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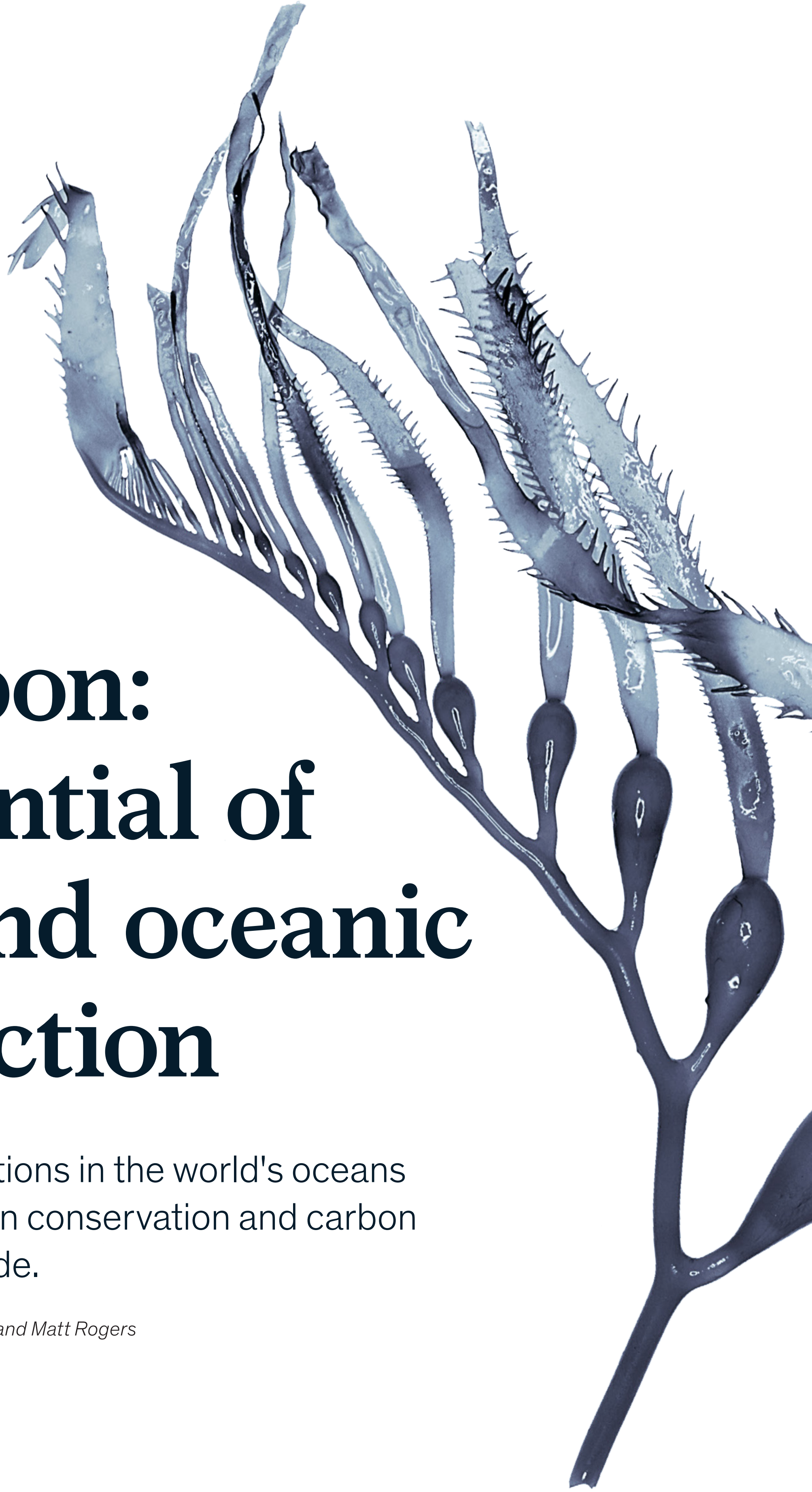

Blue carbon: The potential of coastal and oceanic climate action

Nature-based climate solutions in the world's oceans can play an important role in conservation and carbon abatement efforts worldwide.

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Executive summary

The oceans and coasts are the Earth's climate regulators. Covering 72 percent of the planet's surface, they have absorbed about 40 percent of carbon emitted by human activities since 1850.[1] Coastal ecosystems such as mangroves, tidal marshes, and seagrass meadows act as deep carbon reservoirs, while marine ecosystems and fauna absorb and sequester greenhouse gases (GHG) through the carbon cycle.[2] However, over recent decades, both oceans and coasts have come under pressure from atmospheric and marine warming, habitat destruction, pollution, and the impacts of overfishing and industrial activity. These destructive factors undermine the effect of oceanic systems in reducing atmospheric carbon.

Humankind's impact on coastal and offshore ecosystems is a double-edged sword. While we are responsible for significant destruction, we also have agency over potential outcomes. Through our efforts, we can avert damage to or even restore ocean ecosystems, removing carbon from the atmosphere and moving the world toward net-zero emissions, as envisaged by the Paris Agreement on climate change.

Here we consider three categories of blue-carbon solutions, classified by their scientific and economic maturity (Exhibit 1):

— *Established solutions:* Focused on mangroves, salt marshes, and seagrass meadows, these solutions are widely understood, offer scientifically verifiable levels of carbon abatement, and are amenable to funding through established approaches, such as the purchase of carbon credits.[3]

— *Emerging solutions:* This category includes the protection and restoration of seaweed forests, the extension of seaweed forests, and strategies to reduce bottom trawling. These solutions have undergone initial peer-reviewed research to quantify their potential to abate CO_2, but significant scientific uncertainty still needs to be addressed. Given this uncertainty, and the fact that practical solutions are not sufficiently mature, solutions in this category cannot yet be financed through carbon markets.

— *Nascent solutions:* This potentially powerful group of solutions is mainly focused on protecting and restoring marine fauna, from oysters to whales. These solutions involve challenges such as quantifying their impact, establishing permanence, preventing leakage, and proving additionality—that is, proving that without the solution a particular benefit would not have happened.

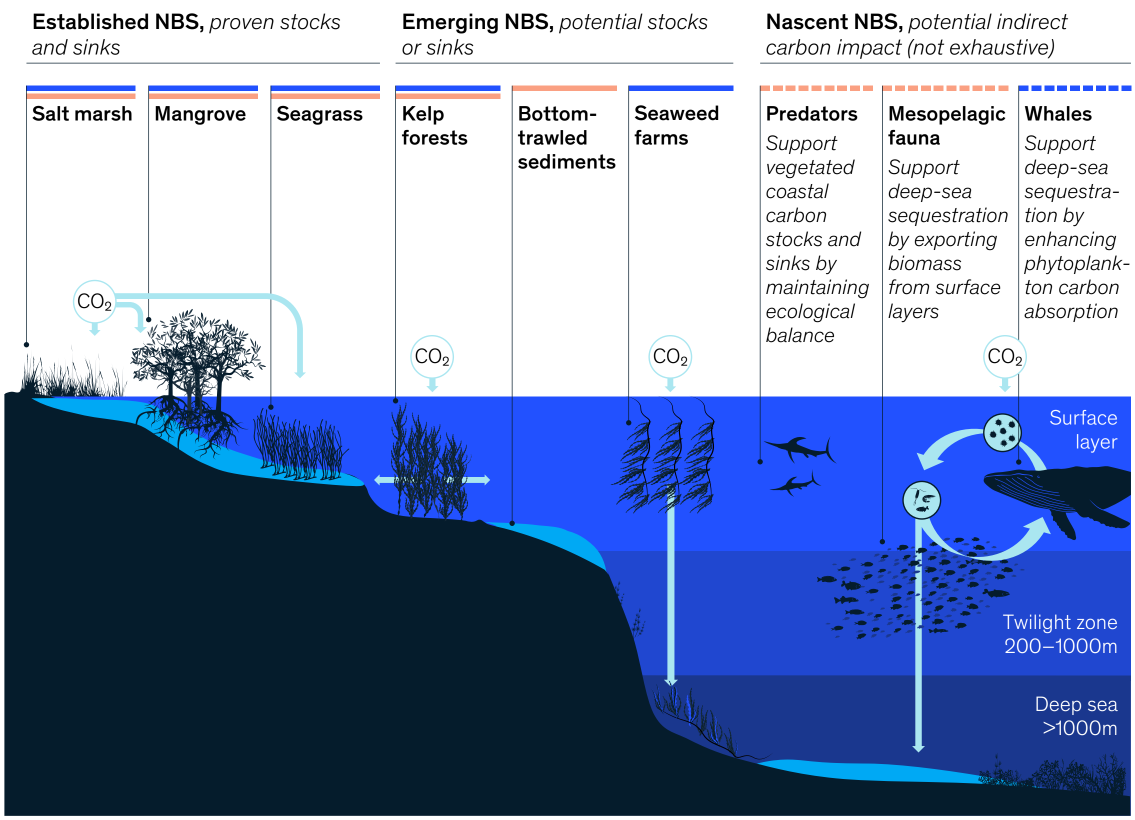
For each category of solutions, this report sizes approaches and measures their impacts, costs, and likely access to funding. It highlights the latest scientific research and leverages McKinsey analysis to estimate the potential for abatement or conservation by 2050. This report also includes deeper analysis of kelp reforestation and bottom trawling to show how economies of scale in these emerging solutions could help reduce prohibitive costs.

