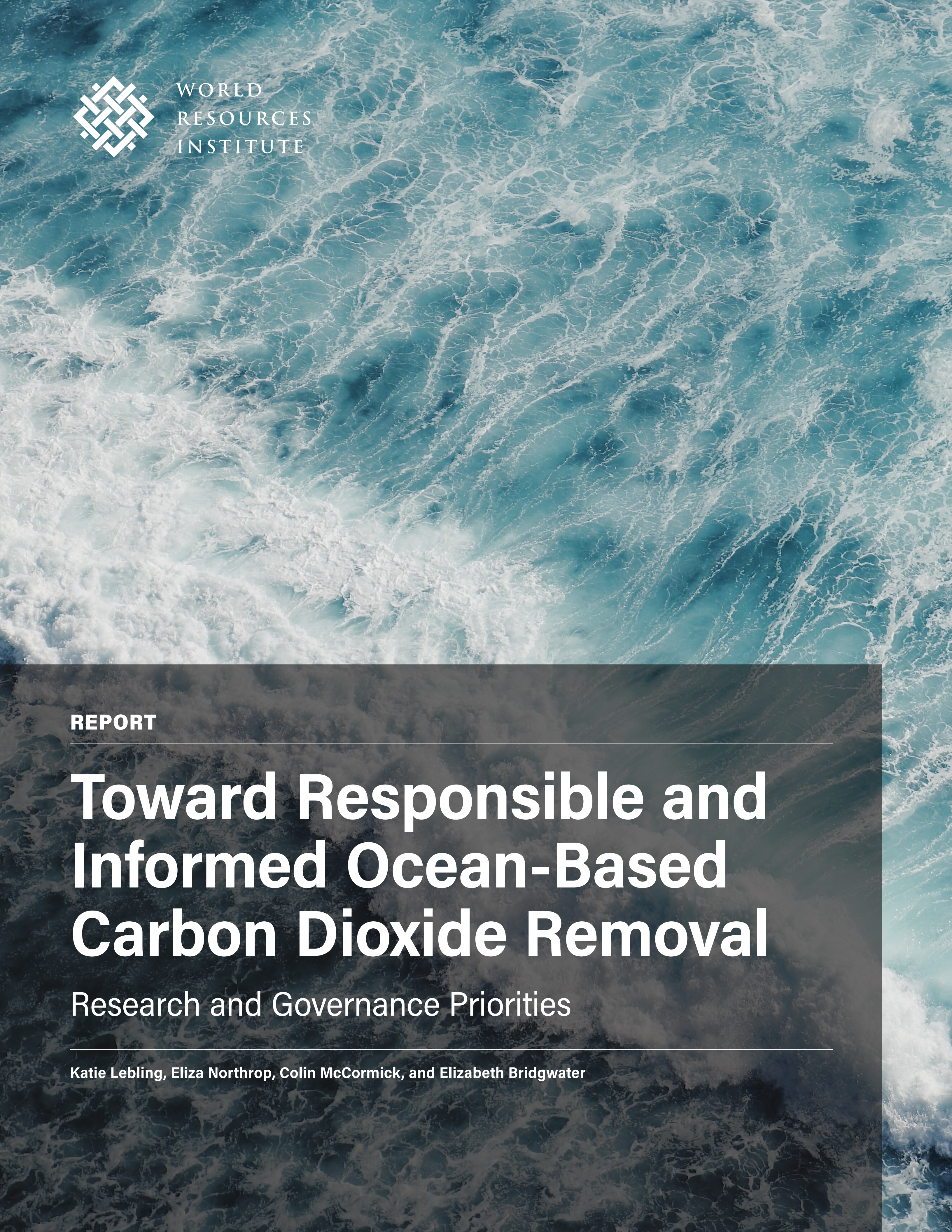


WORLD
RESOURCES
INSTITUTE

REPORT

Toward Responsible and Informed Ocean-Based Carbon Dioxide Removal

Research and Governance Priorities

Katie Lebling, Eliza Northrop, Colin McCormick, and Elizabeth Bridgwater

AUTHORS

KATIE LEBLING
is an associate in WRI's Climate Program, where she focuses on research and analysis to accelerate sustainable and equitable scale up of carbon removal technologies.

Contact: katie.lebling@wri.org

ELIZA NORTHROP
is the Policy Lead for WRI's Global Ocean Program, currently leading the Program's work on ocean-based climate solutions and supporting the Secretariat to the High Level Panel for a Sustainable Ocean Economy.

Contact: eliza.northrop@wri.org

COLIN MCCORMICK
is an adjunct professor in the Science, Technology and International Affairs program at the Walsh School of Foreign Service, Georgetown University, and the chief innovation officer at Carbon Direct.

Contact: colin.mccormick@georgetown.edu

ELIZABETH BRIDGWATER
was a research analyst in WRI's Climate Program, where her work focused on carbon dioxide removal and U.S. subnational climate action.

Contact: bridgwater.elizabeth@gmail.com

DESIGN AND LAYOUT

BILLIE KANFER
billiek.designs@gmail.com

ACKNOWLEDGMENTS

The authors would like to acknowledge the following people for their guidance, critical reviews, and research support:

We thank our internal WRI reviewers who have shared their expertise and insights: Angela Anderson, Jonathan Baines, Cynthia Elliott, Taryn Fransen, Rizky Haryanto, Haley Leslie-Bole, Jillian Neuberger, Maria Potouroglou, and David Waskow. We are grateful to our external reviewers for their time and expertise: Brad Ack, Chelsey Baker, Wil Burns, Sarah Cooley, Rebecca Loomis, Kelly Levin, Jamey Mulligan, Sam Savitz, and Frances Wang.

While the contributions from reviewers are greatly appreciated, the views presented in this paper are those of the authors alone.

The authors are grateful to Jamey Mulligan for his guidance and leadership on an earlier, unpublished version of this report; to Renata Marston for her research advice; and to Dan Lashof, Kristian Teleki, and Nicola Frost for their reviews and guidance. We also wish to acknowledge WRI colleagues and others for their support in the production of the report, including administrative assistance, editing, graphic design, and layout: Romain Warnault, Renee Pineda, Sarah DeLucia, and Billie Kanfer. We received communications and outreach support from Matt Herbert, John Lyons, and Katie Wood.

This report was made possible through the generous support of ClimateWorks Foundation and William and Flora Hewlett Foundation.

We are also pleased to acknowledge WRI's institutional strategic partners who provide core funding to WRI: the Netherlands Ministry of Foreign Affairs, the Royal Danish Ministry of Foreign Affairs, and the Swedish International Development Cooperation Agency.

SUGGESTED CITATION

Lebling, K., E. Northrop, C. McCormick, and E Bridgwater. 2022. *Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities*. Report. Washington, DC: World Resources Institute.

VERSION 1
November 2022

CONTENTS

Foreword

The ocean is an unsung hero in the fight against climate change—it has already absorbed 30 percent of excess carbon dioxide emissions and 90 percent of excess heat. Without it, we would be experiencing even more severe levels of climate impacts.

But the ocean is also a victim of climate change. Increased acidification and higher temperatures are bleaching corals, shifting the distribution of fish stocks, changing critical ocean circulation patterns, and threatening the livelihoods of billions who depend on a healthy ocean.

As climate change worsens, there is an increasing focus on approaches—both natural and technological—that utilize the ocean for enhanced climate action. Some nascent—and contentious—options leverage the ocean's natural processes to reduce carbon dioxide concentrations in the atmosphere and safely store that carbon in the ocean. Interventions such as the intensive cultivation of seaweed or the addition of crushed alkaline minerals to lock away carbon are gaining increased attention as necessary carbon dioxide removal options to pursue to keep the Paris Agreement goal of 1.5 degrees Celsius within reach.

However, there is a lot we still don't know about these methods and their broader impacts. In addition, the national and international governance frameworks that we rely on to protect and conserve ocean health were not written with these approaches in mind. This report consolidates and synthesizes the current science on ocean-based carbon dioxide removal, highlighting the significant scientific and governance gaps that exist and identifying a pathway forward that is responsible, informed, and equitable.

We must continue to expand the global dialogue and understanding around this quickly evolving topic. Most ocean carbon dioxide removal approaches still have key scientific and technological uncertainties that will need to be resolved, requiring significant increases in funding. At the same time, interdisciplinary dialogues will be critical in examining risks, resolving concerns, and building consensus around priorities. A more robust governance framework with adequate guardrails for testing and potential future large-scale deployment is also needed at the local, national, and international levels. Going forth, it is vital that we balance the enthusiasm for ocean-based carbon dioxide removal approaches with the need for well-resourced and well-governed efforts.

We do not have the luxury of time, so we must work to resolve these uncertainties quickly. But we also have a responsibility to pursue ocean carbon dioxide removal in an informed and equitable manner, one that avoids exacerbating the damage already being done to the ocean's health by warming global temperatures.

ANI DASGUPTA
President and Chief Executive Officer
World Resources Institute

Executive Summary

Ocean carbon dioxide removal approaches have been gaining prominence in international and national climate policy. Yet many of these approaches remain untested with significant scientific gaps and risks to the marine environment and coastal communities. Striking the right balance between the urgency of emission reductions and using appropriate ocean carbon dioxide removal approaches without causing further harm to ocean systems, ecosystems, and coastal communities will require an iterative and adaptive approach that prioritizes responsible and informed development.

HIGHLIGHTS

- The latest science indicates that keeping average global temperature rise to 1.5 degrees Celsius will require large amounts of carbon dioxide removal (CDR), along with deep emissions reductions.
- Ocean-based CDR approaches are receiving increasing attention in plans to achieve net-zero emissions, although most approaches are still in the early stages of development, have a high degree of uncertainty about their efficacy, pose environmental and social risks, and lack sufficient governance to ensure responsible deployment.
- This report distills the potential scale of carbon dioxide removal, expected costs, risks, co-benefits, and areas of research needed for seven ocean CDR approaches.
- It proposes an overall approach centered on informed and responsible development and deployment of ocean CDR that balances the urgency of emissions reductions against the environmental and social risks of ocean CDR, including halting development where risks outweigh expected benefits.
- Significant increases in funding are needed to resolve the scientific and technological uncertainties surrounding ocean CDR approaches, including through at-sea testing.
- Interdisciplinary dialogues are needed to build consensus around priorities, understand risks, and resolve concerns.
- Local, national, and international governance regimes must be clarified and strengthened to provide adequate guardrails for at-sea testing and potential future large-scale deployment.

BACKGROUND

To keep global temperature rise to within 1.5 degrees Celsius (°C), as outlined in the Paris Agreement, there is broad scientific consensus that we need to reach net-zero carbon dioxide (CO_2) emissions as soon as possible (IPCC 2018, 2022a). This will require deep and unprecedented emissions reductions across all sectors, as well as large-scale carbon dioxide removal (CDR) to extract carbon dioxide from the atmosphere. Carbon dioxide removal cannot replace deep emissions reductions but will be needed alongside them to reach global climate goals, and in the long term, bring atmospheric CO_2 down to a safer level.

The amount of CDR that will ultimately be needed is uncertain, but is likely to be multiple billions of metric tons annually by mid-century. The Intergovernmental Panel on Climate Change (IPCC) points to the need for around 600 billion metric tons of CO_2 ($GtCO_2$) to be removed by 2100, or an average of 7.5 $GtCO_2$ per year (/yr) across all scenarios that limit temperature rise to 1.5°C (IPCC 2022a). These include CDR approaches commonly considered natural as well as those considered technological, and could come from applications on land and in the ocean. The ultimate balance between how much carbon is removed through approaches on land compared with approaches in the ocean is uncertain today and will be informed by continued research. The IPCC (2022a) notes that reliance on carbon removal can be minimized through stronger action to reduce emissions in the near term or could be larger if there is less near-term emissions reduction.

While CDR is often discussed in terrestrial settings—for example, tree planting and direct air capture—there are also a number of proposed and ongoing approaches that could use the ocean to increase the amount of carbon dioxide removed from the atmosphere. Ocean-based CDR approaches seek to mimic and enhance existing biological and geochemical processes in the ocean to remove atmospheric CO_2, and in most cases sequester that carbon in various forms in the deep ocean itself. Ocean CDR methods leverage both biotic and abiotic processes in seawater, primarily the photosynthetic conversion of carbon dioxide into biomass and the biogeochemical carbonate cycle.

The ocean is already a major carbon sink and plays a crucial role in global climate regulation. To date, the ocean has absorbed 90 percent of excess heat trapped by anthropogenic greenhouse gas (GHG) emissions and 30 percent of anthropogenic CO_2 emissions, dampening the impacts of climate change on land (Gruber et al. 2019; IPCC 2019). At the same time, this excess heat and CO_2 are damaging marine ecosystems (for example, coral reef bleaching and acidification) and leading to destabilizing effects on existing ocean currents that regulate climate and weather patterns (Peng et al. 2022). Fortunately, the ocean's ability to absorb anthropogenic CO_2 appears to continue to match rising atmospheric CO_2 concentrations, but future reductions in this ability remain a topic of major concern (Friedlingstein et al. 2022). Some of the carbon removal approaches discussed in this report can reduce ocean acidification while they sequester carbon.

The potential negative impacts of large-scale ocean CDR will not be equally distributed. The nature of ocean ecosystems and circulation makes the potential for transboundary impacts high and likely widely dispersed. Ocean health has a profound impact on people in all countries—landlocked and coastal alike—through tourism, food and medicine production, global climate regulation, nutrient cycling, and ecological services (NOAA 2021c). However, the degradation of ocean health can more acutely impact ocean-dependent people in developing and least-developed countries, raising significant equity issues for ocean CDR.

The accelerating damage to ocean and terrestrial ecosystems from climate change has increased the urgency of considering deployment of ocean CDR approaches; this is accompanied by an equally urgent need to fill research and governance gaps in a responsible manner. The vast majority of the 52 national, long-term, low-emission development strategies (LTSs) that have been announced by national governments include plans to use CDR (either natural or technological) as a means to reach net-zero goals in the second half of the century. More than one-third of the 52 LTSs mention plans to rely on technological CDR, and Japan and the United States specifically refer to ocean CDR (Schumer and Lebling 2022). Additionally, private companies have begun to invest in ocean CDR for carbon offsetting and technology innovation purposes (Stripe 2021; XPrize 2022). Any significant scale-up of ocean CDR deployment must be accompanied by appropriate research codes of conduct and governance structures to prevent negative ecological impacts on the ocean, maximize overall climate benefits, and protect communities that rely on the ocean for food and livelihoods. This is particularly important for private companies that are pursuing ocean CDR for the purpose of carbon offsetting, since they could face major reputational risks if negative impacts occur, and also fail to achieve tangible climate benefits despite significant investment.

This report explores seven ocean CDR approaches that are in various stages of development and deployment: coastal blue carbon restoration, seaweed cultivation, ocean fertilization, alkalinity enhancement, electrochemical approaches, artificial upwelling, and artificial downwelling (Table ES-1 and Figure ES-1). These seven approaches have been selected from the larger set of proposed ocean CDR approaches (GESAMP 2019) because of their near-term likelihood of significant investment and development and/or their potential for deployment at scale. This report distills the potential scale of carbon dioxide removal, expected costs, risks, co-benefits, and areas of research needed for these seven ocean CDR approaches. It then assesses the governance landscape at the international, regional, and national levels in terms of legal frameworks and additional governance considerations, including stakeholder engagement; measurement, reporting, and verification (MRV); and equity.

