biomass, focusing on the recovery of whales and big fish, an important international goal, could reap carbon storage benefits.

Box 3. UN High Seas Treaty

What happens in one part of the ocean can affect seas across the globe. But countries don't always agree on how to manage resources or control activities in shared international waters informally known as the "high seas."

In 2023, members of the United Nations signed a legally binding agreement, known as the Biodiversity Beyond National Jurisdiction treaty. The treaty provides a framework to preserve marine biodiversity in international waters through development of marine protected areas, environmental impact assessments of new activities (and existing activities that do not currently require such assessments), and capacity building for developing nations, among other tools and mechanisms.

ESTABLISHING MARINE PROTECTED AREAS

Marine protected areas (MPAs) are one way to regulate activities that can potentially harm marine life and the carbon they store. MPAs are defined marine areas in which certain activities, such as fishing or fossil fuel extraction, are limited or banned to preserve ecosystems with significant ecological and cultural value.

Around one-quarter of marine areas in the U.S. are designated MPAs, and most of the protected area (around 98%) is within the Pacific Islands region. Around 23% of U.S. MPAs do not allow commercial fishing, but only 3% have prohibitions on all extractive activities (such as fishing or mining).

COASTAL ECOSYSTEM RESTORATION

The conservation and restoration of coastal wetlands and nearshore ecosystems—including mangroves, seagrass meadows, and saltmarshes—have many benefits to people and wildlife. In the U.S., MPAs often include these important habitats. Healthy, intact coastal ecosystems have tremendous potential for carbon storage in soils, sediment, and plant biomass.

In some cases, restoring ecosystems can enhance their capacity to store carbon. Other times, conservation of existing, intact ecosystems will prevent loss of important carbon storage. Seagrass meadows contain around 11% of buried blue carbon, but are among the world's most imperiled coastal ecosystems. At least 7% of global seagrass ecosystems are lost to development or degradation each year. When these ecosystems are diminished, the blue carbon they contain is released back into the atmosphere where it contributes to warming.

Box 4. Blue carbon markets

Through voluntary carbon markets, conservation and restoration projects generate credits based on an amount of carbon captured and stored. Businesses can purchase credits on carbon markets—essentially paying to restore or enhance an ecosystem that can absorb an amount of CO_2 equivalent to the emissions from certain business-related activities.

Monitoring conservation efforts and measuring outcomes is challenging for global resources, such as those in the open ocean. Researchers have developed methodologies to assign credits for blue carbon projects, mainly in coastal ecosystems where conservation practices are well-understood and carbon capture can be quantified with relatively high confidence (such as for wetlands or mangroves). For example, such methodologies for coastal ecosystems credits are set forth in the Verified Carbon Standard (VCS) Program through the nonprofit Verra.

Conservation International and partner organizations put forth a framework on High-Quality Blue Carbon Principles and Guidance.

Emerging approaches for ocean CO_2 removal

Several emerging approaches aim to enhance the ocean's capacity to remove CO_2 by leveraging biotic and abiotic processes. These approaches are often categorized as **geoengineering**. Research into most geoengineering solutions for ocean-based carbon dioxide removal (CDR) is nascent, but some may hold promise.

These approaches would involve manipulating or modifying large swaths of the ocean for significant lengths of time, and therefore come with considerable scientific, legal, financial, and social challenges. More research is needed to understand potential consequences on ecosystems, and whether these approaches can be practically applied to have near-term impact on CO_2 removal.

The following list provides brief descriptions of several categories of ocean-based CDR projects or research.

- **Seaweed cultivation** or farming refers to growing macroalgae and kelp, which take in CO_2 through photosynthesis. Seaweed can serve as alternative livestock feed or be processed into fuel. Cultivation projects that focus on carbon sequestration, however, would require sinking seaweed deep into the ocean for longer-term storage (rather than using the seaweed for other purposes). Large-scale seaweed cultivation would require access to significant coastal habitat as well as expansion into deeper waters, which could have consequences for natural ecosystems and require significant funds and logistics. To sequester around 0.1 $GtCO_2$ annually would require a series of farms equivalent to half the size of Iowa.