If fully implemented, the established class of solutions described here would abate 0.4 to 1.2 metric gigatons of carbon dioxide ($GtCO_2$) annually—1 to 3 percent of total current annual CO_2 emissions (Exhibit 2). That potential jumps to approximately three $GtCO_2$ of annual abatement (about 7 percent of total current

Exhibit 1

This report examines three categories of nature-based, blue-carbon solutions.

Nature-based solution (NBS) type:
- Increase carbon storage; eg, restoration
- Avoid emissions or loss of carbon sink; eg, protection from threat



Source: McKinsey analysis

annual CO_2 emissions) if the solutions in the emerging category, such as large-scale seaweed farming and bottom-trawling management, were fully confirmed and implemented. When it comes to cost, preliminary analytics suggest that about one-third of the total potential abatement would be viable below $18 per metric ton of carbon dioxide (tCO_2).

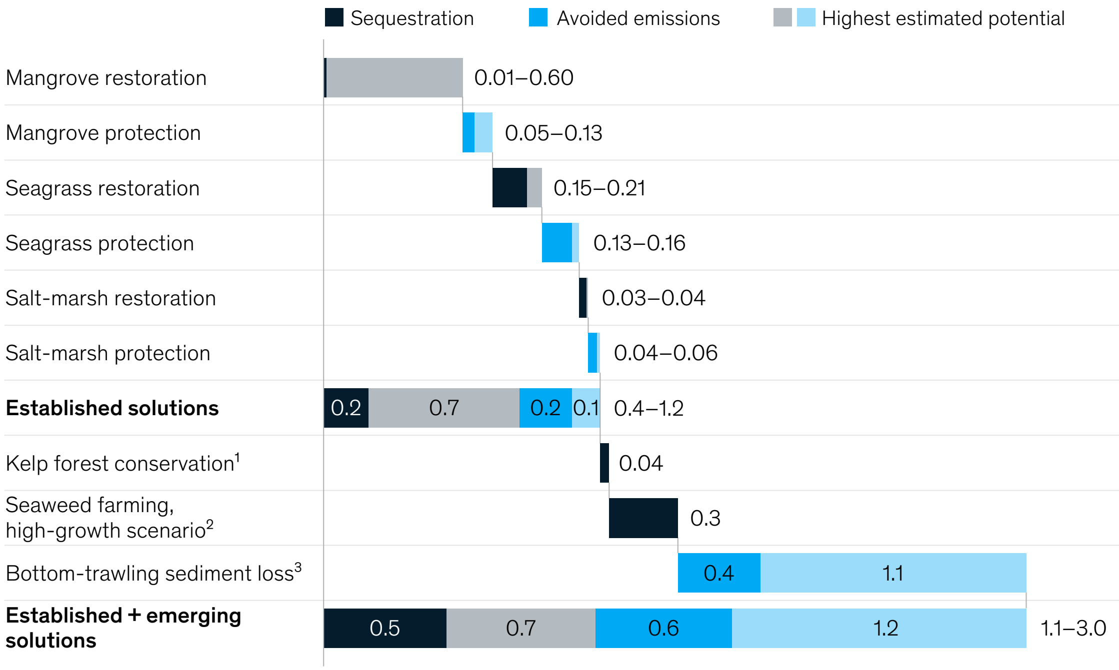
Nascent solutions that support rebuilding marine fauna might abate one to two $GtCO_2$ annually in the longer term, but the science remains highly uncertain.[4] To put these numbers into context, anthropogenic CO_2 emissions are currently about 40 $GtCO_2$.[5]

Alongside the climate case for blue-carbon solutions, these solutions have potentially significant benefits for ecosystems. For example, as mangroves recover, fish and marine fauna populations will expand, supporting both fisheries and nature-based tourism, as well as bolstering coastal protection and filtering runoff.[6]

Exhibit 2

Established blue-carbon solutions offer abatement of 0.4 to 1.2 metric gigatons of carbon dioxide ($GtCO_2$) per year; emerging solutions could add up to about 1.8 $GtCO_2$ per year for a total of approximately 3 $GtCO_2$ per year.

Abatement potential from established and emerging blue-carbon solutions by 2050,
$GtCO_2$ equivalent per year



[1] High-level, high-uncertainty estimate.
[2] Seaweed farming sequestration depends on area of implementation and is potentially much higher. Potential shown is the reported 14% per annum growth-based estimate in the ocean as a solution.
[3] Lower bound is estimated as the long-term abatement potential (40% of current emissions rates) of emissions from bottom trawling in areas shallower than 50 meters.
Source: Source: Peter Macreadie et al., "Blue carbon as a natural climate solution," *Nature Reviews Earth & Environment*, November 2021, Volume 2; Ove Hoegh-Guldberg et al., *The ocean as a solution to climate change: Five opportunities for action*, World Resources Institute, 2019; Enric Sala et al., "Protecting the global ocean for biodiversity, food and climate," *Nature*, March 2021, Volume 592; McKinsey analysis

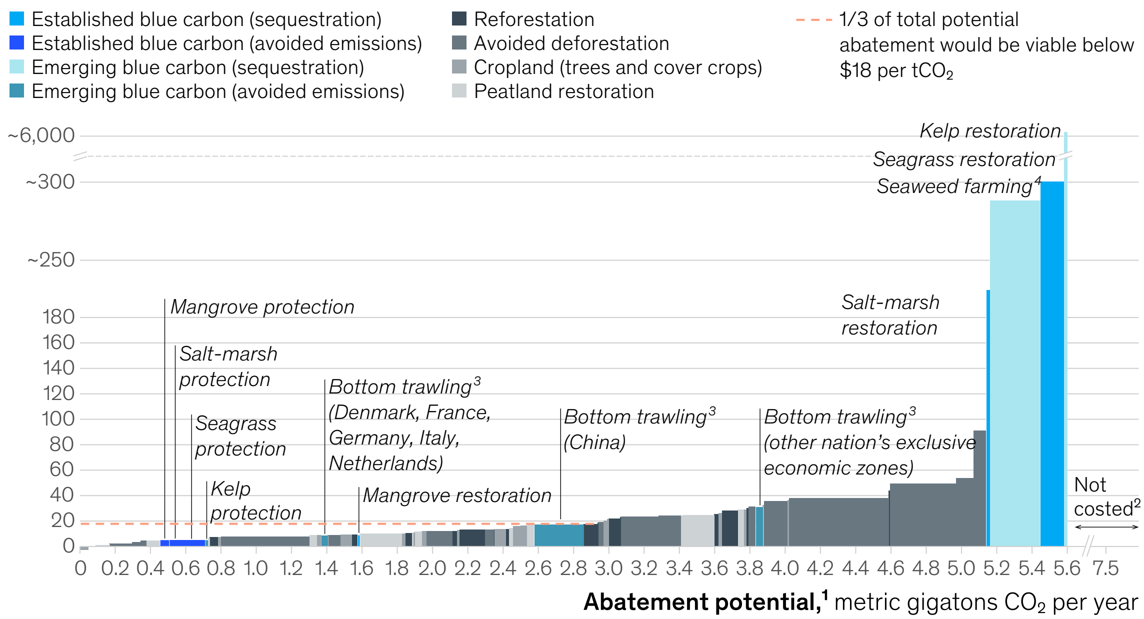
As previously stated, data suggest about one-third of the total potential abatement would be viable below \$18 per tCO_2, a cost that is above the \$5 to \$15 per tCO_2 average price paid in the voluntary carbon markets (VCM) but well below the \$40 to \$100 per tCO_2 paid in the European compliance markets over the past year (February 2021–22) (Exhibit 3).[7]

While blue-carbon solutions are an increasingly viable option to help companies and organizations reach net-zero emissions, many promising ideas are accompanied by significant hurdles. Scientific research into many solutions remains underdeveloped, which leaves uncertainty about the impacts of abatement. For example, the science has yet to quantify to what extent underwater carbon capture through seaweed farming reduces atmospheric CO_2; there is a similar lack of data regarding the effect of reducing bottom trawling. (Current research suggests that complex biogeochemical cycles in seawater and ocean currents influence net exchange of CO_2 with the atmosphere.[8]) In addition, there is insufficient modeling to show

Exhibit 3

Several established and emerging blue-carbon solutions are presently cost-competitive with terrestrial nature-based solutions.