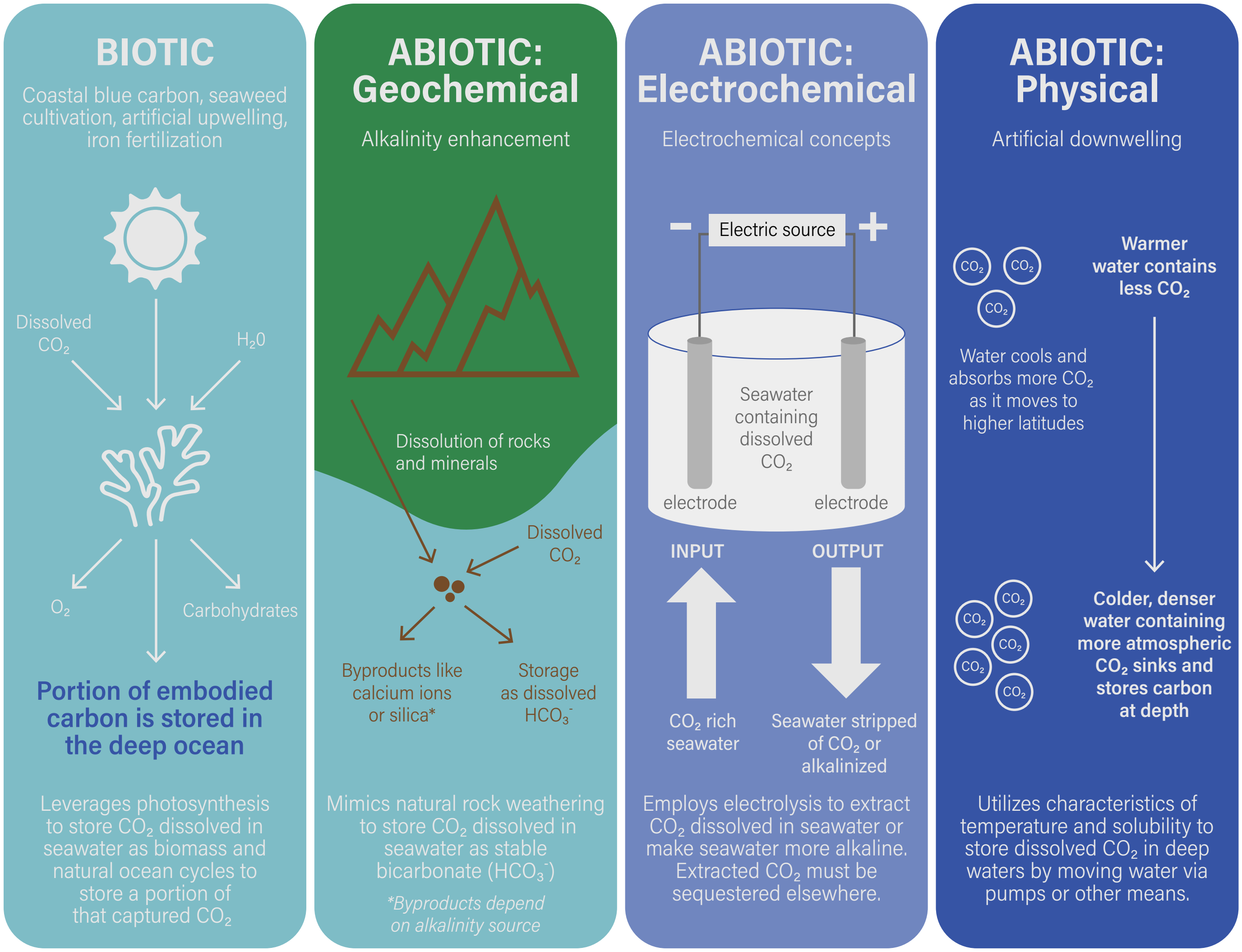
This report outlines a pathway forward that is centered on informed and responsible development and deployment of ocean CDR to appropriately balance the urgency of emissions reductions with taking a precautionary approach regarding the environmental and social risks of ocean CDR. Ultimately, the choice of deploying ocean CDR versus the impacts of climate change if ocean CDR is not part of the solution involves a trade-off between different sets of risks. For these purposes, the report defines informed and responsible development and deployment such that it does the following:

- Occurs iteratively to ensure research priorities adapt with new findings about viability, including ceasing investment if negative impacts are insurmountably high, as defined by the National Academies (NASEM 2021)
- Balances the potential ecological and social impacts (positive and negative) of these approaches with the broader impacts of climate change on the ocean under a no- or insufficient-action scenario
- Is aligned with the precautionary principle under international law

- Is conducted with rigorous monitoring and transparent reporting when implementing small-scale field trials for the purpose of conducting foundational research
- Operates within a robust national and global governance framework when deploying mid- or large-scale ocean CDR that allocates liability for harm and provides safeguards and an MRV framework
- Includes stakeholders in the development and deployment process
- Equitably distributes benefits and costs (see Section 5.2, Additional Governance Considerations)

The findings in this report are aimed at informing decision-makers at international institutions, particularly in this United Nations (UN) Decade of Ocean Science for Sustainable Development (2021–2030) and UN Decade on Ecosystem Restoration (2021–2030), as well as researchers in nongovernmental organizations (NGOs), the private sector, philanthropy, academic institutions, and government bodies who are assessing the potential of ocean CDR approaches over the coming years.

FIGURE ES-1 | Ocean CDR Approaches



Notes: Abbreviations: CO_2 = carbon dioxide; O_2 = oxygen; H_2O = water; HCO_3^- = bicarbonate ion. Ocean carbon dioxide removal approaches leverage biotic and abiotic (non-biological) processes to convert atmospheric CO_2 into carbon stored as dissolved bicarbonate or biomass stored on the ocean floor.

Source: Authors, based on information in NASEM (2021).

KEY FINDINGS

There is scientific uncertainty associated with most ocean-based CDR approaches, so additional theoretical, laboratory-scale, and small-scale at-sea testing is needed before their merits and trade-offs can be adequately evaluated. Ocean CDR approaches are diverse, generally poorly understood, and vary with regard to risk. Only one approach considered here—coastal ecosystem restoration—is an exception, having been practiced for decades, though generally not with the goal of atmospheric carbon dioxide removal. For other approaches, this lack of empirical evidence creates uncertainties that limit our understanding of the potential reasonable scale of deployment and practical constraints to ocean-based carbon removal and storage, as well as potential positive and negative ecological and social impacts at different scales of deployment. Well-managed research and, if lab-based testing shows promise, at-sea testing will be needed to resolve these uncertainties. The latter is necessary to be able to fully understand how different ocean CDR approaches will work and their environmental effects. A summary of key points by approach is in Table ES-1.

While ocean CDR approaches hold enormous potential, the current research landscape is inadequately resourced to resolve the scientific and technological uncertainties at hand. Although ocean-based approaches could theoretically provide carbon removal at a significant scale, there is insufficient funding for the research necessary to resolve uncertainties. Private-sector and philanthropic investment is growing, but substantial government funding is required to achieve the necessary scale and ensure that research and testing are conducted transparently. In parallel with efforts to resolve scientific uncertainties, resources are needed to address other challenges for responsibly applying ocean CDR at large scale, the most important of which is the development of robust systems for ongoing measurement of carbon removal efficacy and monitoring of ecological impacts. While research funding should primarily be dedicated to advancing, revising, or discarding the existing ocean CDR concepts that have been proposed to date, a small fraction should be reserved for investigating novel concepts or variations.

Ocean carbon removal approaches, if deployed at large scale, could have significant ecological and social impacts, both positive and negative, that would vary substantially by approach, location, and scale. The potential for these impacts makes ocean CDR contentious (some approaches more than others), particularly given the strong social, cultural, and economic connections that many people have to the ocean. In most cases, further research and, where appropriate, at-sea testing will be needed to better understand these risks and benefits, and determine which approaches are viable where and at what scale. Research will also be needed to better understand public perceptions and potential social impacts. The possible risks of deployment must be balanced against the potential climate risks associated with excluding ocean CDR approaches from consideration for deployment.

Existing international and national governance frameworks for regulating activities in the ocean are not sufficient to comprehensively and proactively regulate ocean CDR approaches as they are being developed and deployed. Existing international law frameworks predate the development of novel ocean CDR approaches and are designed to minimize and regulate environmental harm. There are limited and/or conflicting assessments of how these frameworks would apply to ocean CDR approaches, creating a great deal of uncertainty, and potentially allowing unsuitable or excessively risky projects to proceed without adequate safeguards or monitoring while also potentially delaying research or test projects unnecessarily (Brent et al. 2019; Webb et al. 2021).

Ocean CDR approaches will not just impact the marine environment—many will also require extensive land-based infrastructure. The environmental and social impacts of land-based infrastructure associated with ocean CDR—for example, infrastructure to access and transport alkaline material and renewable energy to power some ocean CDR approaches—must also therefore be considered, and appropriate governance frameworks and safeguards put into place to protect the local coastal environment as well as coastal and inland communities. Governance of ocean CDR approaches must extend beyond the national and international frameworks for the use of the ocean and also consider the land-based impacts and onshore infrastructure associated with their operation.

Governance of ocean CDR must not only involve regulation but also include public policy participation, equitable benefit sharing, and transparent access to information. Public participation is critical to allowing society to make an informed decision on how to proceed with the research and deployment of these emerging approaches and how they should be governed. Governance for ocean CDR approaches also offers the opportunity for greater policy coherence. The current lack of coherence between legal framework interpretations, and actions by countries, intergovernmental organizations, and nongovernmental organizations, makes it hard for the scientific and research community to engage with the policymaking community to adequately consider the interests of all actors.

To responsibly undertake ocean CDR at the necessary scale, a comprehensive international governance regime will be required to establish rules for development; mechanisms for environmental impact and risk assessment; MRV systems; principles for stakeholder consultation and participation in decision-making processes; and appropriate liability regimes if harm occurs. The challenge for advancing ocean CDR approaches is finding the balance between the urgency of developing and deploying new, effective ways to reduce greenhouse gas emissions (which are already having an outsized impact on the ocean) while seeking to protect and preserve marine ecosystems and avoid harm to human societies that are dependent on the ocean. Governance frameworks will be critical to guiding this process and must be in place to support and respond to research, development, and field testing for ocean CDR approaches.

Some ocean CDR approaches have the potential to provide co-benefits for ocean health, resilience, and a sustainable ocean economy that can make them more appropriate for near-term investment. For example, projects to protect, conserve, and restore coastal and marine ecosystems are usually motivated primarily by the many demonstrated co-benefits from coastal resilience to habitat creation, not by carbon removal. Seaweed (also referred to as macroalgae) cultivation and some forms of ocean alkalinity enhancement can reduce acidification locally, potentially benefiting oyster farming or protecting coral reefs. Seaweed cultivation may also be able to reduce wave energy to reduce the impacts of storms. When harvested, macroalgae can be used in fertilizer to improve soil health (which may also improve the ability of soil to sequester carbon) and in products such as fishmeal and biofuel to reduce their carbon intensities.

TABLE ES-1 | Overview of Ocean CDR Approaches

OCEAN CDR APPROACH	COASTAL BLUE CARBON RESTORATION	SEAWEED CULTIVATION	OCEAN FERTILIZATION	ARTIFICIAL UPWELLING	ALKALINITY ENHANCEMENT	ELECTRO-CHEMICAL TECHNIQUES	ARTIFICIAL DOWNWELLING
HOW IT WORKS	Storage of organic carbon in coastal sediment	Embodied carbon in seaweed can be sunk for sequestration in deep ocean water or seafloor sediment; other end uses such as food or biofuel (with minimal carbon removal)	Addition of nutrients (e.g., iron, nitrogen, phosphorus) to nutrient-depleted areas to promote phytoplankton growth; some fraction of this moves to the deep sea for storage where it is sequestered	Upwelling nutrient-rich deep water to the surface spurs phytoplankton blooms; some fraction of this is exported to the deep sea for storage in seabed sediment	Addition of alkaline materials to react with dissolved CO_2, which stores carbon as bicarbonate and carbonate ions and results in additional uptake of atmospheric CO_2 into the ocean	Using electricity to remove CO_2 from seawater, or producing alkalinity for a variant of alkalinity enhancement.	Accelerating natural currents that carry carbon-rich surface water into the deep ocean by cooling surface water or pumping it to depth
CARBON REMOVAL POTENTIAL	0.2–0.33 $GtCO_2$/yr by 2050;[a] maximum potential estimates are closer to 0.8 $GtCO_2$/yr;[b] protecting existing ecosystems could avoid an additional estimated 0.25–0.76 $GtCO_2$/yr[c]	Estimated to be >0.1 $GtCO_2$/yr but <1.0 $GtCO_2$/yr[f]	Wide range based on modeling of theoretical potential—the National Academies estimates 0.1–1 $GtCO_2$/yr with medium confidence;[k] experiments performed to date have shown increased primary productivity, but the necessary transfer of organic matter from the surface to the deep ocean and a corresponding uptake of atmospheric carbon into the ocean has not been verified[l]	Estimated up to 0.18 $GtCO_2$/yr;[n] may be more useful in combination with seaweed cultivation than for dedicated CDR	Uncertain; estimates vary widely from as little as 0.1 $GtCO_2$/yr up to 1.0 $GtCO_2$/yr[p]	Uncertain; estimates vary from 0.1 $GtCO_2$/yr to 1.0 $GtCO_2$/yr[r]	Uncertain but estimated to be 1.4 $GtCO_2$ cumulatively from 2020 to 2100, or 0.018 $GtCO_2$/yr on average through 2100[t]
COST OF DEPLOYMENT	$\$10/tCO_2$[d] to more than $\$500/tCO_2$;[e] variable depending on ecosystem type, location, and other factors	$\$65/tCO_2$ to more than $\$3,000/tCO_2$ depending on species, cultivation method, geography, and other factors;[g] the United States Department of Energy is aiming to reach $\leq\$80/tCO_2$[h]	Estimated to be $\$8–\$80/tCO_2$[m]	Uncertain; estimated to be $\$100–\$150/tCO_2$ with low confidence, excluding monitoring costs[o]	Estimated to be $\$100–\$150/tCO_2$, not including the additional monitoring costs that would be required[q]	Expected to be high as electrochemical processes are capital and energy intensive; estimated costs range from $\$150$ to $\$2,500/tCO_2$ removed[s]	The few modeling studies that have been done show that costs would be very high—on the order of thousands of dollars per metric ton of carbon removed[u]
RISKS AND CO-BENEFITS, IF APPLICABLE	Risks are minimized if native coastal wetland species are used and restoration sites are appropriately selected; significant co-benefits for ecosystem functioning, coastal climate resilience, and livelihoods	Nutrient depletion and diversion from other habitats; competition for light; changes in oxygen, CO_2, pH levels; introduction of non-native species; competition for space; durability of infrastructure—potential co-benefits include reduced acidification in surface waters and uptake of excess nutrients	Risks include ecological impacts like reduced oxygen, nutrient depletion, and reduced light, which can change ecosystem composition, and changes to populations of grazer and predator marine organisms; a potential co-benefit is increased fish stocks	Similar risks to ocean fertilization, along with potential for outgassing of CO_2 from the deep ocean, use of plastic pipes that could interfere with ocean biota, and increased heat at the surface once upwelling stops; a potential co-benefit is increased fish stocks	Changes to biogeochemistry and food systems, changes to the species composition and growing locations of phytoplankton, introduction of trace minerals; expanded mining and possible termination shock if application suddenly ceased are also risks—a potential co-benefit is locally reduced acidification	Risks are similar to those of alkalinity enhancement, with additional risk from manipulating large volumes of seawater and from effluent discharge; further risks include mining for material inputs and safely managing chemical byproducts like chlorine gas and hydrogen	Cooler surface waters and warmer subsurface waters can alter weather patterns, reduce net carbon flux, and impact ecosystems

TABLE ES-1 | Overview of Ocean CDR Approaches (Cont'd)

OCEAN CDR APPROACH	COASTAL BLUE CARBON RESTORATION	SEAWEED CULTIVATION	OCEAN FERTILIZATION	ARTIFICIAL UPWELLING	ALKALINITY ENHANCEMENT	ELECTRO-CHEMICAL TECHNIQUES	ARTIFICIAL DOWNWELLING
GEOGRAPHIC RELEVANCE	Coastal areas, particularly areas where these coastal ecosystems used to exist, with variation by ecosystem type (mangroves in lower latitudes and seagrasses and salt marshes at higher latitudes)	Suitability depends on nutrient availability at cultivation site, which includes significant area at high latitudes as well as some midlatitude locations[i]	The largest opportunity for iron fertilization is in the Southern Ocean—roughly 20% of the ocean is suitable for iron fertilization based on where iron is a limiting nutrient; roughly 70% of the ocean is suitable for macronutrient fertilization, based on where they are limiting nutrients to primary production	Likely best in mid- and low-latitude waters where nutrients are depleted at the surface	No consensus exists yet, but possible criteria for selecting a location include season, upwelling velocity, and the possibility of providing co-benefits; carbonate minerals can be added only to locations that are not already saturated with carbonate	Multiple criteria could inform optimal siting, including ocean access, energy availability, synergies with existing infrastructure like desalination plants and/or infrastructure to transport and sequester CO_2	Most applicable where major downwelling currents are located, such as the North Atlantic Deep Water near Greenland and the Antarctic Bottom Water
INTERNATIONAL LEGAL FRAMEWORK	N/A; applied within national jurisdictions	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS[i] ▪ Potential concerns under UNCLOS of introduction of alien and new species ▪ Small-scale scientific research studies permitted under CBD within coastal waters ▪ Large-scale, commercial deployment could contravene the nonbinding ban on climate geoengineering under CBD	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Nonbinding ban on ocean fertilization and climate geoengineering under CBD except for small-scale scientific research ▪ Non-legally binding Assessment Framework for Scientific Research under London Convention ▪ Amendment to London Protocol (not in force)	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Considerations for equipment and installation in shipping paths under UNCLOS ▪ Nonbinding ban of geoengineering under CBD except for small-scale scientific research	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Nonbinding ban of geoengineering under CBD except for small-scale scientific research ▪ General provisions of the London Convention and London Protocol, potential permit requirements.	▪ Same as that for alkalinity enhancement	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Considerations for equipment and installation in shipping paths under UNCLOS ▪ Nonbinding ban of geoengineering under CBD except for small-scale scientific research