- **Ocean fertilization** would involve adding shiploads of a critical nutrient, such as iron, into the ocean surface to feed and promote growth of phytoplankton. Uneaten phytoplankton would die and sink, carrying carbon into the deep ocean for long-term storage. The potential effectiveness of this method is unclear. Some research suggests that ocean fertilization could result in global sequestration of around 3.7 $GtCO_2$ annually, and other estimates vary widely.

- **Artificial upwelling and downwelling** would simulate the natural vertical movement of ocean water to carry nutrients to the surface (upwelling) or sink water holding dissolved CO_2 deeper (downwelling). Theoretically, either mechanism could be used to artificially enhance carbon sequestration, but sufficient capacity (spatial or temporal) has not been demonstrated in experiments to date. Based on current knowledge, it is considered unlikely that any large-scale deployment would effectively lead to sustainable, long-term CO_2 sequestration.

- **Ocean alkalinity enhancement** refers to the alteration of ocean water chemistry by adding large amounts of alkaline minerals, such as silicates or carbonates, to lock in more CO_2 from the atmosphere. This would accelerate a natural process through which minerals are dissolved into the ocean over thousands of years. Enhancing alkalinity could have the added benefit of reducing ocean acidification. Models suggest that alkalinity enhancement at the global scale could sequester more than 1 $GtCO_2$ annually, but the impacts on marine ecosystems are not clear.

- **Electrochemical ocean CDR approaches** employ electrolysis to remove dissolved CO_2 from seawater and/or increase alkalinity before returning water to the sea. These processes require substantial infrastructure and energy to operate, such that scaling up could be prohibitive. For example, an electrochemical approach to remove 1 $GtCO_2$ per year would require an annual amount of electricity equivalent to 20% of the total projected increase in the global electricity supply by 2040.

Note: Descriptions are primarily based on summaries in A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2022), produced by the National Academies of Sciences, Engineering, and Medicine. For more detailed information about ocean-based CDR research and technology, see the full report at: https://nap.nationalacademies.org/read/26278

GLOSSARY

Biomass—the total mass of organisms (e.g., plants, animals) in an ecosystem

Blue carbon—carbon captured by oceans and coastal ecosystems

Carbon dioxide removal (CDR)—technologies and methods for removing CO_2 from the atmosphere for longer-term storage in a human-made or natural system

Carbon sequestration—the process of removing CO_2 from the atmosphere, measured as annual uptake of carbon

Carbon sink—any natural system in which large amounts of CO_2 are captured and held for long periods of time.

Carbon storage—storing captured CO_2 to keep it out of the atmosphere, measured as total carbon stored

Gigatonne of carbon (GtC)—equivalent to one billion metric tons. Quantities are presented in this report in units of gigatonnes of carbon (GtC) or gigatonnes of carbon dioxide ($GtCO_2$). For reference, 1 GtC is equivalent to 3.67 $GtCO_2$. In 2021, human-caused CO_2 emissions from burning fossil fuels were approximately 10 GtC (36 $GtCO_2$)

Geoengineering—large-scale modifications to natural processes with the goal of counteracting effects of climate change

RESOURCES

- A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2022), the National Academies of Sciences, Engineering, and Medicine
- High-Quality Blue Carbon Principles and Guidance
- NOAA Blue Carbon Fast Facts
- NOAA Carbon Dioxide Removal Research
- NOAA Fisheries Stock Status Updates
- Oceanic Blue Carbon, GRID-Arendal
- Ocean Carbon Dioxide Removal Methods (2022), Natural Resources Defense Council, Environmental Defense Fund, and Ocean Conservancy

- The Blue Carbon Initiative
- Toward Responsible and Informed Ocean-Based Carbon Dioxide Removal Research and Governance Priorities (2022), World Resources Institute

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