Abatement cost curve, nature-based solutions, $ per metric ton of carbon dioxide (tCO_2)



[1] The abatement potential shown for blue-carbon solutions corresponds to the lower-end estimates in Exhibit 2.
[2] An additional 1.9 metric gigatons (Gt) of natural-climate-solutions abatement is not costed (avoided deforestation: 0.95 Gt; peatland restoration: 0.21 Gt; reforestation: 0.36 Gt; cover crops: 0.22 Gt; trees in cropland: 0.11 Gt). This analysis filters out low-feasibility lands (those with high economic returns—eg, >$45/hectare—from agriculture), which are more likely to be accessed by mechanisms other than voluntary carbon markets.
[3] Lower-end estimate of bottom-trawling emission abatement, limited to activity in the top 50 meters of the ocean. The higher-end estimate offers 1.5 Gt at a (lower) average opportunity cost of \$11/tCO_2.
[4] Seaweed farming potential based on current cost and implementation growth estimates; chart does not reflect potential cost reductions from technology learning curves and scaling.
Source: *Nature Analytics*

how terrestrial processes such as agricultural runoff and climate change may influence the ocean's continued ability to sequester carbon.[9]

Beyond scientific uncertainty, matters of coastal and marine law are often complex or opaque. Because they are subject to national jurisdictions, estuarine and coastal environments are often governed by numerous subnational regulatory and administrative agencies. Offshore ocean environments are mainly governed by the consensus-oriented UN Convention on the Law of the Sea and UN Environment Programme, though individual nations retain rights to resources up to 200 nautical miles from their coastlines. Nearer to shore, issues of land tenure abound. Coastal blue-carbon project developers need to closely engage Indigenous peoples and small-scale food-producing communities and respect access and tenure rights. Indeed, in many cases, empowering traditional and community[10] stewardship[11] of marine resources may be sufficient to achieve coastal protection and natural regeneration.[12]

In situations where active restoration is required, projects need to be evidence-based and ecologically appropriate. For example, mangrove restoration should target areas where mangroves traditionally have grown to re-create biologically diverse ecosystems, avoiding conversion of other native ecosystems such as mudflats to monoculture plantations. Resilient restoration also requires an understanding of the causes of original ecosystem loss and actions to ensure they do not reoccur, backed by monitoring and evaluation. In this report, we show how some organizations are working to tackle challenges in these areas.

Despite varying levels of practicality and scientific certainty, viable arguments suggest that blue-carbon solutions present an opportunity. Indeed, companies are starting to leverage blue-carbon solutions as part of their portfolio of solutions to get to net-zero emissions. Apple[13] is working with the nonprofit Conservation International in Colombia to preserve a 27,000-acre mangrove forest.[14] The first fully accounted carbon offset credit for a mangrove habitat, the forest is expected to sequester almost one million metric tons of carbon dioxide equivalent (tCO_2e) over its lifetime. Procter & Gamble, meanwhile, has partnered with the same organization to safeguard 31 species of mangroves in the Philippines.

Another tailwind is the ongoing development of methodologies to report and quantify the impact of projects. In September 2020, for example, standards-setter Verra released the first blue-carbon conservation methodology approved under any major GHG program. The VCS REDD+ Methodology Framework makes blue-carbon conservation and restoration activities eligible for inclusion in the program, unlocking new sources of financing for tidal wetland conservation and restoration.

We show here that as more methodologies are published, established blue-carbon solutions that could already have access to VCMs or compliance carbon markets (or may get access to them in the near future) could offer up to 1.2 $GtCO_2$ of annual abatement potential (about 1.5 times the amount of carbon emitted by the aviation industry). Analytics suggest that about 0.4 to 1.0 GtCO2 could be abated at less than $18 per metric ton.

Imperatives to support funding

Blue-carbon solutions are, for the most part, in their infancy. Just a few projects have qualified for carbon markets to date, and there are significant financial, practical, and legal hurdles to scaling these solutions in oceanic and coastal environments. In short, there are deficits in terms of both supply and demand, resulting in a challenging risk/return profile. That said, the science that supports established blue-carbon sequestration is sound, and there is clear opportunity to extend abatement activities. With their beneficial impact on biodiversity and coastal communities, blue-carbon solutions are particularly rich in co-benefits beyond their abatement profiles. In a world with only narrow pathways toward a 1.5°

Coastal blue-carbon project developers need to closely engage Indigenous peoples and small-scale food producing communities, respecting access and tenure rights.

outcome, a scientifically feasible, multi-metric-gigaton set of solutions with significant co-benefits cannot be ignored.[15] There is no reason why companies and organizations should not now consider blue-carbon, nature-based solutions as a potential way to meet their net-zero targets, and initiatives across sectors can encourage such investment.

Any nascent technology requires sufficient scale early on to achieve critical mass. At financial institutions, the current investment in blue-carbon projects is rooted in a broader mismatch between climate ambition and operational resources. Outside the top tier, many banks and investors lack the strategy and capabilities to commit to a relatively marginal asset class. Ticket sizes tend to be small compared with the effort required, and there is often a gap to cost parity with incumbent technologies. To resolve these challenges, financial institutions need to find ways to layer blue carbon into portfolio allocation frameworks and source the knowledge resources that can help them navigate new markets. Even then, there are doubts about risk/return profiles and timelines. These doubts present significant barriers that will need to be overcome if blue carbon is to become an established alternative to terrestrial solutions.

Companies looking to offset their carbon emissions face challenges similar to those faced by financial institutions. In comparison with more readily available terrestrial credits, blue-carbon offset opportunities may appear high risk, subscale, and expensive. Still, Apple and others have shown there are opportunities, particularly in the established class of solutions. For some companies whose business is closely linked to the world's oceans, such as nature-based expedition cruise lines, blue-carbon solutions also offer the chance to align their net-zero programs with their real-world activities. Tackling the challenge of scaling both supply and demand, the recently announced Blue Carbon Buyers Alliance aims to educate buyers and create a clear demand signal, with members committing to funding or purchasing credits from high-quality blue-carbon projects.[16] Such collective, early-mover signals can have significant impact on supply, potentially bringing down prices rapidly.

Leaders of blue-carbon projects have an important role to play in supporting decision making at financial institutions and corporations. To attract more risk-tolerant financing, they need to design projects convincingly, pilot successfully, and demonstrate real sequestration potential so that they establish the track record that will support financing. To create early momentum, they should share their early successes as widely and as comprehensively as possible.

Finally, governments are critical in scaling participation and funding. A good blueprint is the work of the US Advanced Research Projects Agency-Energy (ARPA-E), which promotes and funds research into advanced energy technologies. Multilateral and development-assistance agencies can fund innovative and scalable programs. For example, members at the 2021 UN Climate Change Conference in Glasgow (COP26) made significant progress when they ratified Article 6 of the Paris Agreement, which focuses on how countries can “pursue voluntary cooperation” to meet their climate targets. Governments could also signal support for blue-carbon solutions by including them in nationally determined contributions (NDCs) under the Paris Agreement. Through these kinds of initiatives, governments could nudge blue carbon toward the mainstream—and push the world toward a promising new carbon-capture-and-storage opportunity.

Introduction

The demands of growing economies around the world have led to the destruction of hundreds of thousands of hectares of coastal ecosystems, eliminating plants and sediments that would otherwise remove carbon from the atmosphere. Marine biomes, meanwhile, are under pressure from factors that include overfishing, pollution, and acidification caused by carbon absorption. These losses could not come at a worse time. With global temperatures rising by about 0.18°C every ten years,[17] the world is on track for increasingly severe climate hazards including damaging storms, flooding, and lethal heat waves. Degradation of coastal and marine ecosystems has eroded their ability to cool the planet.

In reversing damage to ocean environments, there is little time to waste. Approximately 20 to 35 percent of mangroves have been lost since 1980 due to clearing for farming, aquaculture, and coastal development, among other factors.[18] Tidal marshes (grassy wetlands flooded by high tides) and seagrasses are seeing similar rates of attrition. Every year, almost five million square kilometers of seafloor are disturbed by fishing gear, which stirs up a significant amount of carbon and potentially releases it into the atmosphere.[19] The fraction of fish stocks extracted within biologically sustainable levels fell from 90 percent in 1974 to 67 percent in 2015.[20] As a result, fish biomass has reduced across species, with the largest classes seeing a near 90 percent reduction since 1800.[21] As fish stocks and sizes decline, so do their roles in carbon cycling and their contributions to deep-sea sequestration.[22] Assuming that 10 percent of fish fecal matter is carbon and that a third of fecal particles sink into the deep ocean (storing carbon away from where it causes warming in the atmosphere), the reduction in fish stocks since preindustrial times has led to a 0.1 metric gigaton of carbon dioxide ($GtCO_2$) decrease in carbon sequestered in the deep ocean per year.[23]

One way to help the world align with the Paris Agreement objective of keeping warming below 2.0°C—and ideally below 1.5°C—is to use nature-based solutions (NBS). These are focused on the protection, restoration, and management of aquatic and land-based ecosystems. In this report, we analyze the potential of oceanic and coastal NBS, or blue-carbon solutions, to protect or enhance ecosystems and to produce scientifically proven mitigation benefits. We do not consider the natural processes by which carbon dioxide is exchanged between the atmosphere and ocean surface, absorbed by phytoplankton and the food chain, or buried in ocean sediments, except insofar as human actions can support and restore these processes. We also do not consider ocean-based carbon dioxide–removal strategies that are primarily geo-engineering approaches, such as nutrient fertilization, artificial upwelling and downwelling, ocean alkalinity enhancement, or electrochemical approaches.[24]

Financing these solutions remains a challenge. In particular, funding and transaction fees are a notable variable in project feasibility. The median cost of restoring mangroves, for example, is $9,000 per hectare.[25] Based on losses between 1996 and 2016, about 600,000 hectares need to be restored, implying a total cost of $5.4 billion for this solution alone.[26] Another challenge in mobilizing finance is alignment with frameworks that facilitate carbon offsetting. These may be either voluntary carbon markets (VCMs) or the much bigger but less flexible compliance markets.[27] One such framework is the Core Carbon Principles, published in 2021 by the Taskforce on Scaling Voluntary Carbon Markets in 2021. A key element of these principles is scientific certainty about the impacts of abatement actions.