TABLE ES-1 | Overview of Ocean CDR Approaches (Cont'd)

OCEAN CDR APPROACH	COASTAL BLUE CARBON RESTORATION	SEAWEED CULTIVATION	OCEAN FERTILIZATION	ARTIFICIAL UPWELLING	ALKALINITY ENHANCEMENT	ELECTRO-CHEMICAL TECHNIQUES	ARTIFICIAL DOWNWELLING
RESEARCH PRIORITIES	▪ Improving the understanding of carbon accumulation as climate changes ▪ Improving the mapping of blue carbon ecosystems and their sequestration potential ▪ Reducing uncertainty in carbon accounting across ecosystems and locations ▪ Reducing uncertainty around GHG emission rates following disturbance	▪ Optimization of near-shore and open ocean cultivation and harvest ▪ Better understanding of ecological impacts ▪ Field studies to better understand air-sea CO$_2$ equilibrium ▪ Improved MRV, including in deep ocean water and the ocean floor for sunk biomass ▪ Optimal end uses for cultivated biomass	▪ Factors that control the amount of carbon exported to the seabed ▪ Ecological impacts ▪ Impact of air-sea CO$_2$ equilibrium time ▪ Optimal locations for and methods of application	▪ Optimization of materials, engineering, and design to effectively upwell ocean water, with attention to durability in the open ocean and other design questions like upwelling rate and energy source ▪ Small-scale field tests for proof of concept and to better understand ecological impacts ▪ Improved monitoring and verification capacity to be able to accurately quantify carbon removal	▪ Small-scale, contained trials to understand the ecological impacts, efficacy, and feasibility of alkalinity enhancement deployment in different geographies and conditions ▪ Addressing engineering, materials supply, transportation, and cost questions, including holistic supply chain impacts	▪ Engineering feasibility of large-scale applications ▪ Holistic life-cycle assessments ▪ Optimal sources of energy ▪ Understanding the disposal or utilization needs of byproducts like chlorine gas and hydrogen	▪ At-sea tests would be needed to test carbon removal efficacy and understand environmental impacts

Notes: Abbreviations: GtCO$_2$/yr = billion metric tons of carbon dioxide per year; tCO$_2$ = metric tons of carbon dioxide; N/A = not applicable; GHG = greenhouse gas; CO$_2$ = carbon dioxide; pH = potential of hydrogen; UNCLOS = United Nations Convention on the Law of the Sea; MRV = measurement, reporting, and verification; CBD = Convention on Biological Diversity; OAE = ocean alkalinity enhancement; London Convention = Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter; London Protocol = Protocol to the London Convention.

[a] *Hoegh-Guldberg et al. 2019.*

[b] *NASEM 2019; Griscom et al. 2017.*

[c] *Hoegh-Guldberg et al. 2019.*

[d] *NASEM 2019.*

[e] *Taillardat et al. 2020.*

[f] *NASEM 2021.*

[g] *Milledge and Harvey 2016; van den Burg et al. 2016; Bjerregaard et al. 2016.*

[h] *von Keitz 2020.*

[i] *See Figure 9.*

[j] *UN 1982.*

[k] *NASEM 2021.*

[l] *Yoon et al. 2018.*

[m] *Boyd 2008; NASEM 2021.*

[n] *Koweek 2022.*

[o] *NASEM 2021.*

[p] *NASEM 2021.*

[q] *NASEM 2021.*

[r] *NASEM 2021.*

[s] *Rau 2008; NASEM 2021.*

[t] *Lenton and Vaughan 2009.*

[u] *Zhou and Flynn 2005.*

RECOMMENDATIONS

We recommend a path forward that is based on informed and responsible development and deployment of ocean CDR that balances the potential impacts of advancing ocean CDR with the risks to the climate (and ocean) of not leveraging the ocean's CDR potential, including not pursuing development where environmental or ecological risks are shown to outweigh expected benefits (Figure ES-2).

To advance an informed and responsible approach while responding to the urgency of climate change, we propose three priorities with several recommendations for each. The priorities should be initiated in the order presented but will need to be advanced simultaneously. The recommendations under each priority are in no particular order.

Priority One: Resolve uncertainties to understand which approaches are viable for large-scale deployment with minimal negative impact on ocean systems, ecosystems, and coastal communities

1. Increase public, private, and philanthropic funding for collaborative research on ocean CDR, prioritizing the following:

- Improved models for large-scale ocean CDR simulations, including integration with smaller-scale models, to understand the impacts on ocean systems, ecosystems, and coastal communities
- Research, including mesocosm trials and field testing for approaches where uncertainty cannot be resolved in a laboratory setting, to assess efficacy and ecological impacts
- Research on safeguards and emergency measures
- Tracking research and commercial deployment taking place (national, regional, international) in a transparent and accessible public database
- Improved methodologies for measurement, reporting, and verification, including development or improvement of baselines needed for accounting, as well as monitoring for environmental and ecological impacts
- Understanding social impacts and whether/how ocean CDR could affect other priorities like sustainable development, biodiversity, job provision, and food production
- Capacity development for early-career researchers in climate-vulnerable communities, underrepresented groups, Indigenous Peoples, and the Global South
- Collaborative and co-produced research partnerships with Indigenous and coastal communities

2. Establish an independent interdisciplinary committee, drawing on scientific experts from the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the IPCC, and other groups, to advance consensus on an international research agenda, including what constitutes responsible field tests and priorities for clarifying the international governance framework, building on work done already at the national level.

Priority Two: Improve governance frameworks at the local, national, and international levels to ensure research and small-scale pilots are undertaken responsibly and all stakeholders are informed and included

1. Convene a ministerial dialogue on ocean CDR under the joint auspices of the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention), and the Protocol to the London Convention (London Protocol) to respond to the recommendations from the scientific committee (identified in Priority One), lay the foundation for further discussions, and promote greater coherence across existing international frameworks.
2. Develop an international code of conduct for at-sea research trials and require adherence to this code to receive public and/or philanthropic funding or permits.
3. Ensure national and local regulatory and permitting processes are clear in their application to ocean CDR approaches. Where necessary, develop new regulatory and permitting processes that include robust environmental impact assessments and incentivize research (either for scientific or commercial purposes) for which data are shared transparently.
4. Develop a publicly accessible and transparent platform to share standardized data from research efforts and any at-sea trials.
5. Embed robust, inclusive, and funded community consultation in all nationally and philanthropically funded ocean CDR research and deployment processes and promote use of shared benefits agreements (where relevant).

Priority Three: Lay the foundation for robust governance of large-scale deployment in the future

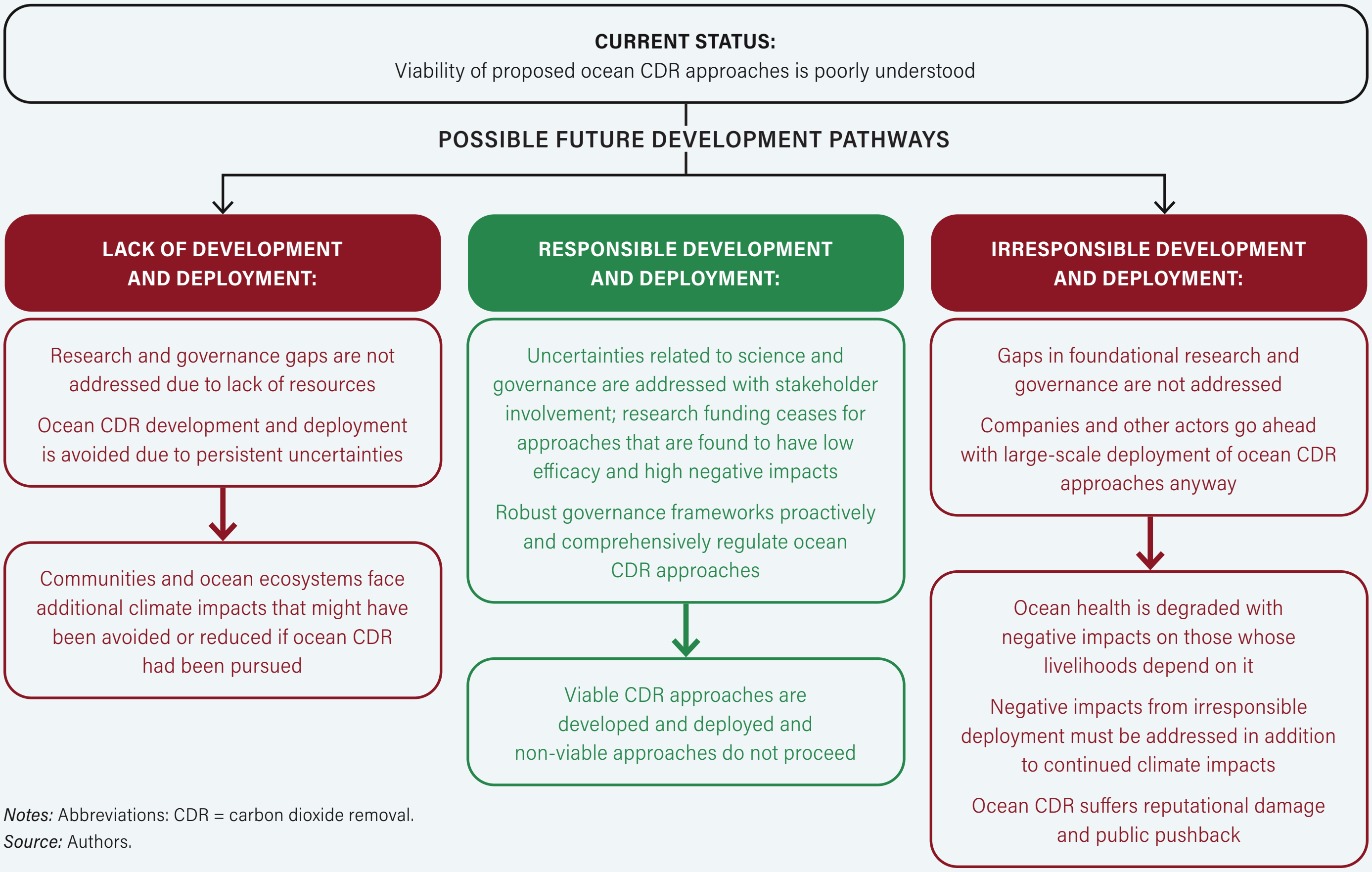
1. Initiate a process to explore a new agreement or framework to proactively govern ocean CDR, including consideration of the following:

- Which institution (new or existing) will have the mandate to regulate ocean CDR as a cross-cutting issue
- Governance of different jurisdictional zones
- Independent and peer-reviewed assessments of impacts
- Clear thresholds for unacceptable levels of harm or unacceptable levels of uncertainty in terms of achieving sustainable development goals and social, equity, economic, and ecological impacts of deployment
- Stage-gated, science-based decision-making
- Clarity on what constitutes research versus commercial deployment of ocean CDR approaches
- Liability in the event of harm
- Transparency and information-sharing requirements, including data standardization
- Equitable benefit sharing and avoidance of developing countries bearing the burden of research and at-sea testing
- Robust and inclusive stakeholder engagement processes (building on codes of conduct and existing safeguards)
- Obligation to either apply the instrument domestically or adopt other measures to implement the operative provisions domestically

2. Initiate a process to resolve uncertainties related to MRV methodologies; accounting and reporting under the UNFCCC; and use of credits in voluntary carbon markets.

One or more ocean CDR approaches will likely be required at some stage in the future to remove carbon dioxide from the atmosphere and limit global temperature increase. There is an opportunity to resolve and clarify the extensive scientific, technological, ecological, social, and governance uncertainties and risks that currently exist before development and large-scale deployment starts.

FIGURE ES-2 | The Case for Responsible Development of Ocean CDR



CURRENT STATUS:
Viability of proposed ocean CDR approaches is poorly understood

POSSIBLE FUTURE DEVELOPMENT PATHWAYS

LACK OF DEVELOPMENT AND DEPLOYMENT:

Research and governance gaps are not addressed due to lack of resources

Ocean CDR development and deployment is avoided due to persistent uncertainties

Communities and ocean ecosystems face additional climate impacts that might have been avoided or reduced if ocean CDR had been pursued

RESPONSIBLE DEVELOPMENT AND DEPLOYMENT:

Uncertainties related to science and governance are addressed with stakeholder involvement; research funding ceases for approaches that are found to have low efficacy and high negative impacts

Robust governance frameworks proactively and comprehensively regulate ocean CDR approaches

Viable CDR approaches are developed and deployed and non-viable approaches do not proceed

IRRESPONSIBLE DEVELOPMENT AND DEPLOYMENT:

Gaps in foundational research and governance are not addressed

Companies and other actors go ahead with large-scale deployment of ocean CDR approaches anyway

Ocean health is degraded with negative impacts on those whose livelihoods depend on it

Negative impacts from irresponsible deployment must be addressed in addition to continued climate impacts

Ocean CDR suffers reputational damage and public pushback

Notes: Abbreviations: CDR = carbon dioxide removal.
Source: Authors.

INTRODUCTION:

The Need for Informed and Responsible Development of Ocean Carbon Dioxide Removal

The ocean is a major carbon sink that has already dampened the effects of climate change by taking in excess carbon dioxide and heat, which is negatively impacting ocean health. As the effects of climate change worsen, pressure to use the ocean for climate action, including for carbon removal, will only increase. Development of ocean carbon removal approaches must be done in a responsible manner to avoid further damage to ocean ecosystems.

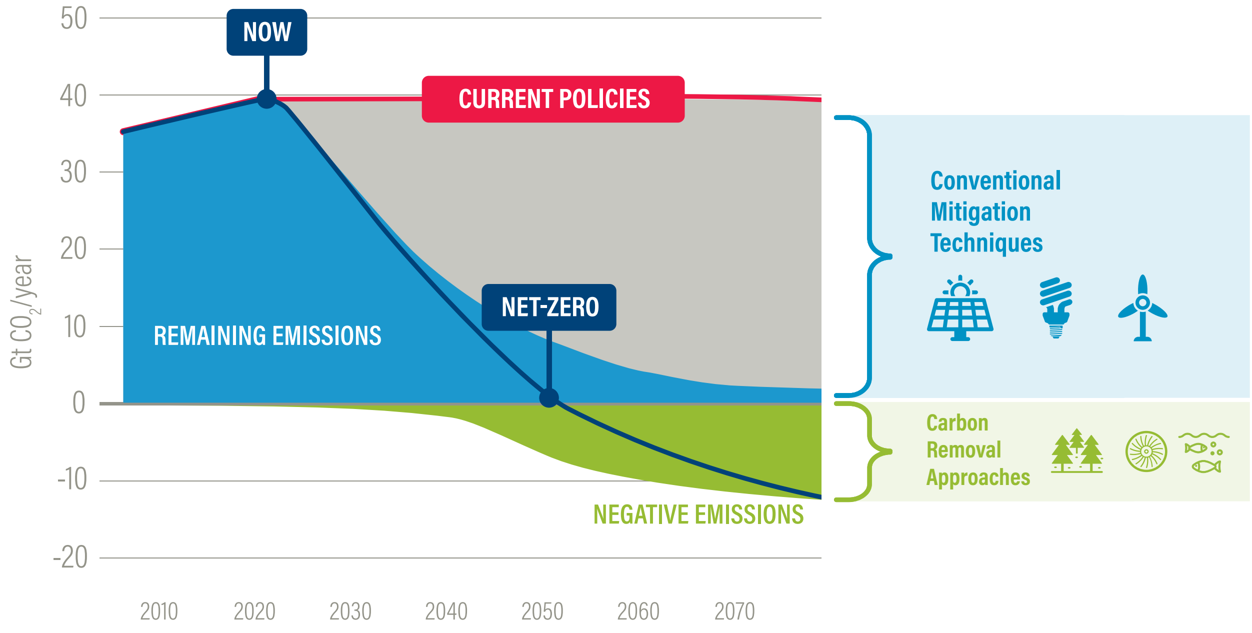
Avoiding the worst impacts of climate change requires limiting global temperature rise to 1.5 degrees Celsius (°C), as outlined in the Paris Agreement—and meeting this temperature goal means reaching net-zero carbon dioxide (CO_2) emissions by mid-century and net-zero greenhouse gas (GHG) emissions soon thereafter (IPCC 2018; see Figure 1). Climate modeling scenarios analyzed by the Intergovernmental Panel on Climate Change (IPCC) indicate that along with deep emissions reductions, significant carbon dioxide removal (referred to as carbon removal, or CDR) is also present in every scenario that meets this goal (IPCC 2018, 2022a). Carbon removal can play multiple roles: In the near-term, it can balance out residual emissions that cannot be reduced because abatement technologies are not yet available or are not cost-effective at scale (e.g., non-CO_2 emissions in agriculture; some portions of long-haul aviation, shipping, and heavy industry) (Honegger et al. 2021b; IPCC 2022a). In the long term, because CO_2 has a long lifetime in the atmosphere, carbon removal will be needed to reduce the excessive concentration of CO_2 in the atmosphere from past emissions to return it to safer levels, closer to pre-industrial concentrations.