Unfortunately, many blue-carbon solutions do not yet meet this standard. For example, there are significant uncertainties about the proportion of carbon accumulated and cycled by marine fauna, which is ultimately sequestered in ocean sediment. If blue carbon is to be included in major regulated (compliance) schemes such as the EU Emissions Trading System (EU ETS), additional scientific research, policy design, economic analysis, and policy advocacy are required.

For these reasons, financing for blue-carbon solutions has been thin on the ground, reflecting insufficient revenue sources, commercial arrangements, and project delivery. Indeed, the science of blue-carbon solutions is still in its infancy, and only over the past decade have many solutions been studied in depth. As a result, just 0.001 metric gigatons of CO_2 equivalent ($GtCO_2e$)—a 0.7 percent share—of blue-carbon NBS credits have been issued on VCMs since 2013.

That said, over the past two years, the number of projects under development has risen amid publication of new VCM methodologies for both avoided-loss and restoration projects. A revision to the Verified Carbon Standard REDD+ Methodology Framework adds blue-carbon conservation and restoration activities as eligible project types; this change will likely enable monetization of all coastal wetland conservation and restoration activities.[28]

As these emerging frameworks start to have an impact, the number and scale of blue-carbon solutions will grow. Furthermore, many of the solutions discussed here are aligned with the work of coastal communities, conservationists, nongovernmental organizations (NGOs), and scientists around the world. There is therefore an opportunity, where financing methodologies are in place, to double down on these efforts, tackle challenges, and make powerful contributions to long-term carbon drawdown efforts to restore our climate.

In reversing damage to ocean environments, there is little time to waste.

Three tiers of blue-carbon solutions

Reflecting the diversity of ocean environments, blue-carbon solutions encompass a variety of ecosystems and approaches. Each of these solutions faces distinct abatement or drawdown challenges and therefore different hurdles in accessing VCMs. We consider three categories of solutions: established, emerging, and nascent. Our analysis suggests that the implementation of the established and emerging solutions could result in one to three $GtCO_2$ of annual abatement, or about 3 to 7 percent of current global annual emissions. The nascent category's potential might be similar, but significant scientific uncertainty complicates predictions and will limit access to VCMs.

Across all categories, we distinguish between projects that protect an ecosystem under threat and those that support removal of carbon from the atmosphere via nature-based sequestration (for example, the restoration of a wetland that increases carbon sinks and stocks). One of the challenges in the protection category is proving additionality—that is, showing that the ecosystem would have been degraded if not for the action. The difficulties associated with these kinds of proofs mean that some bodies, including the Science Based Targets initiative (SBTi), only accept sequestration-type projects as contributions toward corporate net-zero-emissions claims.

To be awarded a carbon credit, blue-carbon projects need to meet a high bar of confidence related to their CO_2 drawdown contributions. To ensure that the various standards meet the needs of users, the Taskforce on Scaling Voluntary Carbon Markets in January 2021 established the Core Carbon Principles for carbon abatement projects.[29] These principles include the need for projects to have real, permanent, and additional impact—and for that impact to be verifiable and not double counted. Currently, many projects are unable to meet these conditions.

Established solutions: Mangrove forests, salt marshes, and seagrasses

We consider blue-carbon solutions to be "established" when they meet minimum standards of scientific understanding and implementation potential. These solutions must offer scientifically verifiable levels of carbon abatement such that they can be, and increasingly are, described by methodologies that qualify them for VCMs. These relatively mature approaches are focused on coastal blue-carbon ecosystems—specifically mangroves, salt marshes, and seagrass meadows. The carbon stocks of these ecosystems are disproportionally concentrated, accounting for 50 percent of the ocean's carbon capture in just 0.2 percent of oceanic area.[30]

Coastal and oceanic ecosystems capture and store carbon both in biomass and in sediment. Carbon locked up in sediment is protected from oxidation, effectively removing it from the carbon cycle. However, since the beginning of the 20th century, up to 63 percent of coastal wetlands have been destroyed.[31] In the case of mangroves and salt marshes, destruction has occurred mostly in the interests of urbanization, aquaculture, and agriculture. Seagrass meadows have been degraded by land-based pollutants such as nutrient runoff and destruction from dredging, trawling, and boat traffic. The direct effect has been to convert coastal sediments from carbon sinks to sources of emissions.[32]

One type of blue-carbon solution focuses on conservation. However, where mangrove, salt-marsh, or seagrass vegetation is already degraded or destroyed, the focus has been more on addressing root causes of loss such as restoring water quality (reducing pollution and nutrient runoff), encouraging water circulation (removing dams that drain salt marshes), or actively restoring and assisting natural regeneration (through mangrove seeding or planting interventions).[33]

Based on our geospatial analysis and projections toward 2050, we estimate that in aggregate, conserving and restoring mangroves, seagrass, and salt marshes could account for about 40 percent of the total blue-carbon potential.[34] Protecting existing ecosystems avoids about 0.2 to 0.35 $GtCO_2e$ per year of emissions, and restoring these ecosystems offers an additional 0.2 to 0.85 $GtCO_2e$ per year of sequestration between now and 2050. While costs vary widely among projects, we estimate that the cost of protecting ecosystems is vastly lower (on average under $6 per avoided metric ton of carbon dioxide [tCO_2] emissions) than the cost of restoring lost or degraded ecosystems ($15 to $250 per sequestered tCO_2). Still, our estimates are tempered by uncertainty about historical mangrove coverage and our conservative approach to defining feasible restoration. The lower-end estimate of the potential for restoration is based on our analysis, which only includes areas lost since 1996.

Emerging solutions: Kelp forests and fisheries

Among emerging solutions, we include those for which there is an existing body of peer-reviewed research to quantify CO_2 abatement potential—albeit with open questions—and those for which further research is required to meet one or more of the Core Carbon Principles. We also include solutions for which a carbon development methodology currently does not exist. Activities to protect, restore, or extend seaweed biomes or to manage bottom trawling fall into this category.

Deep dive: Kelp forests

Seaweed ecosystems currently cover about 3.4 million square kilometers of ocean terrain,[35] with 1.5 million square kilometers[36] of that likely containing kelp—a prolific plant that can grow by as much as two feet per day.[37] This extraordinary productivity means kelp forests rival land-based rainforests in terms of carbon captured per area.[38] However, unlike mangroves, seagrass, or salt marshes, which sequester carbon in their soil, only a fraction of seaweed and kelp biomass offers that benefit. This distinction matters: carbon stored in the soil is in most cases removed from the atmosphere for a long period, while a large portion of the carbon captured in seaweed may disintegrate and become atmospheric again in the near term. Nonetheless, research estimates that seaweeds globally sequester an estimated 0.6 (in the range of 0.2 to 1.0) $GtCO_2e$ per year[39] in seafloor sediments; kelp forests potentially contribute one-third of that total, based on sequestration rates of 1.4 tCO_2 per hectare of kelp per year.[40]

Kelp forests have been destroyed in recent decades by pollution, ecological shock from human activities, and warming ocean temperatures, which undermine the circulation of nutrients required for growth. Globally, some 40 percent of growing regions have been in decline.[41] Indirect causes have also played a role. In one case, collapsing sea otter populations in Alaska in the 1990s led to explosive growth in sea urchins (the otters' usual prey). These sea urchins, in turn, overgrazed kelp forests. Based on the rate of gross loss, we estimate kelp remediation efforts could contribute up to 0.04 $GtCO_2e$ per year of carbon sequestration (see sidebar, "Methodology").

Methodology

To inform our research, we spoke with more than 15 blue-carbon experts to gather the most authoritative views on a relatively new area of research. We based the abatement potential ranges primarily on a scientific review paper of established solutions (Macreadie et al., 2021) and our own geospatial analysis.[1] Here is how we approached our calculations:

Mangroves: We calculate loss of cover from 1996 to 2016 (0.6 million hectares [Mha] restoration potential) based on Global Mangrove Watch and Griscom et al. 2020[2] and extrapolate the constant gross annual loss rate per country, calculating the area that would be lost by 2050 (1.3 Mha). We cap this avoided loss at a maximum of 70 percent of the current mangrove area; we assume the remaining amount will be included in protected areas by 2050.3 Carbon impact is based on 23.5 metric tons of carbon dioxide (tCO_2) per hectare per year for restoration and 42.9 tCO_2 per hectare per year for avoided loss. Cost of protection and restoration is assessed from existing research and expert interviews.[4]

Seagrasses: We use data from Ocean Health Index Science on the global distribution of seagrass meadows in 2012. We obtain total and annual loss rates from literature review.[5] Seagrass loss (29 percent since the beginning of the 20th century) is used to obtain the restoration area potential (11.8 Mha). Projection of a constant 1.1 percent annual gross loss rate out to 2050 (capped at 70 percent of ecosystem extent) is used to estimate the area of avoided loss (9.5 Mha). These are converted to carbon sequestration potentials using 12.5 tCO_2 per hectare per year for restoration and 17.4 tCO_2 per hectare per year for avoided loss. Cost estimate based on median of restoration costs reviewed by Bayraktarov 2015.[6] There is potential for these costs to come down as, for example, restoration processes increase in efficiency or make greater use of community volunteer support. We assume protection cost to be similar to mangrove or salt-marsh protection.

Salt marsh: Our calculations of abatement potential by 2050 are based on average reported estimates by the World Resources Institute's report, *The ocean as a solution to climate change: Five opportunities for action.*[7] We assume protection costs to be similar to mangrove and salt-marsh protection. Restoration costs are based on median cost per hectare from Taillardat et al. 2020.[8]

1 Peter Macreadie et al., "Blue carbon as a natural climate solution," *Nature Reviews Earth & Environment*, November 2021, Volume 2.
2 Bronson W. Griscom et al., "National mitigation potential from natural climate solutions in the tropics," *Philosophical Transactions of the Royal Society B*, 2020, Volume 375, Number 1794.
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5 Linwood Pendleton et al., "Estimating global 'blue carbon' emissions from conversion and degradation of vegetated coastal ecosystems," *PLOS ONE*, September 2012, Volume 7, Number 9; Bronson W. Griscom et al., "Natural climate solutions," *Proceedings of the National Academy of Sciences (PNAS)*, October 2017, Volume 114, Number 44.
6 Elisa Bayraktarov et al., "The cost and feasibility of marine coastal restoration," *Ecological Applications*, November 2015, Volume 26, Number 4.
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8 "Climate change mitigation potential," 2020.

Methodology (continued)

Kelp forests: We calculate the extent of potential losses based on global patterns of changes in kelp forest over the past several decades.[9] Based on the observed 7 percent per annum declines across 38 percent of assessed kelp habitat regions, we project a 90 percent decline in global kelp abundance by 2050 across these regions. (We do not consider the potential natural growth of kelp abundance because this is outside the control of nature-based actions.) We assume 70 percent of the loss can be avoided by implementing protection and restoration interventions in equal measure, and we use a carbon sink rate of 1.4 tCO_2 per hectare per year.[10] The kelp restoration cost estimate is based on the median restoration cost of a limited number of projects reported by Eger et al. 2020.[11]

Seaweed farming: Our calculated potential by 2050 is based on growth scenario estimates reported in *The ocean as a solution to climate change: Five opportunities for action*, in which seaweed farming is projected to grow as much as 14 percent per year and 100 percent of production is sequestered.[12]

Bottom-trawling sediment emissions: We based our calculations on the global estimate of (aqueous) CO_2 emissions from bottom-trawling disturbances per 55-by-55-kilometer pixels from Sala et al. 2019.[13] For a conservative lower-bound estimate, we consider only bottom-trawling emissions shallower than 50 meters, and we apply the long-term emissions rate factor of 40 percent, based on repeat trawling activity, to estimate the avoided emissions per year by 2050. The nature-based solution implementation cost is estimated by the opportunity cost of forgone demersal fishing, based on geospatial demersal fish catch data in Sea Around Us using a global average value of $1,626 per metric ton of landings.[14] For each exclusive economic zone (EEZ), we filter out the 10 percent of pixels with the highest demersal fishing value per tCO_2 emissions; the emissions and fishing value across the remaining areas are aggregated to compute average opportunity costs by national EEZs.

9 Kira A. Krumhansl et al., “Global patterns of kelp forest change over the past half-century,” *PNAS*, November 2016, Volume 113, Number 48.
10 Karen Filbee-Dexter and Thomas Wernberg, “Substantial blue carbon in overlooked Australian kelp forests,” *Scientific Reports*, July 2020, Volume 10, Number 12341.
11 Aaron M. Eger et al., “Financial and institutional support are important for large-scale kelp forest restoration,” *Frontiers in Marine Science*, September 2020, Volume 7, Number 81.
12 Ibid.
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14 M.L.D. Palomares, D. Pauly, and D. Zeller, Sea Around Us, accessed March 17, 2022.

Remediation efforts for kelp forests could focus on protection (for instance, from overharvesting) and restoration by improving water quality and assisting natural recovery (by culling grazing populations such as urchins, as in the above example). However, such efforts face three challenges. First, measuring and tracking the amount of carbon sequestered by a particular kelp forest is not yet possible, largely due to the propensity of kelp to drift. Second, depending on the type of intervention required, kelp NBS can be expensive. For example, while grazer control is relatively affordable, transplanting or assisted replanting is typically much more costly. Existing kelp restoration efforts range between $21 and $10,000 (median $6,400) per tCO_2 abated, based on published costs-per-area data.[42] Finally, the science related to the impact of climate change on kelp growth is uncertain, which calls into question the long-term viability of kelp projects.

Another option is to farm kelp, expanding forests beyond their current natural boundaries. This approach would involve growing seaweed on artificial structures that are anchored in coastal regions or floating in the open ocean. Seaweed farming can abate carbon via two routes:

— growing biomass and sinking it to great depths (typically below 1,000 meters), likely removing its carbon from the atmosphere for centuries

— growing biomass and harvesting it for human or livestock consumption, biofuels, and other products

The second approach would not capture carbon permanently in the ocean system but might reduce carbon in total because it could displace more carbon-intensive activities or fossil fuels. In one example, researchers have recently seen indications that the addition of the red seaweed *Asparagopsis taxiformis* to cattle feed may cut the cattle's enteric methane emissions (a powerful greenhouse gas) by as much as 90 percent.[43] Farmed seaweed may also be used in bioenergy with carbon capture and storage (BECCS) systems, which may increase the permanence of the removed carbon.[44]

Based on pilot studies and scientific assessments of the likely carbon sequestered per unit of ocean area cultivated, we estimate the cost of farming and sinking to be around $200 to $300 per tCO_2 abated (see sidebar, "Methodology"). However, several projects aim to leverage economies of scale and technical advances to reduce the cost to about $50 to $80 per metric ton. These projects use low-cost substrate solutions or active nutrient circulation through wave- and solar-powered deep-water pumps that were recently developed by the Climate Foundation.[45]

If the cost of offshore seaweed farming can be reduced, there is almost no limit to the theoretical potential of ocean afforestation given the ocean's vast size, contingent on the implementation effort and timeline required, as well as the availability of substrate material and natural nutrients. Still, there may be "unknown unknowns"—for example, regarding the impact of kelp farms on ecosystems. This uncertainty suggests that piloting is likely the most practical way forward.

Given that costs are still relatively high, here we consider what it would require for seaweed farming to sequester 1.0 $GtCO_2e$ per year. We find this rate of sequestration would require 0.9 million square kilometers, roughly 40.0 percent of the space currently taken up by wheat farming on land. Across the ocean, given suitable temperatures, nutrient levels, depths exceeding 1,000 meters (to facilitate deep sinking), and low shipping traffic, and assuming 30.0 percent of the ocean area is used for conservation, seaweed farming under this scenario would require just 1.7 percent of the remaining suitable ocean space. At that level, space may not be the constraint. In a scenario of industry growth of about 15.0 percent per year, as described by the High Level Panel for a Sustainable Ocean Economy, seaweed farming could sequester approximately 0.3 $GtCO_2e$ per year by 2050.[46]

The technical feasibility and ecological impact of large-scale implementation have yet to be fully assessed. However, there are potential co-benefits. Seaweed aquaculture could help reduce acidification and clean up excessive nutrient concentrations in coastal regions, such as parts of the Gulf of Mexico, which are plagued by toxic algae blooms and oxygen-depleted "dead zones."[47]

Attendant risks and uncertainties remain. For example, nutrients absorbed by large-scale seaweed farming in the open ocean might instead have fueled phytoplankton growth, in which case the carbon sequestration of seaweed farming is not fully additional and its net effectiveness as an NBS could be reduced.[48] Another risk that remains to be assessed, ideally by launching and closely monitoring pilot farms, is the ecological impact on marine life of large floating artificial structures.

Deep dive: Bottom trawling
Bottom trawling is a fishing method that involves dragging weighted nets across the sea floor. This practice stirs up carbon-rich sediments and releases them back into ocean waters and potentially the atmosphere. Improved management of the process may provide a route to sequestration.[49] However, the solution will require further modeling and research to establish the volume of carbon released and the portion that eventually ends up affecting CO_2 concentration in the atmosphere (and can therefore be counted as an abatable emission). Beyond scientific certainty, access to VCM funding might also require concerted multistakeholder approaches and policy action to ensure that reduction in bottom trawling in one area does not transfer that activity to other geographies, disregarding the carbon principles of additionality and avoided leakage.