The IPCC points to the need for around 580–650 billion metric tons of carbon dioxide ($GtCO_2$) to be removed by 2100 across all modeled scenarios that limit warming to 1.5°C (roughly 7.7 $GtCO_2$ per year (/yr) across all CDR approaches, which can encompass natural and technological approaches on land and in the ocean) (IPCC 2022a). The amount of CDR that will be deployed from land-based approaches versus those applied in the ocean remains uncertain, though given the total amount, it could plausibly be at the scale of multiple billions of metric tons per year both on land in and the ocean by mid-century.

The ocean is a significant natural carbon sink, holding around 42 times more carbon than the atmosphere (Friedlingstein et al. 2022; see Figure 2). It has also played a major role in dampening the impacts of climate change thus far: It has already absorbed around 90 percent of excess heat in the climate system and around 30 percent of anthropogenic CO_2 emissions (Gruber et al. 2019; IPCC 2019). Fortunately, the ocean's ability to absorb anthropogenic CO_2 appears to match rising atmospheric CO_2 concentrations to date, but its ability to continue to do so at the same rate is a topic of major concern (Friedlingstein et al. 2022).

The ocean and its systems and ecosystems are being significantly impacted by the absorption of excess anthropogenic CO_2 emissions. Excess CO_2 is causing ocean warming,

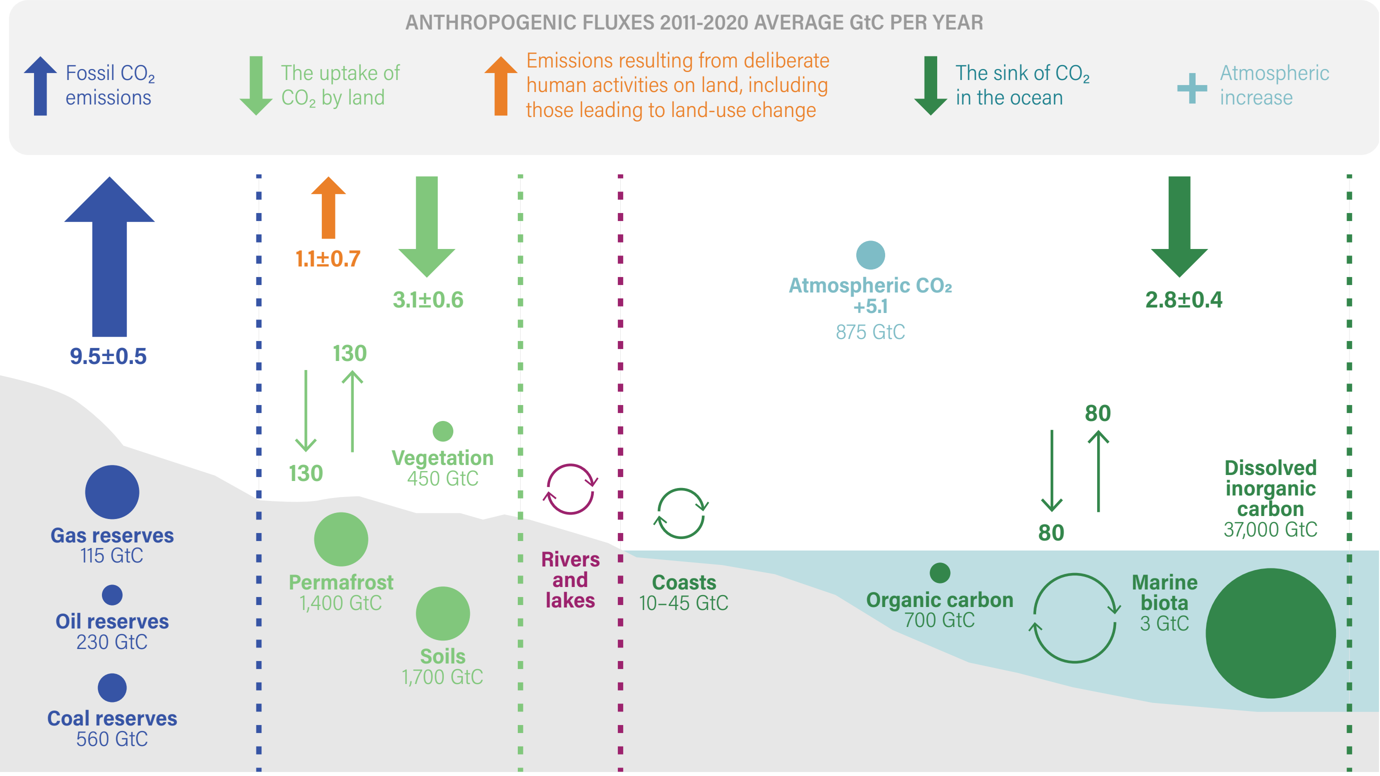
FIGURE 1 | Staying below 1.5 Degrees Celsius of Global Temperature Rise



Note: Abbreviation: $GtCO_2$/yr = billions of metric tons of carbon dioxide per year.

Sources: Based on IPCC (2018) and CAT (2021).

FIGURE 2 | The Global Carbon Cycle



Note: Abbreviations: CO_2 = carbon dioxide; GtC = billion metric tons of carbon.

Source: Friedlingstein et al. 2022.

acidification, and oxygen loss, which is affecting marine life and changing nutrient cycling and primary production in some places. This is compromising the ocean's ability to provide food, support livelihoods, and act as a climate buffer (IPCC 2019; Hoegh-Guldberg et al. 2019). For example, fishery catches in multiple regions are already changing in composition, distribution, and abundance; coastal ecosystems are threatened by sea level rise; and instances of harmful algae blooms have increased (IPCC 2019, 2022b).

Ocean currents regulate the global climate by functioning like conveyor belts that redistribute warm water and precipitation from the tropics toward the poles and move cold water from the poles to the tropics. This conveyor belt process produces the climate we experience now; without it, the tropics would be extremely hot, the poles would be extremely cold, and large portions of the Earth would be uninhabitable (NOAA 2020). As the planet warms due to increased greenhouse gas emissions, ocean waters become warmer. Warmer temperatures have significant impacts, such as producing stronger storms, causing sea level rise that consumes coastal areas, reducing the availability of oxygen for marine life, and disrupting ocean currents, which lead to alterations in climate patterns around the world (EPA 2021; Gong et al. 2021).

As climate change disrupts ocean processes, positive feedback loops can accelerate these negative impacts. For example, sea ice in the Arctic keeps the planet cooler by reflecting solar radiation back into space, but as the planet warms this ice melts, reducing its reflectiveness and thus accelerating planetary warming, which results in further ice melt and sea level rise. Other climate-induced changes are also negatively affecting the ocean: The Atlantic Meridional Overturning Circulation, an important system of ocean currents in the Atlantic, is expected to weaken over the remainder of the century, which could cause changes in precipitation patterns and storm intensity, and increase sea level rise (IPCC 2021).

Climate modeling projections show continued negative impacts on the ocean under both low-emission (Representative Concentration Pathway [RCP] 2.6) and high-emission

(RCP 8.5) scenarios, including increased acidification, reduced oxygen, continued warming, changed tidal amplitudes, and reduced primary productivity, which could result in decreased fish stocks and animal biomass in the deep sea, compromised structure and function of coastal ecosystems, degraded coral reefs, and other impacts (IPCC 2019). The current progression of climate impacts presents significant risk to ocean health and the benefits the ocean provides in terms of supporting livelihoods and serving as a carbon sink and climate regulator.

Given the ocean's vast area—70 percent of the Earth's surface—and its capacity to store large amounts of carbon, a variety of ocean-based carbon dioxide removal approaches have been put forward in the literature, and in some cases have been tested at various scales (GESAMP 2019; Gattuso et al. 2018; NASEM 2021). With the expected large-scale need for carbon dioxide removal, employing approaches on both land and in the ocean would reduce the risk of overreliance on any one approach and spread the total carbon removal burden over larger systems.

Ocean CDR is already garnering increasing interest and traction among governments and companies as a way to help meet climate commitments. Most governments include carbon dioxide removal in their long-term strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC), and two countries—Japan and the United States—specifically include ocean CDR (Schumer and Lebling 2022). Investments into companies actively developing ocean CDR pathways are ongoing, such as Stripe and Shopify investing in ocean CDR companies like Vesta, Running Tide, and Planetary Technologies (Stripe 2021; Shopify 2020). Interest in ocean CDR across the public and private sectors will likely increase in coming years as the impacts of the climate crisis become even more pronounced.

This increasing interest and traction have been catalyzed in part by a growing focus on the ocean as a solution to the climate crisis within international climate policy discussions. At the 21st United Nations (UN) Climate Change Conference of the Parties (COP 21), the first "Because the Ocean" declaration was launched by 23 countries, calling for greater attention to the ocean at subsequent COPs and the potential role of ocean-based climate solutions. This has led to countries incorporating ocean-based climate action in their nationally determined contributions (NDCs) (Northrop et al. 2020); ocean-based mitigation options being included in emissions reduction pathways (Hoegh-Guldberg, 2019); and the IPCC's *The Ocean and Cryosphere in a Changing Climate* providing the first-ever focused assessment of the ocean and climate change (IPCC 2019).

Despite this interest and emerging development, most ocean-based carbon removal approaches, aside from coastal blue carbon restoration, are novel and have had little testing to determine their effectiveness, cost, carbon removal potential, and environmental and social impacts (NASEM 2021; GESAMP 2019). As ocean CDR approaches are diverse, some carry more risk and uncertainty than others; for example, coastal ecosystem restoration is broadly accepted and poses minimal risk, while less-understood approaches like iron fertilization pose significant risk around ecosystem impacts and uncertainty related to efficacy. Some of the carbon removal approaches discussed in this report can provide co-benefits like reducing ocean acidification while sequestering carbon.

The ocean also presents additional complexities compared with carbon removal on land. These include measurement, reporting, and verification (MRV) for carbon removal efficacy and monitoring for ancillary impacts of each approach; international and national governance; and public perception. While the risks of deploying ocean-based CDR approaches are numerous, they must also be balanced with the climate change impacts likely to occur from inaction or inadequate action. Increasing climate pressures may prompt some governments or companies to take radical action in the form of ocean CDR deployment, even with approaches that are not sufficiently understood or that impose significant negative side effects.

Additionally, it is important to recognize that some forms of at-sea field research will be required to resolve scientific uncertainties associated with promising forms of ocean-based CDR. Research of this type should be governed differently from deployment of ocean-based CDR. In general, research activities are conducted on a relatively small scale—no larger than is necessary to draw statistically valid scientific conclusions—and the results are shared openly through avenues such as scientific publications. By contrast, deployment activities may be conducted at small, medium, or large scales, and are usually based on commercial arrangements of some form. Any data and scientific/technical findings that result are frequently (although not always) proprietary, and may not be shared openly. As policymakers consider regulatory frameworks that are appropriate for research and deployment activities, they should bear in mind the broader public value of scientific findings that may result from research and establish relatively easier pathways to conducting research compared with the requirements for deployment activities.

In considering the opportunities presented by emerging and developing pathways, the global climate community must strive not just to develop ocean CDR approaches based on carbon removal efficacy and cost, but also to do so *responsibly*, including not pursuing development where environmental or ecological risks are shown to outweigh expected benefits. Ultimately, ocean CDR deployment and unabated climate change involve a trade-off among different sets of risks. For these purposes, we define "informed and responsible" development as development that does the following:

1. Occurs iteratively to ensure research priorities adapt with new findings about viability, including ceasing investment if negative impacts are insurmountably high, as defined by the National Academies (NASEM 2021)
2. Balances the potential ecological and social impacts (positive and negative) of these approaches with the broader impacts of climate change on the ocean under a no- or insufficient-action scenario
3. Is aligned with the precautionary principle under international law (see Box 7)
4. Is conducted with rigorous monitoring and transparent reporting when implementing small-scale field trials for the purpose of conducting foundational research
5. Operates within a robust national and global governance framework when deploying mid- or large-scale ocean CDR that allocates liability for harm and provides safeguards and an MRV framework
6. Includes stakeholders in the development and deployment process
7. Equitably distributes benefits and costs (see Section 5.2, Additional Governance Considerations)

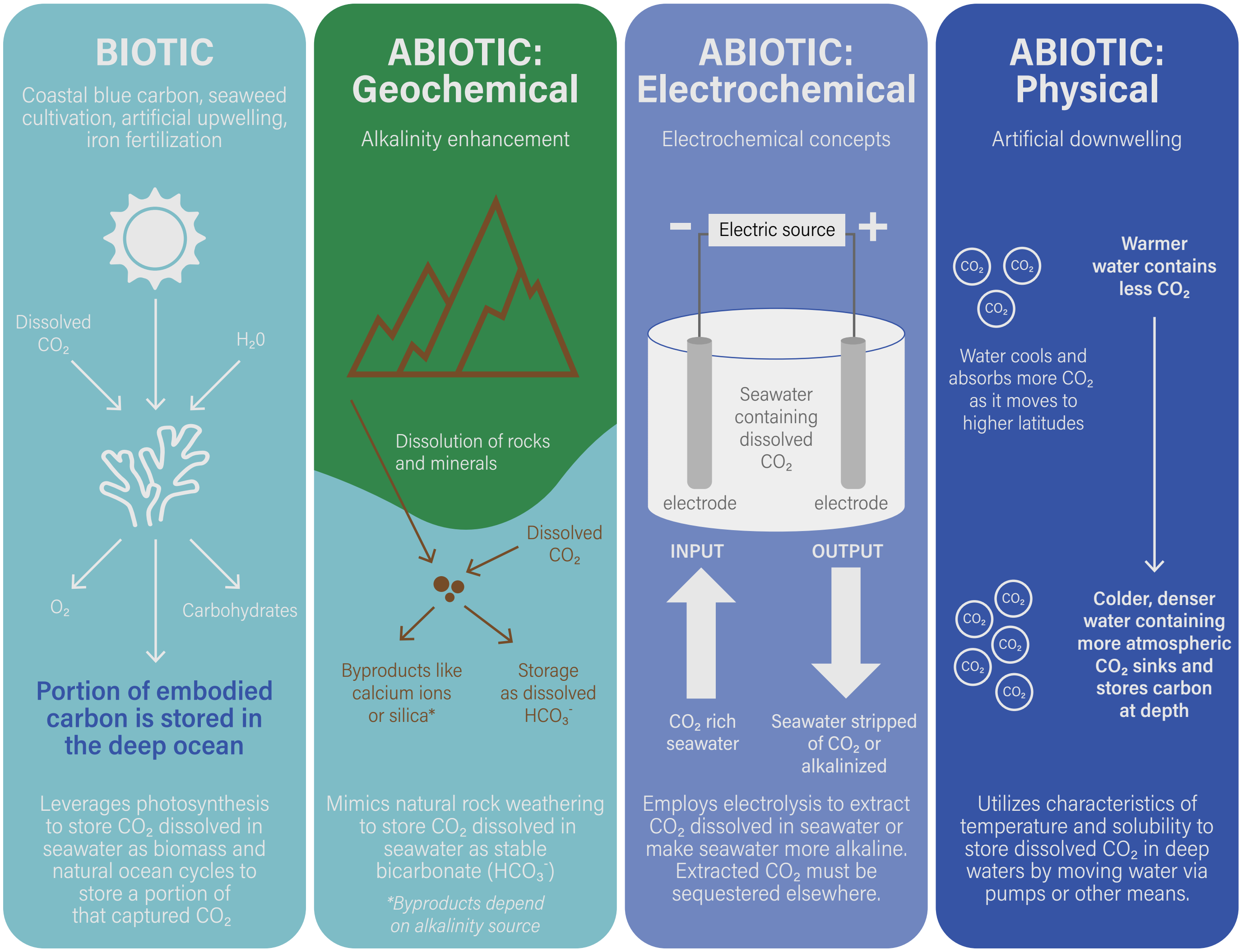
We do not consider development of ocean CDR approaches that solely prioritize cost effectiveness and carbon removal efficacy as responsible, although these considerations will be foundational to whether a given approach is viable for deployment.