Early peer-reviewed research indicates that the climate impact of bottom trawling may be significant. Experts estimate that up to 1.5 $GtCO_2e$ per year are currently emitted into the water by bottom trawling.[50] However, emissions are likely to decline over time as repeat disturbances deplete the carbon in sediments. In addition, some researchers have suggested that carbon disturbed at greater depths may be less likely to be emitted into the atmosphere. Still, if we assume that only carbon disturbed at depths shallower than

If the full societal benefits of improved fishery management were accounted for, including yields, subsidies, and other ecosystem services, the solution might come at negative marginal cost.

50.0 meters (which is assumed to be in contact with the atmosphere at least once each year)[51] becomes atmospheric, we find that the long-term (2030 to 2050) impact of bottom trawling may still be 0.36 $GtCO_2e$ per year, if the early findings are confirmed by other scientific studies.

Our analysis indicates that carbon credits at a relatively modest carbon price ($18 per tCO_2) could be a useful incentive to support a transition away from bottom trawling. Fisheries management is often poorly implemented, and the world currently lacks the political will to support its implementation, especially in the high seas. Theoretically, however, by selectively fishing only the highest-yielding grounds, fisheries could land approximately 80 percent of the global bottom-trawling catch by value, while about 95 percent of the seafloor carbon emissions in the top 50 meters could be avoided. That amount represents about 60 percent of current bottom-trawling emissions.

Nascent solutions: Marine-fauna protection

The “nascent” blue-carbon NBS category—which might have the greatest potential for carbon abatement and sequestration—focuses on the protection or restoration of marine-fauna populations. There are several ways in which abundant marine fauna may have beneficial carbon effects.[52] The first is based on the simple fact that a fish is about 10 percent carbon by weight. In a scenario in which commercially targeted fish populations are allowed to grow to ecosystem “carrying capacity” in 30 percent of oceanic area,[53] the fourfold increase in predominantly epipelagic fish populations in these areas by 2050 would accumulate an additional 0.9 $GtCO_2e$ in their bodies.[54]

While fish themselves are not considered a form of long-term carbon sequestration, they can contribute to the effectiveness of the biological carbon pump and therefore to the export of carbon into the deep sea. Fish also excrete “marine snow”—carbon-rich waste that falls out of the surface layer—and these sinking particles are critical to regulating how much carbon the ocean sequesters in deep waters and sediments.[55] While research to quantify sedimentation effects is ongoing, fish are estimated to remove 1.5 $GtCO_2e$ per year out of the sunlit zone.[56] If the full societal benefits of improved fishery management were accounted for, including yields, subsidies, and other ecosystem services, the solution might come at negative marginal cost.

Notably, mesopelagic fish, living between the sunlit surface layer and the deep ocean, may play a significant role in vertical carbon transport, essentially taking carbon in the form of food from ocean layers where it could become atmospheric and transporting it to longer-term storage at depth. Mesopelagic fish are currently not consumed by humans at scale—but if that were to change (as is being considered), there could be a significant impact on the ocean's capacity to sequester carbon.[57]

Another impact of an abundant marine-fauna biomass would be the potential increase in fertilization of photosynthetic carbon-capturing plankton, which could increase the amount of carbon moved each year from the surface layer into the deep ocean. The fecal plumes produced by whales, for example, are rich in the nutrients that phytoplankton need to grow. Sometimes referred to as "ecosystem engineers," large whales and whales that feed in the deep may be particularly significant in this respect because they migrate long distances across otherwise low-nutrient ocean areas, surfacing nutrients in the process.[58] Speculatively, if fully recovered global populations of whales were to bump up phytoplankton growth and sequestration by 1 percent, the phytoplankton would help sequester one to two $GtCO_2e$ per year.[59]

Healthy predator populations also contribute to carbon sequestration by preventing herbivores from overgrazing and eroding coastal vegetated ecosystems. Recent research suggests that the loss of predators such as sharks (or more mundanely, Atlantic blue crabs, which are of equal impact in certain salt-marsh regions) can lead to reductions of carbon burial in ocean ecosystems of 20 to 90 percent. When declines in marine predators lead to the erosion of just 1.0 percent of vegetated coastal ecosystems, about 0.5 $GtCO_2e$ is released.[60]

Finally, healthy reefs may contribute to carbon sequestration in indirect ways. Even though the calcifying growth phase of coral reefs and shells is associated with emissions of carbon dioxide, those emissions may be more than offset by the carbon sequestered throughout the organism's lifetime that is buried in surrounding sediments or that sustains neighboring seagrass beds—consequences impossible without the healthy reef. For example, oysters and other shellfish capture and digest carbon-rich particles filtered out of the seawater and deposit them into sediments.[61] Restoration efforts can help oyster reefs globally—85 percent of which have been lost—and these efforts may become a valuable blue-carbon solution if the net-carbon impact can be better quantified.[62]

Financing blue-carbon solutions

Most of the $270 billion annual carbon market comes from government mandated schemes such as the European Union's vast Emissions Trading System (EU ETS), which caps high-emitting sector emissions and requires companies above their limits to buy carbon credits. VCMs, conversely, are worth just $1 billion annually and remain in a process of development amid fuzzy accounting for carbon credits.[63] Indeed, just 0.001 $GtCO_2e$ (0.7 percent) of NBS credits have been issued on VCM since 2013.

Multilateral and development-assistance agencies can fund innovative and scalable programs. For example, members at the 2021 UN Climate Change Conference in Glasgow (COP26) made significant progress when they ratified Article 6 of the Paris Agreement, which focuses on how countries can "pursue voluntary cooperation" to meet their climate targets. Work to flesh out the implementation details—for example, by defining which activities can generate credits—is ongoing.

Under Article 6, countries can use emissions trading to pursue their nationally determined contributions (NDCs) and move toward their 2030 emissions-reduction targets under the Paris Agreement. Paragraph 6.4 makes the United Nations a certifier of carbon projects that can generate credits for NDCs. Meanwhile, paragraph 6.2 sets out the rules by which countries can exchange internationally transferred mitigation outcomes (ITMOs). These can be measured in metric tons of carbon dioxide equivalent (CO_2e) or in other metrics, such as kilowatt-hours (KWh) of renewable energy.

The process prevents most, but not all, cases of double counting, in which a carbon emissions reduction is counted toward the NDC of both the project supplier country and the country of the credit buyer. It may not prevent double claiming, in which an emissions reduction is claimed both by a supplier country (and thus counted toward its NDC) and by a private-sector credit buyer that financed the project and also claims the emissions reduction toward their private target (but it does not count toward the NDC of the country of the buyer). Double claiming is a conviction-based issue: some buyers may wish to contribute to supply countries' NDCs when they use voluntary carbon markets. These buyers may take the view that double claiming by a country and a corporate is not an issue. These buyers may also take an optimistic approach that supplier countries will in either case apply their maximum efforts toward climate change.

The process may also implicitly link part of the overall voluntary carbon market to the NDC scheme. Fair accounting provisions may also provide VCMs with a boost.

Ahead of Article 6, national and regional authorities around the world had already established some 31 emissions-trading schemes as climate-policy instruments.[64] The largest of these compliance markets is the EU ETS, which launched in 2005 and operates in 31 countries. The scheme limits emissions from more than 11,000 installations and airlines and covers about 45 percent of the European Union's greenhouse-gas (GHG) emissions. As part of the European Green Deal, climate legislation will be updated to raise the European Union's 2030 GHG emissions-reduction target to at least 55 percent from 1990 levels, compared with 40 percent previously.

Compliance markets and voluntary markets tend to attract different users. While the former is a focus for major emitters such as energy companies and airlines, the latter attracts all types of organizations, including private companies and NGOs. The two markets are also of opposing scales. The value of traded global markets for CO_2 permits grew by 164 percent to a record €760 billion ($851 billion) in 2021, according to Refinitiv.[65] The EU ETS accounted for 90 percent of the total. By contrast, trading in voluntary markets was around $1 billion. Still, McKinsey predicts that global demand for voluntary carbon credits could increase by a factor of 15 by 2030 and by a factor of 100 by 2050.[66]