It bears emphasizing that the potential negative impacts of large-scale ocean CDR will not be equally distributed. The nature of ocean ecosystems, systems, and currents makes the potential for transboundary impacts high and likely widely dispersed. Technology deployed by one country either within its national jurisdiction or on the high seas has the potential to impact communities across the globe. Ocean health has a profound impact on people in all countries—landlocked and coastal alike—through tourism, food and medicine production, global climate regulation, nutrient cycling, and ecological services (NOAA 2021c). But, degraded ocean health can more acutely impact people living in developing countries: Of the 10 percent of the global population that relies on the ocean as a food and employment source, 95 percent live in developing countries (Taylor et al. 2019), making ocean health an aspect of climate justice.

Given the increasing interest in and possibility of ocean CDR deployment, this report presents a landscape of prominent proposed ocean CDR approaches; provides an overview of global governance considerations; and offers cross-cutting recommendations for how global climate and ocean researchers, stakeholders, and decision-makers can pursue responsible development and deployment.

The following sections summarize seven ocean CDR pathways (Figure 3) that have been proposed in the literature and in some cases tested (and in the unique case of coastal blue carbon restoration, deployed for decades), including their associated carbon removal potentials, costs, geographic considerations, risks, key research priorities, and governance considerations. The ocean CDR approaches covered here include coastal blue carbon restoration, macroalgae cultivation, iron fertilization, alkalinity enhancement, electrochemical approaches, artificial upwelling, and artificial downwelling.

FIGURE 3 | The Basic Functions and Underlying Ocean-Based Carbon Removal Approaches



Notes: Abbreviations: CO_2 = carbon dioxide; H_2O = water; O_2 = oxygen; HCO_3^- = bicarbonate ions. Ocean carbon dioxide removal approaches leverage biotic and abiotic processes to convert atmospheric CO_2 into carbon stored as dissolved bicarbonate or biomass stored on the ocean floor.

Source: Authors, based on information in NASEM (2021).

1.1 ABOUT THIS REPORT

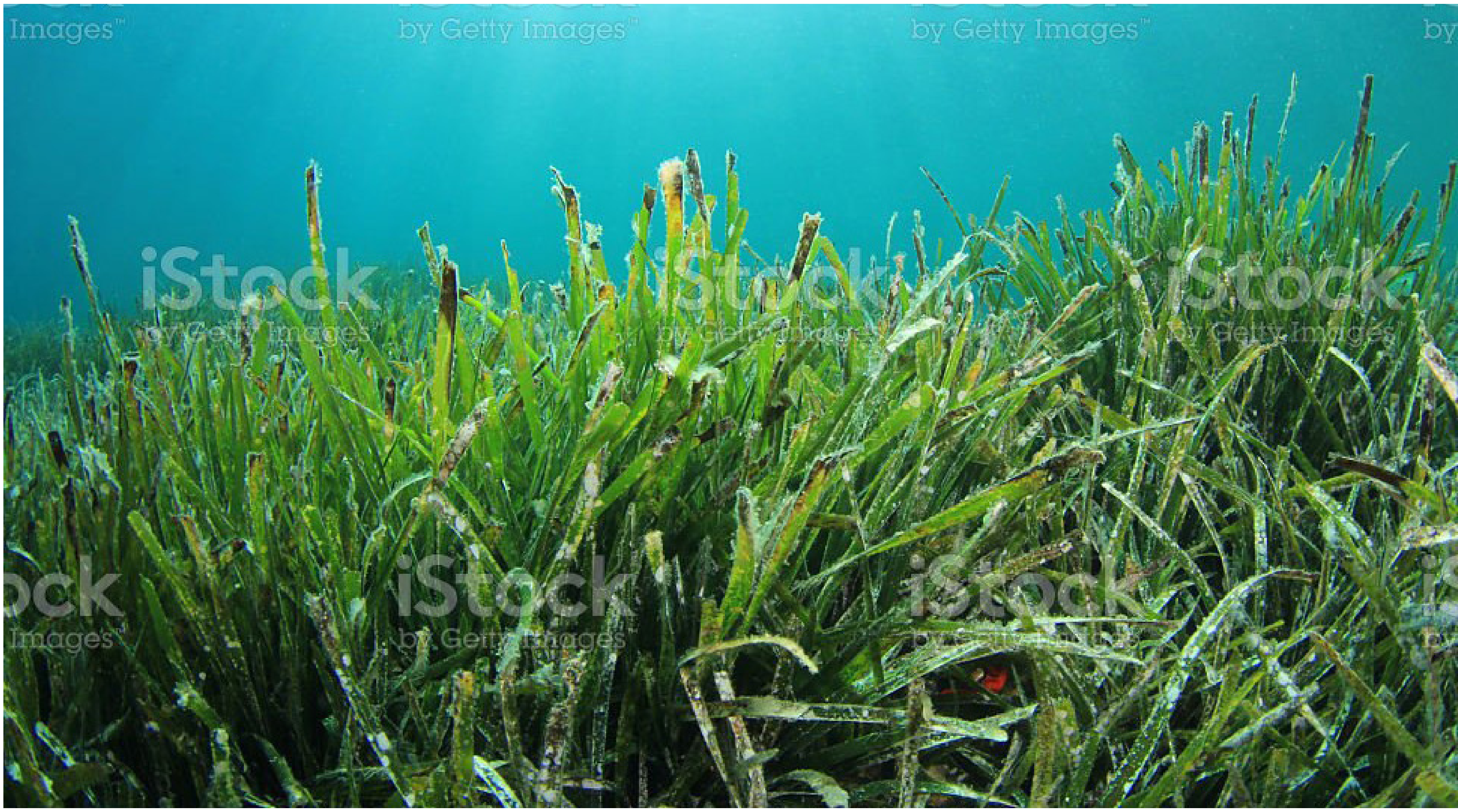
This report first presents an overview of leading ocean carbon removal approaches, including information on how the carbon removal pathway works, its potential scale of carbon removal, expected costs of deployment, potential ecological and social risks of deployment, geographic hotspots, and research priorities. The second half of the report focuses on the governance landscape, including the legal framework in national and international waters, and additional governance considerations like stakeholder engagement and measurement, reporting, and verification.

The information presented here is synthesized using recent comprehensive reports—namely, the National Academies of Sciences, Engineering, and Medicine's *Research Strategy for Ocean Carbon Dioxide Removal and Sequestration* (NASEM 2021) and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection's *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques* (GESAMP 2019)—as well as scientific journal articles, gray literature, and interviews with scientists and researchers working in these fields.

We include in scope concepts that increase the capture and sequestration of atmospheric CO_2 occurring in the ocean or in coastal regions. Because of this, we exclude from consideration concepts where CO_2 that is captured on land is ultimately transported to and stored in the ocean, such as the addition of reactive minerals to croplands (in which removed CO_2 is converted to dissolved bicarbonate in runoff water that ultimately flows into the ocean); depositing terrestrial biomass into deep ocean water (in which CO_2 fixed through photosynthesis by terrestrial plants is directly stored in the ocean); and storing concentrated CO_2 captured from industrial sources, such as power plant flue gas, in seawater or in geological formations below the seabed. Similarly, because our focus is on carbon removal, we exclude solar radiation management and albedo modification concepts, which are proposed geoengineering approaches that do not reduce atmospheric CO_2 concentrations.

We divide proposed approaches into two broad categories based on how carbon is captured and stored—biotic and abiotic approaches. There are multiple ways to categorize ocean CDR approaches—this classification is helpful for understanding how the approaches function, but other types of classification—for example, those based on technological or operational aspects—may be more useful for governance and deployment considerations. For example, both ocean fertilization and some forms of alkalinity enhancement involve adding materials to seawater, so these approaches would be considered similar activities under international law and would require similar infrastructure (e.g., ships), despite having very different underlying scientific principles.

This report is meant to inform decision-makers at international institutions, particularly in this UN Decade of Ocean Science (2021–2030), as well as researchers in nongovernmental organizations, the private sector, philanthropy, academic institutions, and government bodies who are assessing the potential of ocean CDR approaches over the coming years.



CHAPTER 2

Ocean Science Concepts

Natural patterns of water, nutrient, and carbon circulation are the basis of the complex ocean ecosystem and the ecosystem and climate benefits it provides. The physical, chemical, and biological aspects of oceanography are interlinked and can be leveraged to facilitate and influence ocean carbon removal approaches.

Several key ocean science concepts that help facilitate or influence ocean-based carbon removal approaches are explained here and referred to in the following sections, which examine each ocean CDR approach.

2.1 PHYSICAL OCEANOGRAPHY

The global ocean covers 70 percent of the Earth's surface, and contains approximately 1.3 billion cubic kilometers of water with an average depth of 3,700 meters (NOAA n.d.a).

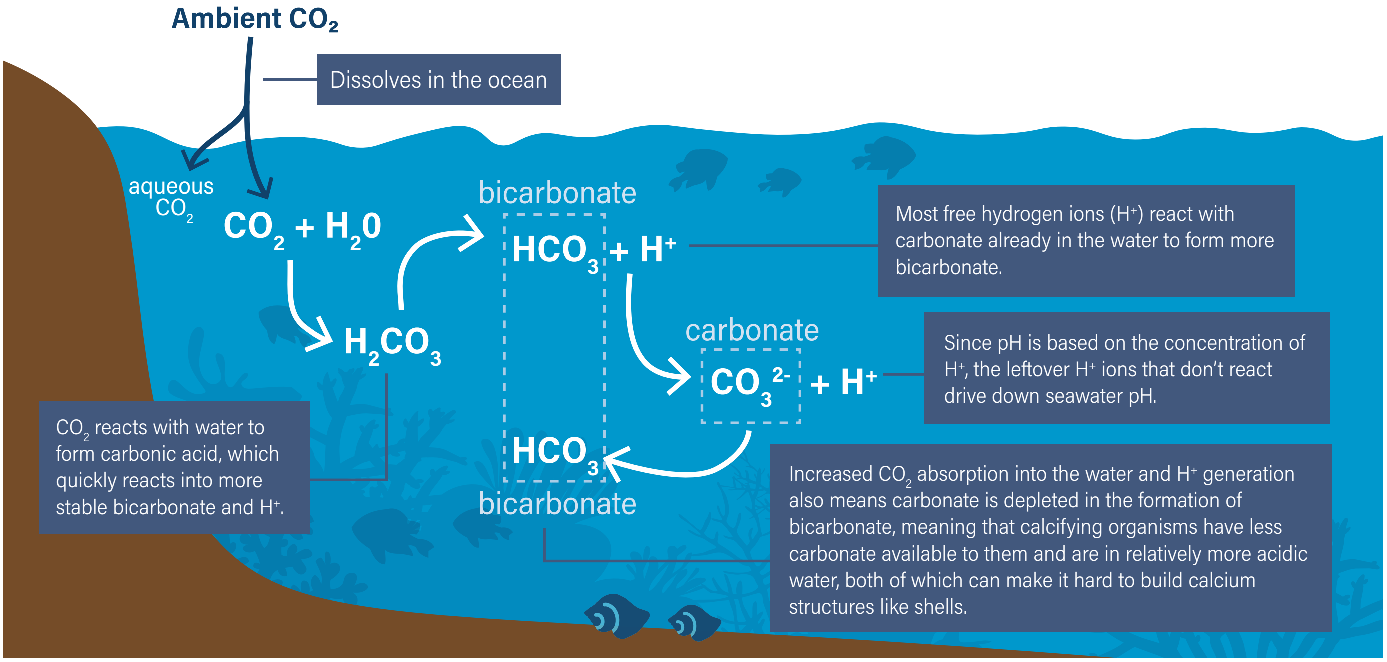
Water in the ocean forms three main layers. The uppermost is the surface (or mixed) layer, in which wind and other processes mix the water, making temperature and salinity (salt content) the same throughout the layer. It can be shallower than 20 meters in summer and deeper than 500 meters in winter, and varies significantly by location (de Boyer Montégut et al. 2004). Below the surface layer is the thermocline, where temperature falls quickly and salinity increases. The bottom-most layer is the deep ocean, which is colder and saltier than the surface, and represents about 90 percent of the ocean's volume.

Ocean waters are constantly in motion, with complex circulation patterns. The largest of these is the global ocean conveyor belt, in which warm surface waters cool in the Northern Atlantic, becoming denser and sinking to the deep ocean. This deep water flows south into the Indian, Pacific, and Southern Ocean basins, eventually upwelling back to the surface and warming before flowing northward to repeat the cycle (NOAA 2021b). Many local regions of upwelling and downwelling also occur throughout the ocean and along coastlines. Water in the deep ocean remains there for 300 to 500 years, or even longer in some locations (Priede 2017).

2.2 CHEMICAL OCEANOGRAPHY

The ocean is a significant natural carbon sink, holding around 42 times more carbon than the atmosphere (Friedlingstein et al. 2022). Most of this is in the form of molecules such as CO_2, bicarbonate ions (HCO_3^-), and carbonate ions (CO_3^{2-}), which are collectively known as dissolved inorganic carbon (DIC).

FIGURE 4 | Fate of Carbon Dioxide Absorbed into the Ocean



Most free hydrogen ions (H^+) react with carbonate already in the water to form more bicarbonate.

Since pH is based on the concentration of H^+, the leftover H^+ ions that don't react drive down seawater pH.

CO_2 reacts with water to form carbonic acid, which quickly reacts into more stable bicarbonate and H^+.

Increased CO_2 absorption into the water and H^+ generation also means carbonate is depleted in the formation of bicarbonate, meaning that calcifying organisms have less carbonate available to them and are in relatively more acidic water, both of which can make it hard to build calcium structures like shells.

Note: Abbreviations: CO_2 = carbon dioxide; H_2O = water; H_2CO_3 = carbonic acid; pH = potential of hydrogen; HCO_3^- = bicarbonate ion; CO_3^- = carbonate ion; H^+ = hydrogen ion.

Source: Authors.

The ocean and the atmosphere are constantly exchanging CO_2 and other gases. The net flux of CO_2 is determined by the relative concentration in air and surface seawater, and on average CO_2 moves from the air to dissolve into the surface of the ocean.

As ocean water absorbs CO_2 from the atmosphere, it reacts with water to form carbonic acid (H_2CO_3), which then quickly reacts into more stable bicarbonate and hydrogen ions (HCO_3^- and H^+) (Figure 4). Most free hydrogen ions react with carbonate (CO_3^{2-}) in the water to form more bicarbonate, but the leftover hydrogen ions lower the pH (potential of hydrogen) of the ocean, causing acidification, and the decrease of carbonate ions reduces the ability of certain organisms to build shells (Dickson n.d.).

The exact balance of how much CO_2 is converted to bicarbonate and carbonate ions is determined by seawater pH. Certain ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) raise pH, so their presence can shift this balance. The interconversion among DIC components is known as the ocean carbonate chemistry system. Ocean alkalinity enhancement and electrochemical approaches using alkalinity enhancement manipulate the ocean carbonate chemistry system by adding alkalinity, converting dissolved CO_2 into bicarbonate; this reduces the CO_2 concentration of the surface ocean and thereby increases the amount of atmospheric CO_2 that is dissolved in the ocean.

The exchange of CO_2 between air and seawater, known as air-sea gas exchange, takes place on relatively slow timescales that can vary from days to over a year depending on several factors, most importantly the depth of the surface (mixed) layer and the average wind speed (Jones et al. 2014). The time it takes to reach equilibrium has implications for several ocean CDR approaches that rely on CO_2-depleted surface waters absorbing atmospheric CO_2 and thus providing carbon removal.