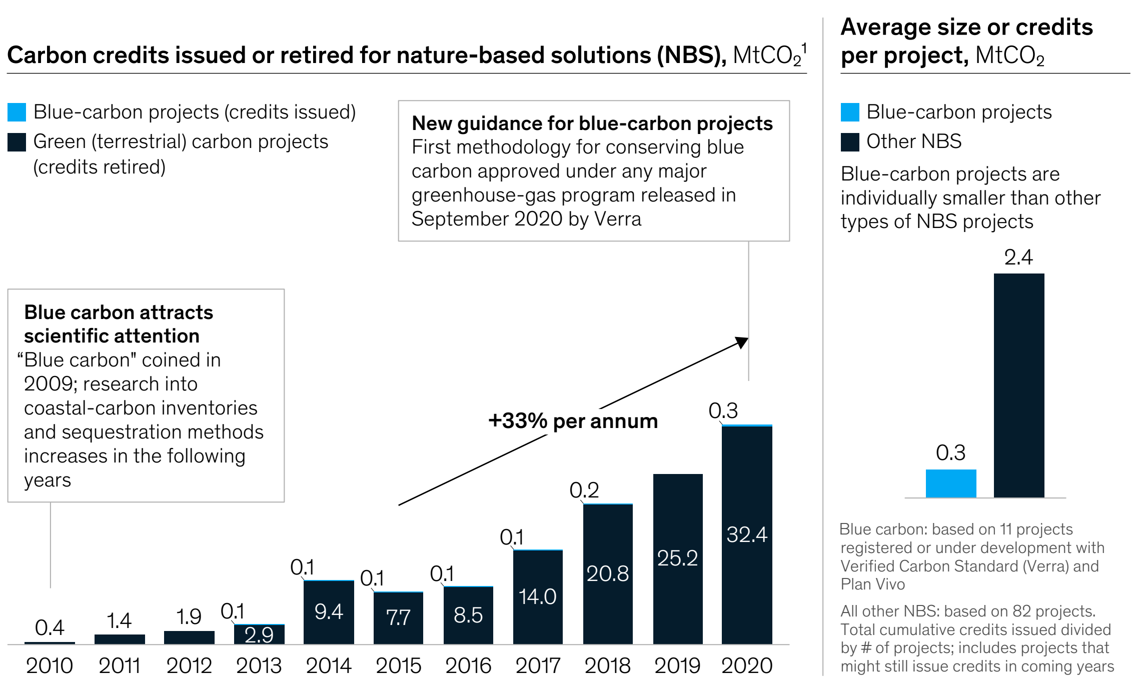
One limitation to including blue-carbon solutions in carbon emissions markets is that only a few projects have been launched to date. By 2020, five projects were registered under approved methodologies, and all five are fairly small scale: the current average project size is 0.3 million tCO_2e over the project lifetime, compared with 2.4 million tCO_2e for other NBS (Exhibit 4). In addition, multiple challenges remain in meeting carbon offset criteria, including establishing certainty around the permanence of solutions (Exhibit 5).

Still, we expect the number of projects to increase, driven in part by Article 6 and the publication of new VCM methodologies for both avoided loss and restoration. For example, a revision to the Verified Carbon Standard REDD+ Methodology Framework adds blue-carbon conservation and restoration activities as eligible project types.[67] This shift will enable monetization of all coastal wetland conservation and restoration activities.

continued on page 22

Exhibit 4

Blue-carbon projects lag in scale compared with other types of nature-based solutions on voluntary carbon markets.



[1]Metric megatons carbon dioxide. One metric megaton = one million metric tons.
Source: American Carbon Registry; Catherine E. Lovelock and Carlos M. Duarte, 2019; Climate Action Reserve; The Gold Standard; Plan Vivo; Verra

Exhibit 5

Established blue-carbon solutions have access to voluntary carbon markets (VCMs), but projects face challenges.

Blue-carbon stock or sink maturity: ■ Established VCM methodologies exist ■ Emerging; potential future VCM access ■ Nascent; unlikely future VCM access

(!) Challenge to satisfy offset credit criteria ✓ Criteria typically not a challenge to fulfill

Mangroves, seagrass, salt marsh

Solution: Restore carbon sink

Challenges faced by projects in satisfying offset credit criteria

✓ **Real**	(!) **Permanent** Long-term viability affected by multiple stressors, incl climate change (eg, sea level rise, warming); can account for long-term uncertainty with, eg, buffer system or metric ton–year accounting approach
✓ **Additionality[1] based on credible baselines**	✓ **Leakage**
(!) **Monitored, reported, and verified** Potentially high costs to monitor and verify carbon sequestered in sediments, especially those of large underwater seagrass meadows	(!) **Counted once** If on public land or in marine jurisdiction; accounting process outlined by Article 6 prevents most, but not all, cases of double counting, but not double claiming
✓ **No net harm**	

Implementation changes

Large dependence on upstream or nonlocal environmental factors (eg, pollution and warming affecting viability of seagrass restoration)

Large up-front costs before credit issuance

Key new opportunities

- Implement latest science-based standard restoration methods to increase project success rates
- Consider methodologies to support required upstream interventions, eg, runoff nutrient load reduction

Solution: Avoid loss of carbon stock and sink (eg, halt deforestation, development, and pollution)

Challenges faced by projects in satisfying offset credit criteria

✓ **Real**	(!) **Permanent** Depends on continued protection; uncertainty can be addressed with, eg, buffer system
(!) **Additionality based on credible baselines** Projects can face similar challenges to REDD+,[2] eg, additionality depends on assumptions of future socioeconomic incentives and environmental policy; for seagrass, limited data on historical extent	(!) **Leakage** Can be an issue for small-scale, fragmented projects
✓ **Monitored, reported, and verified**	(!) **Counted once** Pending further Article 6 negotiations on whether emissions avoidance credits (eg, project-based and/or jurisdictional REDD+) may be internationally traded and counted toward NDCs
✓ **No net harm**	

Implementation changes

Typically involves many stakeholders and requires multifaceted community-led development projects to address underlying drivers of destruction and unsustainable use; in some cases, lack of clear ownership or carbon rights within the tidal zone can pose challenges

Key new opportunities

- Large-scale jurisdictional approach to facilitate baseline setting, avoid leakage, and address nonlocal upstream threats
- Project bundling approach and cost-efficient remote monitoring to decrease verification cost per credit
- Consider methodologies to support required upstream interventions, eg, runoff nutrient load reduction

[1] The ecosystem would have been degraded if not for the action described.
[2] Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries.

Exhibit 5

Established blue-carbon solutions have access to voluntary carbon markets (VCMs), but projects face challenges. (continued)

Blue-carbon stock or sink maturity: ■ Established VCM methodologies exist ■ Emerging; potential future VCM access ■ Nascent; unlikely future VCM access

(!) Challenge to satisfy offset credit criteria ✓ Criteria typically not a challenge to fulfill

Macroalgae

Solution: Avoid loss of, and restore, kelp forests (eg, avoid overharvest or pollution, control grazers, transplant)

Challenges faced by projects in satisfying offset credit criteria

✓ **Real**	(!) **Permanent** Limited to fraction of carbon biomass exported to sediments (nonlocal)
(!) **Additionality based on credible baselines** Limited historical data	✓ **Leakage**
(!) **Monitored, reported, and verified** Complex due to the dispersal of carbon biomass to nonlocal sinks	(!) **Counted once** Similar issues faced by coastal blue-carbon projects
✓ **No net harm**	

Implementation changes

Large dependence on upstream or nonlocal environmental factors (eg, pollution and warming)

Non-standardized, context-dependent restoration

Key new opportunities

- Map extent and trends of kelp ecosystems
- Model carbon sequestration of kelp in nonlocal sinks
- Develop cost models for restoration

Solution: Farm and sequester biomass (via sinking)

Challenges faced by projects in satisfying offset credit criteria

✓ **Real**	(!) **Permanent** Likely 100-year duration if sunk below 1,000 meters
(!) **Additionality based on credible baselines** Additionality depends on role of limited nutrients in counterfactual scenarios	✓ **Leakage**
(!) **Monitored, reported, and verified** Requires process monitoring and likely requires modeling	(!) **Counted once** Requires clear rules about attribution between farm operator and sediment jurisdiction
(!) **No net harm** Uncertain ecological impact of large-scale farms and large-scale, deep-sea sinking	

Implementation changes

Unproven technical viability and financial requirements of large-scale or offshore farming

Key new opportunities

- Conduct pilot projects to verify sequestration models and study environmental impacts
- Develop methods to mitigate impacts on ecology and commerce
- Establish policy framework regulating large-scale biomass sinking at sea

Exhibit 5

Established blue-carbon solutions have access to voluntary carbon markets (VCMs), but projects face challenges. (continued)

Blue-carbon stock or sink maturity: ■ Established VCM methodologies exist ■ Emerging; potential future VCM access ■ Nascent; unlikely future VCM access

(!) Challenge to satisfy offset credit criteria ✓ Criteria typically not a challenge to fulfill

Macroalgae

Solution: Farm and harvest biomass (eg, food consumption, processing as a biofuel)

Challenges faced by projects in satisfying offset credit criteria

✓ **Real**

(!) **Permanent**
Satisfied only for avoided emissions

(!) **Additionality based on credible baselines**
Avoided emissions depend on type of displaced product and production process

✓ **Leakage**

(!) **Monitored, reported, and verified**
Requires process monitoring, likely modeling

(!) **Counted once**
Requires clear rules about attribution between about operator and sediment jurisdiction

(!) **No net harm**
Uncertain ecological impact of large-scale farms and large-scale, deep-sea sinking

Implementation changes

Unproven technical viability and financial requirements of large-scale or offshore farming

Key new opportunities

- Conduct pilot projects to verify sequestration models and study environmental impacts
- Develop methods to mitigate impacts on ecology and commerce

Seafloor sediments

Solution: Avoid emissions from bottom trawling

Challenges faced by projects in satisfying offset credit criteria

(!) **Real**
Requires further scientific validation

(!) **Permanent**
Depends on future fishery policy and regulations

(!) **Additionality based on credible baselines**
Depends on current fishery policy context

(!) **Leakage**
Likely requires EEZ[3] or fleet-wide approach

(!) **Monitored, reported, and verified**
Requires remote monitoring (eg, AIS[4])

(!) **Counted once**
Requires jurisdictional approach; pending further Article 6 negotiations on whether emissions avoidance credits (eg, project-based and/or jurisdictional REDD+) may be internationally traded and counted toward NDCs

✓ **No net harm**

Implementation changes

Jurisdictional approach depends on political support and legislative action

Key new opportunities

- Verify theoretical emissions calculations with direct observations and ocean circulation models

[3] Exclusive economic zone.
[4] Automatic identification system used by ships.