In some regions of the ocean (the northern North Atlantic, the Atlantic subtropical gyres, and parts of the Southern Ocean) the timescale over which the atmosphere and surface ocean exchange CO_2 can be over one year. This means that seawater that has been depleted of CO_2—for example, due to biomass growth—must stay at the surface of the ocean for approximately this length of time to absorb atmospheric CO_2 equal to the amount fixed in biomass. If this water instead sinks below the surface before this, the atmospheric removal process is stopped, and may not resume for years or decades, depending on local circulation patterns. On a practical level, this means that approaches that rely on CO_2-depleted surface waters absorbing atmospheric CO_2 may have a low efficacy when deployed in certain locations, delivering significantly less than one metric ton of atmospheric CO_2 removal per metric ton of CO_2 fixed in biomass, or otherwise removed from surface waters (NASEM 2021; Bach et al. 2021; Berger et al. 2022).

CO_2 is more soluble in cold water than in warm water, meaning that as ocean temperatures rise due to climate change, solubility of CO_2 in seawater will decrease, lessening the ocean's ability to absorb it (Bopp et al. 2015). As surface seawater cools in the North Atlantic, it absorbs a relatively large amount of CO_2 before sinking to the deep ocean. This process, known as the "solubility pump," moves atmospheric CO_2 into the deep ocean. Deep ocean water tends to have a higher concentration of CO_2 than surface water due to the effects of temperature and pressure; when deep ocean water upwells to the surface, some of this CO_2 comes out of solution (outgasses) and is released back into the atmosphere (Bopp et al. 2015).

2.3 BIOLOGICAL OCEANOGRAPHY

The ocean is full of plant and animal life. At the base of the food chain are phytoplankton, which are microscopic, single-celled organisms that live suspended in near-surface ocean water and play a key ecological role in the ocean. Phytoplankton use photosynthesis to build biomass, consuming CO_2 on a scale comparable to terrestrial forests, and are responsible for most of the transfer of CO_2 from the atmosphere to the ocean (NASA 2010; Sigman and Hain 2012). Because of the important relationship between phytoplankton and atmospheric CO_2, approaches that spur additional phytoplankton growth have been proposed that leverage this relationship to increase the ocean's removal of atmospheric CO_2.

When phytoplankton grow, they take in DIC along with other nutrients in the ocean's surface layer and convert it into organic compounds that make up the phytoplankton's biomass (Bopp et al. 2015; Sigman and Hain 2012).

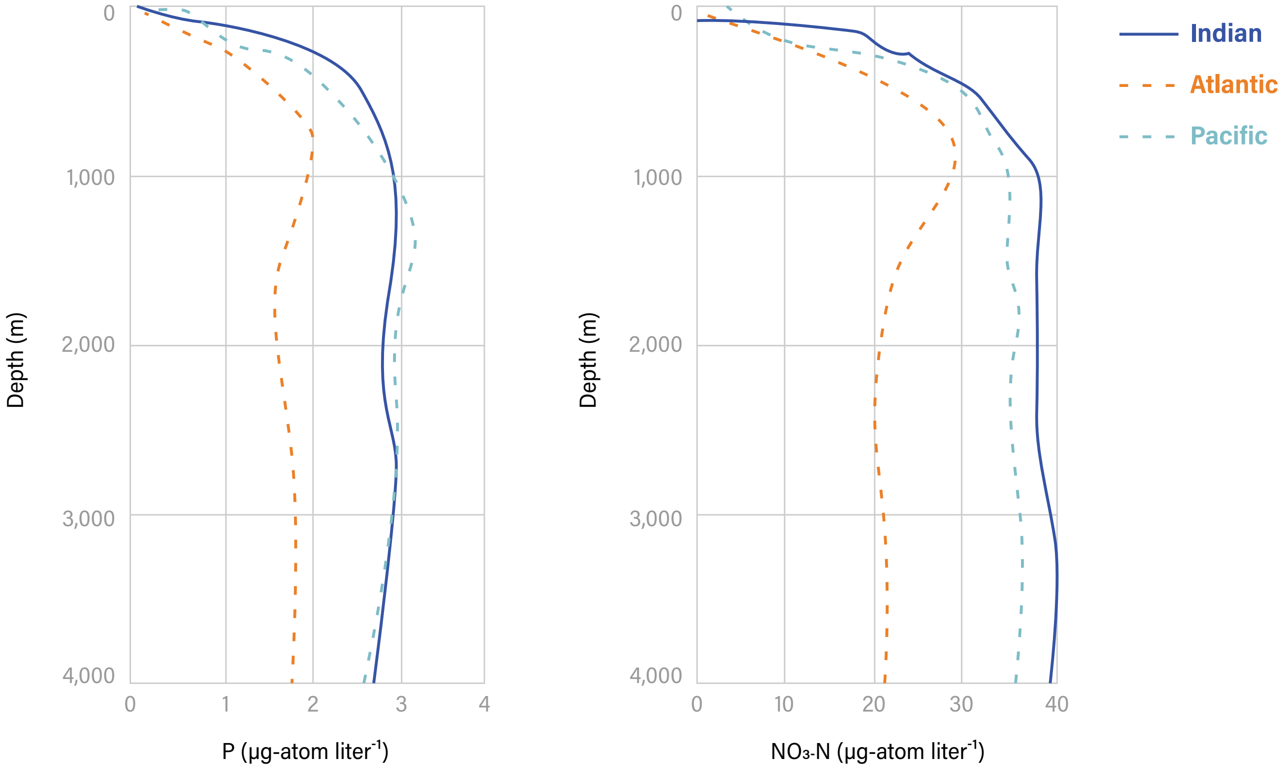
Photosynthesis happens only in the upper depths of the ocean where light penetration is sufficient, and is limited by nutrient availability. In many locations, the surface concentration of nutrients is relatively low because of rapid recycling by biological activity, while deeper waters have higher nutrient concentrations due to the lack of photosynthesis. In some regions known as high-nutrient, low-chlorophyll, an absence of micronutrients such as iron limits photosynthesis, and other nutrients reach higher concentrations at the ocean surface (NASA 2010).

Phytoplankton growth is generally determined by the availability of nutrients such as nitrogen, phosphorus, and iron. In much of the low-latitude ocean, nitrogen is the limiting nutrient, while in the Southern Ocean and eastern equatorial Pacific the limiting nutrient is iron. Nutrients in surface layers of the ocean are taken up by phytoplankton and shifted downward as this biomass sinks. When that biomass decays it releases nutrients at deeper levels of the ocean (Figure 5), causing a steady export to the deep ocean which increases deep water nutrient concentrations. For this reason, upwelling of deep ocean water can often bring large amounts of nutrients to the surface layer, causing rapid growth of phytoplankton (Ustick et al. 2021; Bristow et al. 2017; Moore et al. 2013). However, this can also be accompanied by the release (outgassing) of CO_2 from this deep ocean water.

Nutrient availability varies across latitudes as well, with generally greater nutrient availability at higher latitudes due to the presence of natural upwelling sites (Pickup and Tyrrell 2020).

Small particles of carbon that originally come from plants and animals, usually through decomposition, are known as "dissolved organic carbon" (DOC). While most DOC is recycled in the surface ocean through grazing or decomposition, between 0.1 and 1 percent sinks to depths where it is stored in seabed sediments for millennia (Bopp et al. 2015). This process is known as the "biological carbon pump" (Figure 6).

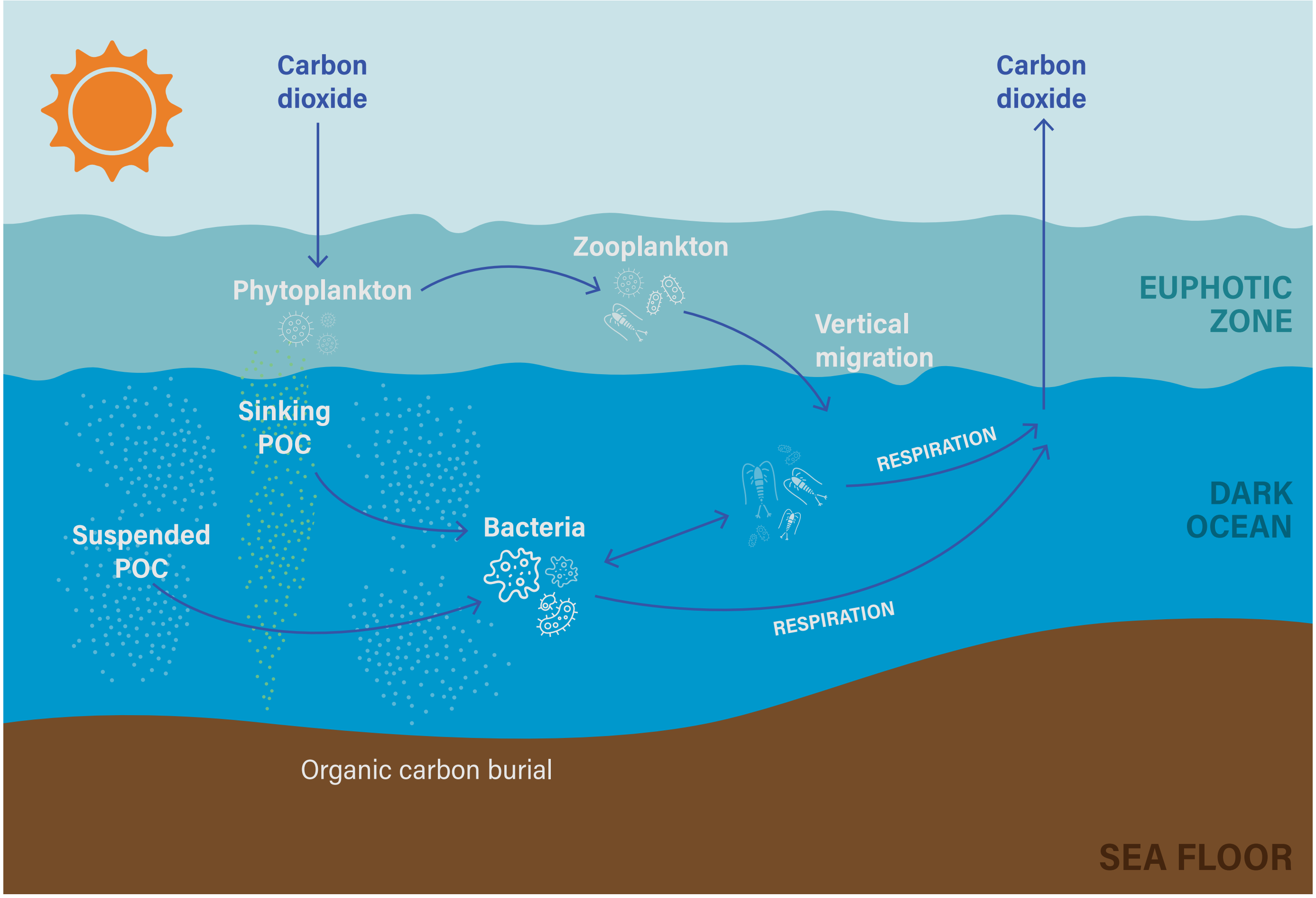
FIGURE 5 | Vertical Distribution of Phosphate and Nitrate in the Ocean



Note: Abbreviations: m = meter; P = phosphate; μg-atom liter^{-1} = microgram atoms per liter; NO_3-N = nitrate nitrogen.

Source: UoH 2016.

FIGURE 6 | Illustration of the Biological Carbon Pump

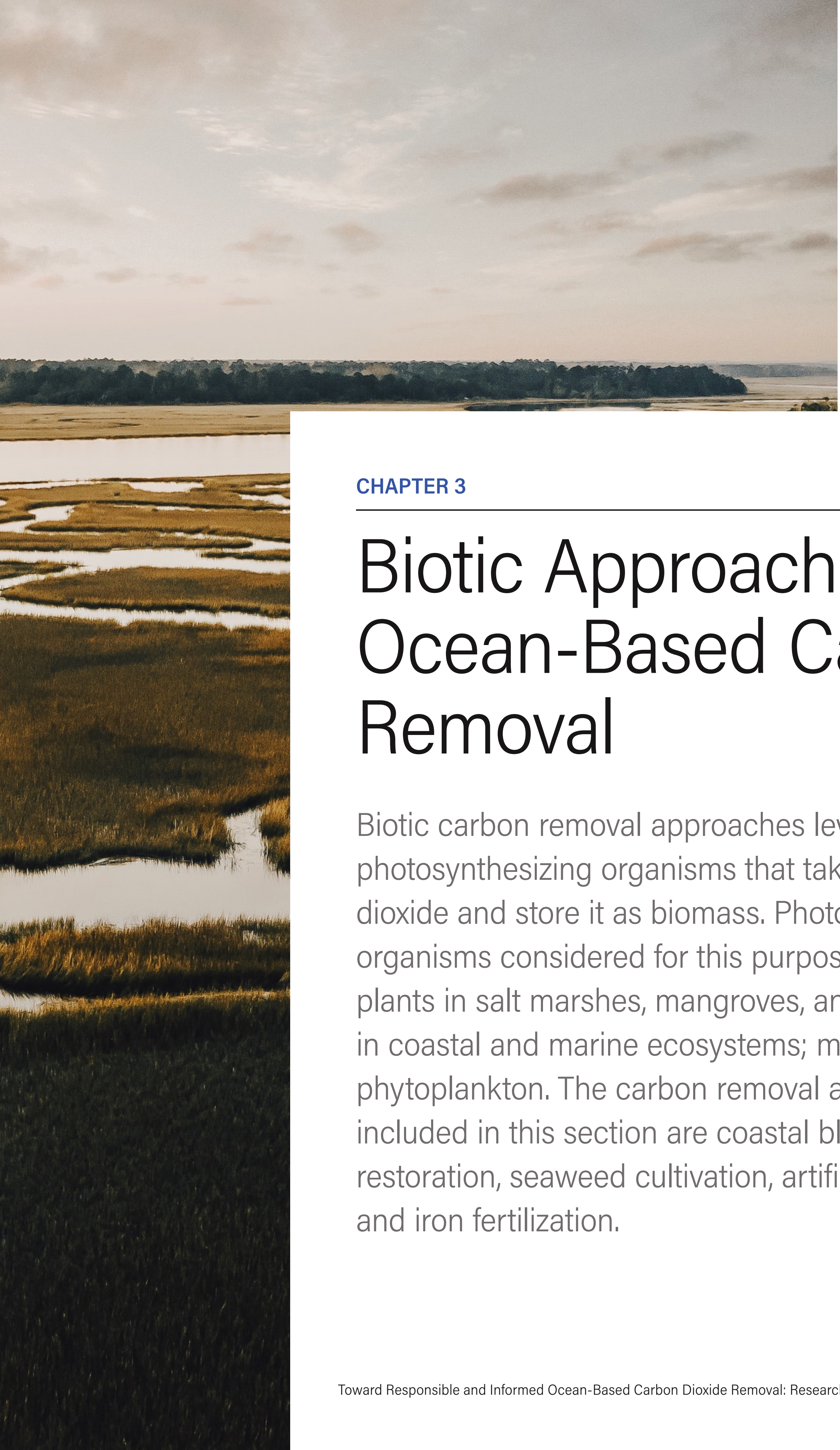


Note: Not to scale. Abbreviations: CO_2 = carbon dioxide; m = meter.
Source: NOAA 2010.

Carbon removal processes that aim to increase phytoplankton growth—iron fertilization, macronutrient fertilization, and artificial upwelling—are attempting to accelerate or increase the biological pump.

Macroalgae, or seaweed, are large aquatic plants that also use photosynthesis to consume DIC and build biomass. While macroalgae are generally buoyant, portions of their biomass can break off and sink to the ocean depth, transporting carbon. Macroalgae methods for carbon removal work by either harvesting the produced biomass for a range of uses to displace emissions-intensive products or intentionally sinking macroalgae to move its embodied carbon to the ocean depth. Studies show that the macroalgae biomass may not all make it to depth; a portion is shown to remineralize, or through a series of reactions, break down into inorganic forms and be re-consumed in the water column (Wu et al. 2022). Some macroalgae methods involve artificial upwelling to bring additional nutrients to the surface to promote growth. Coastal wetland plants, like mangroves, also take up CO_2 via photosynthesis and sequester carbon in plant biomass and (shallow) sediment.

Many marine organisms such as corals, shellfish, crustaceans, and starfish—known generically as "calcifiers"—use dissolved calcium ions in seawater to build shells and skeletons out of calcium carbonate. Their ability to extract calcium from seawater depends on having a relatively high concentration of calcium ions. This concentration is measured using the concept of "aragonite saturation state," referring to the most common marine form of calcium carbonate (aragonite). Ocean acidification directly reduces the concentration of calcium ions and thus the aragonite saturation state, leading to a range of negative impacts on marine calcifiers (Figuerola et al. 2021).



CHAPTER 3

Biotic Approaches to Ocean-Based Carbon Removal

Biotic carbon removal approaches leverage photosynthesizing organisms that take up carbon dioxide and store it as biomass. Photosynthesizing organisms considered for this purpose include the plants in salt marshes, mangroves, and seagrasses in coastal and marine ecosystems; macroalgae; and phytoplankton. The carbon removal approaches included in this section are coastal blue carbon restoration, seaweed cultivation, artificial upwelling, and iron fertilization.

A summary of the ocean CDR approaches covered in this report is included at the end of Section 4 in Table 1.

3.1 COASTAL BLUE CARBON

How It Works

In this report, coastal blue carbon[1] refers to carbon that is captured and stored by coastal and marine ecosystems including salt marshes, mangroves, and seagrasses (NASEM 2019). Plants in these environments capture and fix atmospheric carbon through photosynthesis, and plant organic matter is accumulated and buried in coastal sediment, where it can persist for longer periods than in terrestrial soil (NASEM 2019). Protecting and conserving existing coastal ecosystems is critical to maintaining carbon stores and preventing emissions increases that would come with their degradation (NASEM 2019; Hoegh-Guldberg et al. 2019). Ecosystem restoration can also provide additional carbon removal and is the focus of this section. Carbon removal can be increased by restoring lost or degraded coastal ecosystems, improving management to increase carbon sequestration in existing ecosystems, or establishing new coastal habitats (Williamson and Gattuso 2022).

While these ecosystems cover only around 49 million hectares (Mha), they are of particular interest in terms of carbon removal because their annual carbon sequestration rates are several times greater than those of terrestrial forests per hectare (NOAA 2021a), albeit with high variability across ecosystems and locations (Williamson and Gattuso 2022). Coastal blue carbon ecosystems can also store carbon for centuries to millennia, far longer than carbon in terrestrial soils, due to high salinity and low oxygen conditions that inhibit decomposition (Mcleod et al. 2011; Pendleton et al. 2012).

However, these ecosystems are threatened by human-induced land use change, sea level rise, rising temperatures, and salinity and pH changes. The global area of seagrass extent has decreased by 29 percent since the late 1800s (Waycott et al. 2009) and 20–35 percent of mangrove area has been lost over the last 50 years (Goldberg et al. 2020). Loss of coastal blue carbon ecosystems leads to negative outcomes in terms of increased emissions and the loss of the many other ecosystem services and livelihood benefits these ecosystems provide.

Blue carbon ecosystems provide numerous benefits aside from carbon removal, like coastal resilience, improved water quality, and biodiversity, which make them economically valuable. (As noted above, from the perspective of increasing carbon removal, these are co-benefits, but in most cases, they are the primary intended outcome of coastal ecosystem restoration projects.) Co-benefits of intact coastal wetland ecosystems come from ecosystem services like reducing erosion, improving water quality, maintaining healthy fisheries, providing recreation, reducing the impacts of sea level rise, reducing the onshore effects of storm surges and flooding, and increasing biodiversity, among others (IPCC 2019). Crucially, many of these resiliency benefits will become even more necessary to counter the effects of climate change. Restoring and protecting coastal wetlands also helps support livelihoods that depend on fishing and other coastal activities (Hoegh-Guldberg et al. 2019).

Compared with other approaches, coastal ecosystem restoration has been practiced for decades (though generally not for the purpose of carbon removal) so there are relatively fewer uncertainties regarding the risks of negative impacts on people and the environment. However, as coastal blue carbon is increasingly considered as a means to provide greater levels of carbon removal, accurate and reliable carbon accounting presents uncertainties that can affect carbon crediting (Williamson and Gattuso 2022).

Carbon Removal Potential

Estimates for the potential to increase carbon removal by restoring lost coastal wetlands vary but appear to be relatively modest compared with the total carbon removal need. Hoegh-Guldberg et al. (2019) estimate 64–110 million metric tons of carbon dioxide per year ($MtCO_2$/yr) globally by 2030 and 200–330 $MtCO_2$/yr by 2050; the National Academies estimates a potential maximum rate of 130–800 $MtCO_2$/yr (NASEM 2019), and Griscom et al. (2017) estimate a cost-effective potential of 202 $MtCO_2$/yr and a maximum potential of 841 MtO_2/yr. Some of the higher estimates are based on the total extent of coastal ecosystems that have been lost and assume that this same area can be restored, which may not be viable given development and land use change in the intervening years (Williamson and Gattuso 2022). Protecting existing ecosystems could avoid an additional estimated 250–760 $MtCO_2$/yr (Hoegh-Guldberg et al. 2019).

Mangroves, salt marshes, and seagrasses are estimated to hold up to 25 $GtCO_2$ that has built up over thousands of years (NASEM 2019). The extent of all three ecosystems is declining: Nearly 50 percent of coastal wetlands have been lost over the last 100 years and we continue to lose around 0.6 Mha/yr (IPCC 2019; Griscom et al. 2017). While mangrove degradation has slowed in recent years, seagrasses are declining in net terms (Boehm et al. 2021). Whether these coastal ecosystems are a net sink or source of emissions is uncertain: Estimates point to total emissions from degradation of 150–1,020 $MtCO_2$/yr (Pendleton et al. 2012) and annual sequestration of 308–855 $MtCO_2$ (NASEM 2019). Non-CO_2 gases must also be accounted for, but their fluxes are highly variable by location and over time, making global estimation difficult (Rosentreter et al. 2021).

Despite the relatively limited scale of carbon removal that blue carbon is expected to be able to provide at the global level, it is a critical approach alongside research and development of more frontier and nascent approaches given its numerous co-benefits, limited trade-offs, social acceptability, and relative readiness for increased deployment.

Cost of Deployment

The cost associated with coastal ecosystem restoration varies depending on project size, intervention type, ecosystem, location, and other factors. Estimates point to a wide range, from \$10/tCO_2 (NASEM 2019) and less than \$100/tCO_2 (Griscom et al. 2017) to more than \$500/tCO_2 for mangroves and close to \$500,000/tCO_2 for salt marshes (data were insufficient for seagrasses) (Taillardat et al. 2020). This wide range is due in large part to uncertainty associated with the carbon accounting for these ecosystem restoration activities, both within and across ecosystem types (Williamson and Gattuso 2022). Cost analysis based on area of restoration, rather than metric tons of CO_2 removed, indicates that mangrove restoration projects are generally the largest scale and least costly and seagrass restoration projects are the most costly; most restoration projects did not report monitoring costs (Bayraktarov et al. 2016).

Risks

Negative ecological and other effects are minimized if native coastal wetland species are used in restoration or natural regeneration, particularly in areas of previous known distribution. Potential risks include inappropriate site selection, potential for contaminants in added sediment, and effects of shoreline modification on sedimentation and other coastal landscape processes (NASEM 2019; Abelson et al. 2020). While potential ecological impacts appear minimal, any decisions made about the management and use of coastal ecosystems will affect the lives and livelihoods of the communities that live along these coasts.

Geographic Relevance

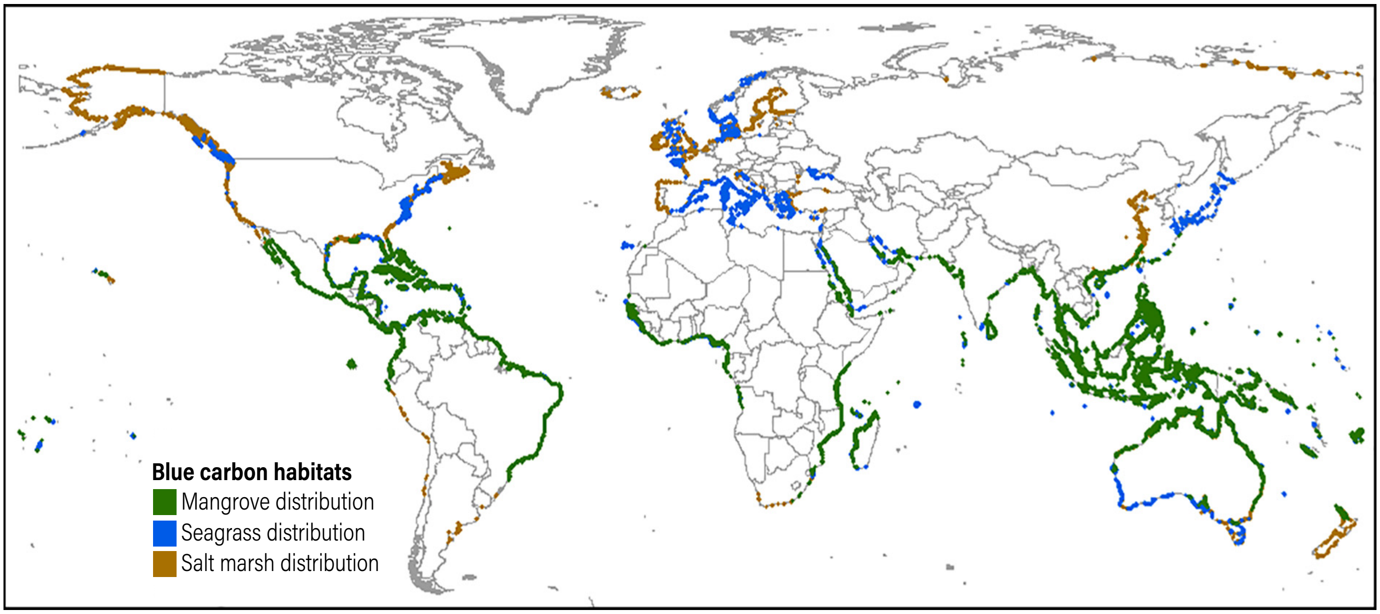
Figure 7 shows the global distribution of coastal blue carbon ecosystems; areas of ecosystem loss overlap with current distributions. Hotspots of loss vary over time, but recent data suggest that there have been disproportionately large mangrove losses in Southeast Asia (Myanmar, Malaysia, Indonesia, Philippines) (Friess et al. 2019), salt marsh losses in more temperate climates, and seagrass loss in areas where polluted water flows into coastal areas.

Priority Research Areas

Unlike the other proposed approaches, coastal ecosystem restoration has been practiced for decades, so further research is not needed to assess whether it is viable for deployment, but rather to improve the underlying process and data collection to better understand where and how it can be applied and how climate change is impacting prospects for restoration. Current research efforts include better understanding the role of climate change on carbon accumulation, improving global estimates of blue carbon ecosystem mapping (particularly for seagrasses), and improving management of these ecosystems (Macreadie et al. 2019).

Research should continue in the above-mentioned areas and also aim to resolve uncertainty around carbon accounting and greenhouse gas emission rates following disturbance. Research should also assess the extent to which alternate varietals of coastal plants could be identified for restoration to enhance carbon removal rates (NASEM 2019; Williamson and Gattuso 2022). If resolved, these could lead to better targeting of interventions and improvement in sequestration rates for coastal restoration projects.

FIGURE 7 | Global Distribution of Blue Carbon Ecosystems



Source: Himes-Cornell et al. 2018.

3.2 SEAWEED CULTIVATION

How It Works

Seaweed (also referred to as macroalgae) takes up dissolved inorganic carbon in water during photosynthesis and fixes it as biomass. As CO_2 in surface water is depleted, air-sea gas exchange moves CO_2 from the atmosphere into the ocean. Growing seaweed also excretes dissolved organic carbon, of which an unknown portion is stable over long time periods and can serve as an additional sequestration pathway (NASEM 2021; Krause-Jensen and Duarte 2016). Natural seaweed growth can contribute to carbon sequestration through both of these pathways; however, cycles of harvest and replanting could capture and sequester carbon at a faster rate.

Seaweed biomass can be purposefully moved to the deep ocean for sequestration through sinking, which reduces the likelihood that ocean mixing processes would bring embodied carbon back into contact with the atmosphere. The sinking depth that is required to ensure more than 50 years of sequestration of embodied carbon varies by location, but is generally in the range of 500 to 3,000 meters (Siegel et al. 2021).

Seaweed cultivation can occur in coastal countries' territorial waters but achieving large-scale carbon removal while minimizing ecological impacts and economic conflicts over space in coastal waters would likely require deployment farther from the coast and potentially in the high seas, where technological and practical challenges and nutrient availability considerations arise. Cultivation would require infrastructure, such as buoys; structural rope and rope on which seaweed grows; possibly infrastructure to upwell nutrient-rich water (which will also upwell CO_2) or pull seaweed to greater depths periodically to access nutrients; and ships and other materials needed for harvesting and transporting seaweed. Cultivation could also be paired with other infrastructure like offshore wind farms to minimize disruption and provide a source of power.

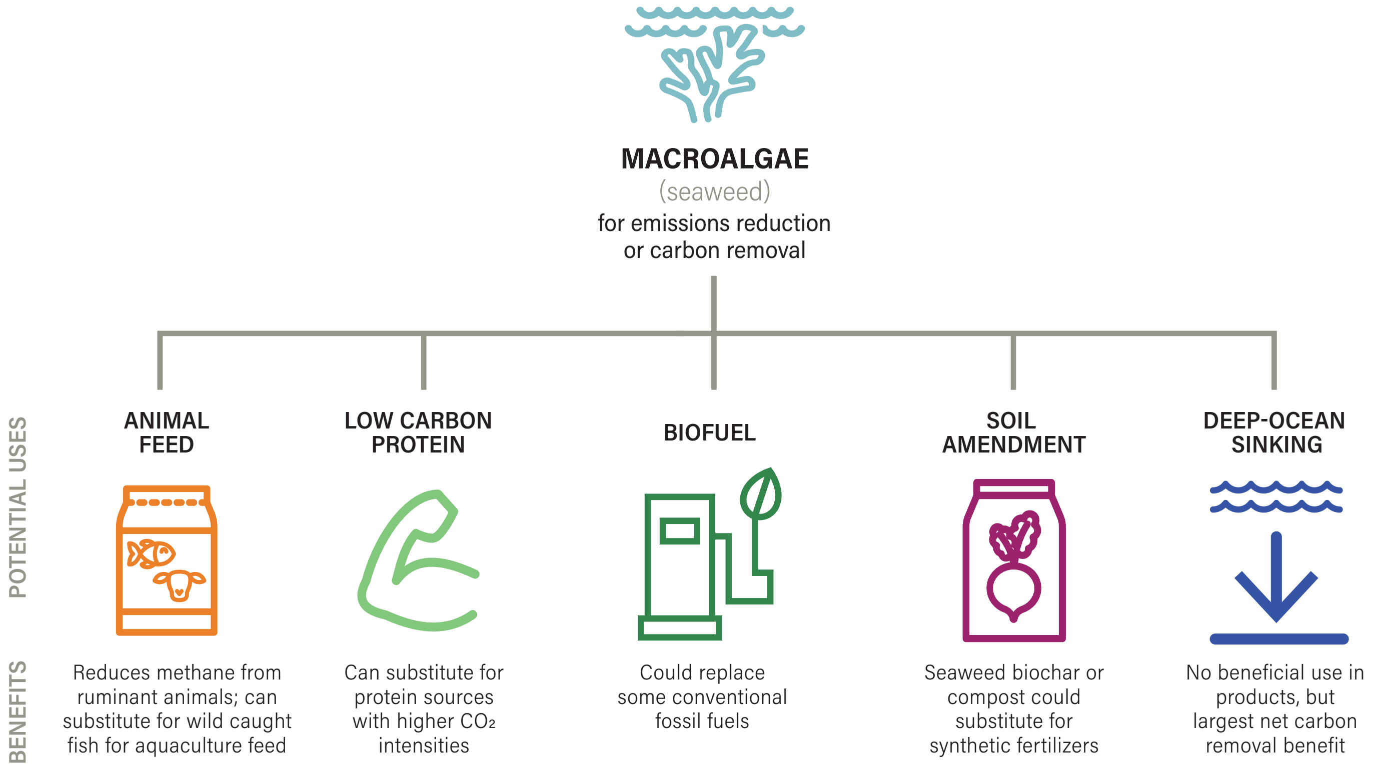
Rather than being sunk in the deep ocean, cultivated seaweed can also be harvested and used in the production of a range of products including food, animal feed, biofuel, pharmaceuticals, and fertilizer, among others (Figure 8). These end uses would generally not constitute carbon removal but could reduce the carbon intensity of these products and offer an economic return as the cost of cultivation is lowered through experimentation. Exceptions that could result in carbon removal include use of seaweed for biochar in soil or pyrolysis of seaweed with carbon capture and sequestration to make biofuel.