Exhibit 5

Established blue-carbon solutions have access to voluntary carbon markets (VCMs), but projects face challenges. (continued)

Blue-carbon stock or sink maturity: ■ Established VCM methodologies exist ■ Emerging; potential future VCM access ■ Nascent; unlikely future VCM access

(!) Challenge to satisfy offset credit criteria ✓ Criteria typically not a challenge to fulfill

Marine fauna

Solution: Avoid losses of and restore fauna that contribute to deep-sea carbon sequestration via biological carbon pump (eg, whales, mesopelagic fish)

Challenges faced by projects in satisfying offset credit criteria

(!) **Real**
Requires further scientific research on carbon fluxes and export to sediment

(!) **Permanent**
OK for carbon exported to sediments; uncertain impact of climate change on ecology

(!) **Additionality based on credible baselines**
Additionality depends on fishery and biodiversity policy context

(!) **Leakage**
Requires national or regional regulation or treaty to avoid leakage (eg, fishing or hunting outside of protected area)

(!) **Monitored, reported, and verified**
Requires high-confidence stock assessments, likely modeling of deep-sea export

(!) **Counted once**
Requires regional or international approach; pending further Article 6 negotiations on whether emissions avoidance credits (eg, project-based and/or jurisdictional REDD+) may be internationally traded and counted toward NDCs

✓ **No net harm**

Implementation changes

Place-based protection (eg, MPAs[5]); cannot guarantee protection of migratory and mobile species

Nonlocal interventions to reduce global mortality (eg, bycatch reduction); can only support but not guarantee recovery

Key new opportunities

- Develop low-cost sensors and monitoring technology to quantify carbon sequestration of marine fauna, incl secondary impacts on carbon sinks, and to improve stock assessments of fauna
- Model sequestration impact of potential protection and recovery interventions, eg, MPAs, collision avoidance, entanglement avoidance

[5] Marine protected areas.

Nascent solutions such as protection and restoration of marine fauna may ultimately contribute significantly to carbon sequestration, But such solutions are unlikely to gain access to VCM funding in the near term because there are challenges in aligning these solutions with several of the Core Carbon Principles, which were developed to facilitate VCM funding. Scientific uncertainties remain about matters such as the proportion of carbon accumulated and cycled by marine fauna that becomes sequestered in sediments. Additionality and avoiding leakage are hard to demonstrate: reducing fishing in one area to allow populations to restore may simply shift fishing to other areas. Even if fishing itself does not shift, fish populations do, and the migratory nature of many fish and mammal populations further complicates additionality claims. It can also be difficult to prove with certainty the causality between human intervention and fish population growth or decline.

Even if a project can meet the requirements of the Core Carbon Principles, attribution can be challenging. The vast potential of nascent blue-carbon NBS is offshore—with sometimes overlapping and context-dependent jurisdictions and public domains that lack straightforward carbon rights concepts for private property. On the other hand, the fact that fishing is heavily subsidized would mean that the cost of abatement is likely, in effect, to be low or even negative.

Keys to unlocking blue-carbon markets

Just as they access carbon markets for terrestrial projects, companies and other organizations could employ blue-carbon, nature-based solutions to meet their net-zero targets. Right now, they struggle to do so widely. Reasons for this struggle include the difficult risk/return profiles and timelines of blue-carbon projects and the simple lack of awareness regarding these solutions. (Fewer people know about the problem of seagrass degradation than about tropical deforestation.) For emerging and nascent blue-carbon solutions farther out to sea, a complex legal and jurisdictional environment further challenges investment. While nations control living and nonliving marine resources for up to 200 nautical miles beyond their coastlines, numerous subnational regulatory and administrative agencies frequently overlap, especially in the liminal space of coastal wetlands.[68]

All of these challenges are worth addressing. Not only do blue-carbon solutions add multiple metric gigatons of potential abatement to our global set of climate interventions, but they do so with significant biodiversity and coastal-community co-benefits. Stakeholders across sectors can take action to scale blue-carbon solutions to their full potential, accepting a more challenging early investment profile in recognition of the critical need to unlock this part of the climate equation.

Next steps for financial institutions, companies, and governments

To facilitate increased investment in blue-carbon solutions, stakeholders need to tackle bottlenecks within financial institutions, companies, and governments.

At many financial institutions, portfolio allocation strategies limit investment in new asset classes, and institutions struggle to attract the capabilities required to assess and manage the accompanying risks. Blue-carbon ticket sizes and deal flows tend to be small compared to the effort required, and the expected financial return relative to risk is less attractive than for incumbent environmental, social, and governance (ESG) investments. To resolve these challenges, financial institutions can layer blue carbon into portfolio allocation frameworks and source the knowledge resources that can help them navigate new markets.

A significant uncertainty relates to risk/return profiles, and certainly the early evidence is that blue-carbon projects are relatively long-term propositions to scale. For the world's largest seagrass restoration project, in Virginia, researchers and volunteers took the best part of two decades to spread more than 70 million seeds to bring back eelgrass and restore 3,600 hectares of a devastated ecosystem.[69] The necessary acceleration of such investments may require a venture capital risk appetite combined with infrastructure return timelines—but they can result in outsize catalytic impact by creating replicable projects. Engagement on such early projects may build up technical capabilities that can position investors well to reap benefits as solutions scale and timelines improve.

Corporate demand

Companies looking to offset their carbon emissions should follow similar trajectories to those of financial institutions and be driven by ambitions for impact, with a higher tolerance for risk. Companies can create early momentum by partnering with leading local and global NGOs to fund project development or provide in-kind support such as remote sensing and AI-powered analytics. Potential applications include measuring CO_2 concentrations around floating offshore seaweed farms or bottom-trawled nets.

By supporting project leads in designing, piloting, and demonstrating projects in fast-growing segments such as seaweed farming and by publicizing their early successes, companies can establish a track record to grow the market. For some, such as those engaged in cruising and other consumer-facing ocean industries, the attraction of ocean-based offsets is clear.

To stimulate development of the established solutions category, several companies are already collaborating with conservation organizations to provide financing for research and pilots. For example, Apple[70] and Conservation International have collaborated to preserve a 27,000-acre mangrove forest in Colombia.[71] The first fully accounted carbon offset credit for mangroves, the forest is expected to sequester one million tCO_2 over its lifetime. Procter & Gamble partnered with Conservation International to safeguard 31 species of mangroves as part of the Philippines Palawan Protection Project.

The role of governments

Governments have a role to play in scaling up funding, especially for early-stage research and development, mirroring the work of the US Advanced Research Projects Agency-Energy (ARPA-E) which promotes and funds research of advanced energy technologies. Finalizing the terms related to Article 6 would be a good first step so that cap-and-trade emissions schemes can play a more significant role. Governments could also signal support for blue-carbon solutions by including them in nationally determined contributions under the Paris Agreement. This support could help spur more public finance and policies to enable larger-scale, jurisdictional approaches.

Jurisdictional approaches could also enable broader access to VCM. For example, governments could establish frameworks for conservation projects—such as marine protected areas with specific carbon objectives—in regions with the highest potential for abatement. This approach would facilitate baseline setting, avoid leakage, and enable bundling of projects, which in turn would reduce operational and transaction costs per credit. Government-led initiatives are also crucial to address regional threats such as coastal pollution or nutrient runoff and to enable international regulatory frameworks and research into high-seas initiatives such as seaweed sinking.

Based on an emerging body of research, blue carbon presents a significant latent source of abatement potential. Although investments in blue-carbon solutions through the carbon markets are challenged by subscale supply, scientific uncertainties, and high costs, the scale of the solution is too large to ignore. Concerted action is required, and stakeholders should collaborate to build momentum through demand signals and investments in technology and science. There is work to do, but the direction is clear: consideration of blue-carbon solutions is both merited and recommended.

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4 Estimate based on emerging and evolving science and the assumptions we outline in this report; $18 per metric ton of carbon dioxide (tCO_2) based on opportunity cost of lower-end estimate of bottom-trawling impact (about 0.4 metric gigatons [Gt]) in the emerging category. If bottom trawling is confirmed at full potential (about 1.5 Gt), price viability for large portion of abatement potential could drop to approximately $11 per metric ton.

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