In addition to carbon removal, seaweed offers various potential co-benefits including increasing the pH of surface water and reducing the impacts of ocean acidification locally (Wahl et al. 2018; Xiao et al. 2021). These surface water impacts are especially relevant to calcifying organisms like oysters and other shellfish that are damaged by acidic waters. The shellfish aquaculture industry is showing increased interest in this type of integrated, multi-species farming in the northeast and northwest of the United States (Hickey 2018; Bigelow 2018). Seaweed cultivation also has the potential to support job creation and could improve food security—both as a direct source of food as well as by attracting fish to live alongside or in the macroalgae farms.

Seaweed cultivation has been proposed, and in some cases already used, to remove excess nutrients in eutrophic waters. In coastal applications, it can help dampen wave energy—in some cases it has been reported to reduce wave heights by up to 60 percent (Mork 1996). Suspended macroalgae aquaculture may be an option to stabilize shorelines from storm damage assuming structures can be engineered to withstand storm conditions (UoM 2018).

Seaweed cultivation and sinking for the purpose of carbon removal has drawn growing attention, with several companies offering this approach for carbon benefits. However, while seaweed cultivation appears to be a promising approach, some leading scientists contend that the growth in interest is outpacing the scientific knowledge base on environmental and social consequences and there is insufficient governance oversight (Ricart et al. 2022).

FIGURE 8 | Possible Uses and Benefits of Seaweed



Notes: Abbreviation: CO_2 = carbon dioxide. These are potential uses for cultivated seaweed that will have varying net-greenhouse gas benefits and ancillary impacts depending on the location and details of each approach.

Source: Based on Duarte et al. (2017).

Carbon Removal Potential

It is estimated that wild seaweed ecosystems sequester around 0.6 $GtCO_2$/yr (Krause-Jensen and Duarte 2016). Seaweed farming could add to this amount in areas where there is sufficient light and nutrients. Seaweed aquaculture is estimated to cover around 1,900 square kilometers (km^2) globally (roughly 2.5 times the area of New York City), while wild macroalgae covers around 3.5 million km^2 (roughly 2 times the area of Sudan) (Duarte et al. 2017; Froehlich et al. 2019).

Recent data indicate that macroalgae is currently cultivated on a scale of around 3 million metric tons (Mt) dry weight per year globally (capturing around 2.8 $MtCO_2$ assuming roughly 25 percent carbon content) (Duarte et al. 2017; Ferdouse et al. 2018), and the vast majority of macroalgae harvested every year is cultivated rather than wild. The National Academies estimates 7.3 million hectares (roughly the size of Panama or a 100-meter-wide belt around 63 percent of all global coastline) would be needed to produce enough seaweed to sequester 0.1 $GtCO_2$/yr (NASEM 2021). Achieving this scale or larger would require a massive logistical effort and most likely use both coastal and open ocean areas.

Sinking seaweed for carbon removal also comes with inherent risks and challenges around the carbon accounting for and permanence of this approach, which can affect carbon removal potential. Understanding the efficacy of carbon removal through seaweed cultivation is challenging and complex as it requires measuring particulate and dissolved organic carbon in ocean waters that are constantly in motion, along with considering air-sea gas exchange, or movement of CO_2 from the air into locally CO_2-depleted waters (Hurd et al. 2022; see Section 2, Ocean Science Concepts). There is significant scientific uncertainty about the degree to which air-sea gas exchange limits the efficiency and speed of atmospheric CO_2 absorption into seawater where macroalgae have been growing. In terms of permanence, since ocean currents slowly circulate ocean water, carbon that is sunk to depth will eventually make its way back to the surface. The time period over which that happens depends largely on how deep the material has sunk and where (Siegel et al. 2021).

Others contend that carbon removal estimates are incomplete and that seaweed cultivation could add carbon in net terms because of increased consumption and respiration of filter feeders (Gallagher et al. 2022), pointing to the need for more research on carbon accounting and monitoring at an ecosystem level.

Given the complexities of the overall process from seaweed cultivation to atmospheric CO_2 drawdown, new forms of monitoring and verification will likely be needed to ensure that these CDR approaches are achieving their stated climate impact. These will likely include improved modeling, enhanced measurements, and broad accounting frameworks that draw on forensic accounting in other fields (Hurd et al. 2022).

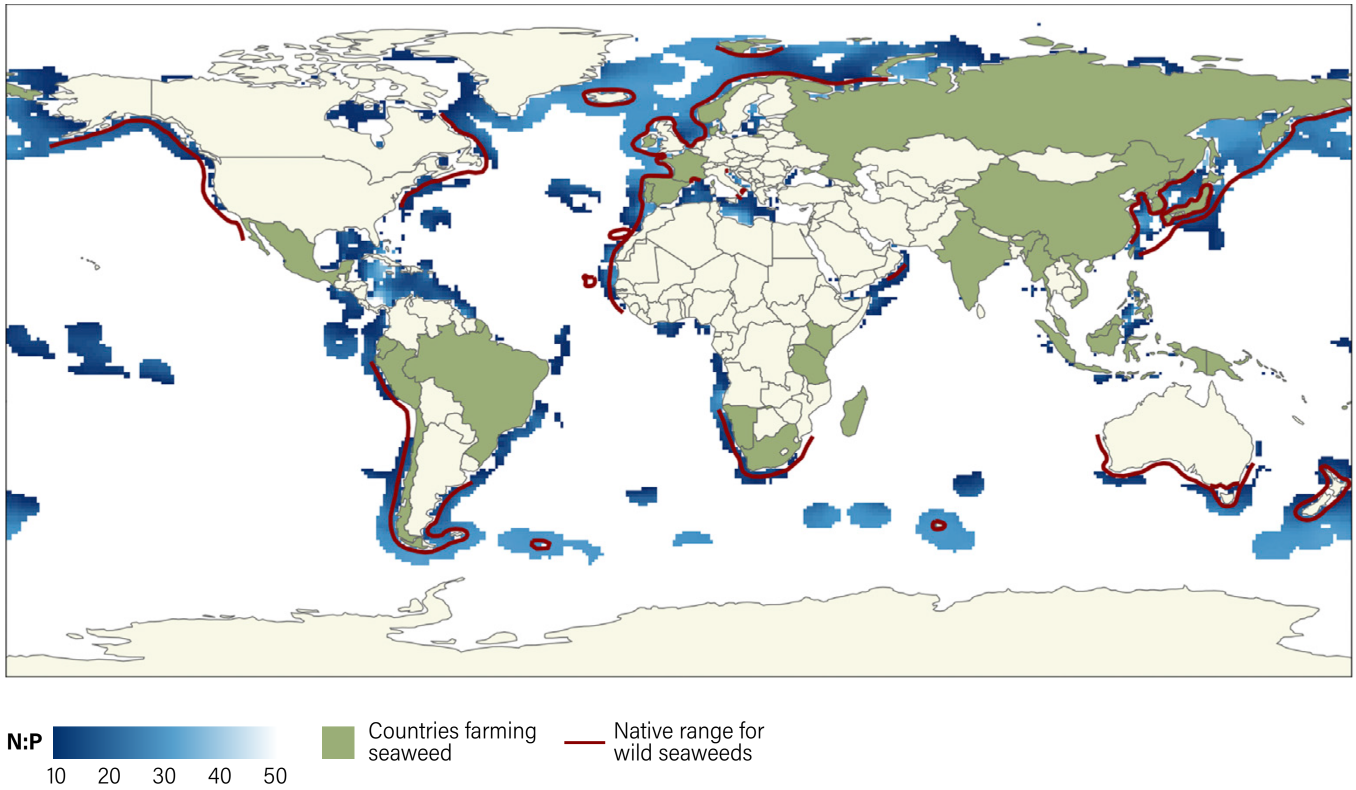
Cost of Deployment

Cost remains highly uncertain and will likely vary by species, cultivation method, and geography. Costs range from \$65/tCO_2 to more than \$3,000/tCO_2 depending on labor costs, productivity per unit area, and other factors (Milledge and Harvey 2016; van den Burg et al. 2016; Bjerregaard et al. 2016). It is likely that costs will decline with larger-scale systems and experience. The U.S. Advanced Research Projects Agency–Energy is targeting \$75/tCO_2 for seaweed cultivation for biofuel (NASEM 2021; see Box 1). Additionally, these costs exclude the revenue that could be generated from using seaweed in the production of economic products (Figure 2) as well as costs related to monitoring for carbon sequestration and environmental impacts. A key complication in understanding the overall carbon removal potential of this approach will be accounting for the larger carbon impact of nutrients that are consumed by seaweed and not available for other organisms (NASEM 2021).

Geographic Relevance

Large-scale seaweed farming today occurs mostly in Asia—particularly in China, Indonesia, Korea, and Japan—and primarily for food, carrageenan, and alginate production (Kim et al. 2017). Figure 9 shows locations that are suitable for macroalgae cultivation based on nutrient availability.

FIGURE 9 | Ecological Suitability Map for Macroalgae Aquaculture Overlaid with Countries Already Cultivating Macroalgae and Native Ranges for Wild Seaweeds



Notes: Abbreviations: N:P = nitrate to phosphate ratio. The optimum N:P ratio for seaweed growth is 30:1, but all ranges highlighted in blue are suitable.

Source: Froehlich et al. 2019.

Risks

The establishment of a new, large-scale seaweed cultivation industry will necessarily result in a range of ecological effects, differing for seaweed harvesting as compared with deep-ocean sinking. These impacts will depend on the scale and location of cultivation and many other factors. Unfortunately, the best current scientific understanding of these effects is incomplete, meaning there is a risk that impacts could exceed those that are discussed here.

Large-scale seaweed cultivation will lead to some degree of nutrient depletion (nitrogen and phosphorus) in surface waters as well as reduced light availability. The impacts of this are unclear, but reduced nutrient availability may limit the growth of natural phytoplankton communities and make them more susceptible to ocean warming. If this occurs at a significant scale, it would have wide-ranging negative impacts across ocean ecosystems and reduce natural carbon drawdown. However, quantifying these effects remains highly challenging (Boyd et al. 2022). Active upwelling of deep-sea water has been proposed to reduce or eliminate nutrient depletion, but this would potentially liberate significant amounts of dissolved carbon into the atmosphere, reducing CDR benefits and adding large additional uncertainties about ecosystem impacts (Koweek 2022).

Purposeful sinking of seaweed to the deep ocean presents risks to those ecosystems. Its decomposition and remineralization in deep waters can alter the natural balance of these processes, reduce oxygen concentrations, and increase nutrient and CO_2 concentrations, increasing acidity (NASEM 2021).

Because cultivated macroalgae are likely to be coastal species, introducing them to the open ocean would likely lead to the dispersal of non-native species to these ecosystems, including microflora (bacteria and viruses) and larger biota that accompany the seaweed. There are many uncertainties about how viable these would be and the impact they would have on native ecosystems, but evidence from tsunami-driven rafting suggests widespread dispersal is possible (Carlton et al. 2017).

The mechanical features of cultivated seaweed such as ropes, buoys, and rafts could potentially physically impact marine life, alter wave kinetic energy, and limit light penetration below the ocean surface. Other potential impacts include changes to dissolved oxygen, dissolved organic carbon, and local pH levels (NASEM 2021; Campbell et al. 2019). For methods that use sinking/deep-sea sequestration of seaweed biomass, impacts could include eutrophication, reduced visibility, and alteration of deep-sea food webs (NASEM 2021).

While macroalgae cultivation would need to be spread over large areas of the ocean to achieve large carbon removal potential, this distribution would also need to avoid impacting natural carbon stocks, particularly seagrass meadows, which are hotspots of carbon sequestration (Duarte et al. 2017).

Non-ecological impacts include competition for space with other marine uses, including potential to interfere with shipping or fishing activity, negative public perceptions of macroalgae being a nuisance, and changes in the distribution and structure of global seaweed production.

Priority Research Areas

Further research is needed in the following areas:

- Development of cultivation, harvesting, and/or sinking techniques, including selection of suitable species by geography, approaches to engineered structures for hosting macroalgae, and approaches to tracking the path of free-floating rafts
- Improved understanding of the selection of optimal sites for cultivation, harvesting, and/or sinking
- Development and assessment of methods to provide sufficient nutrients for growth, with minimal ecosystem impacts; this may include consideration of artificial upwelling techniques with careful attention to ecological impacts
- Improvement of monitoring and verification techniques at local and global levels, with an emphasis on understanding permanence and durability of storage
- Improvement of modeling and field measurements to enable understanding of seawater circulation patterns and their impact on air-sea CO_2 equilibrium and carbon removal efficacy
- Improved understanding of the ecological impact of large-scale macroalgae cultivation through broad modeling and field measurements
- Assessment of optimal end uses of cultivated biomass as there may be conflicts between the optimal uses for net carbon removal and the economically optimal uses for highest profit
- Estimation of life-cycle emissions of various macroalgae-produced products
- Identification of new products or improvement of products made with seaweed
- Identification of optimal approaches for sequestering cultivated seaweed in the deep ocean (e.g., optimal depth, location, species, speed of sinking)
- Improved understanding of the fate of biomass that is sunk, both on the seafloor and in deep ocean water

Recommendations are based on information in NASEM (2021) and GESAMP (2019).

BOX 1 | Federal Funding to Advance Seaweed Cultivation in the United States

The United States' Advanced Research Projects Agency–Energy (ARPA-E) has been working since 2017 through its Macroalgae Research Inspiring Novel Energy Resources (MARINER) project to improve seaweed cultivation and harvesting techniques to enable the United States to be a leader in the production of renewable biomass at an economically viable cost. ARPA-E is focused on improving macroalgae cultivation as a way to provide biomass mainly for applications like synthetic fuel production; however, the experience and learning in modeling, breeding, and cultivation of species; monitoring; and harvesting will be transferrable to seaweed cultivation for carbon removal. The project is ongoing, but key challenges like accessing nutrients, increasing productivity, and optimizing harvesting methods have emerged. With a target of \$75/tCO_2, researchers have also found that significant scale and higher production per hectare will be needed to achieve cost reductions.

Source:

[a] ARPA-E 2017.

3.3 OCEAN FERTILIZATION

How It Works

Phytoplankton growth is limited in various parts of the ocean by a lack of specific nutrients, primarily nitrogen, phosphorus, and iron. The concept of ocean fertilization is to artificially increase the availability of these limiting nutrients, stimulating additional phytoplankton growth and increased removal of dissolved inorganic carbon from seawater through photosynthesis. Some portion of this embodied carbon in phytoplankton biomass is exported to the deep ocean for permanent storage via the biological carbon pump.

In response to phytoplankton uptake of CO_2 from surface waters, additional atmospheric CO_2 will dissolve into CO_2-depleted surface waters, resulting in atmospheric carbon removal. However, the timescale of air-sea CO_2 equilibration varies significantly by location, potentially impacting the efficacy of iron fertilization to result in carbon removal (see Section 2, Ocean Science Concepts).

In this section, we focus primarily on ocean fertilization with iron. Although ocean fertilization can also be done with nitrogen or phosphorus, iron has been the primary focus of this approach because extremely small amounts are needed to spur phytoplankton growth—an iron-to-carbon ratio of approximately 1:100,000. The geological record provides evidence that natural additions of iron to the ocean via atmospheric dust lower atmospheric CO_2 levels (NASEM 2021; Martin et al. 1990). Iron fertilization involves adding small amounts of iron to areas of the ocean where phytoplankton growth is limited by a lack of iron.

In comparison to iron fertilization, macronutrient fertilization with nitrogen and phosphorus has also been proposed, but orders of magnitude more material would need to be applied per theoretical metric ton of carbon removed. However, macronutrient fertilization would be applicable in larger and more accessible areas of the ocean compared with iron fertilization. Overall, macronutrient fertilization has received less attention from the scientific community largely because so much more material would need to be added (NASEM 2021).

Thirteen artificial iron fertilization studies were conducted between 1993 and 2004 in which researchers added iron to the ocean (Yoon et al. 2018; NASEM 2021). Researchers also studied the impact of iron additions to the ocean in six "natural" iron fertilization studies between 1992 and 2011, in which iron was added to the ocean via natural processes, including wildfires and volcanic eruptions (Yoon et al. 2018; NASEM 2021). While all reported ocean fertilization experiments showed increased growth of phytoplankton, the necessary transfer of organic matter from the surface to the deep ocean and a corresponding uptake of atmospheric carbon into the ocean was not verified (NOAA 2010; Yoon et al. 2018). This leaves open the possibility that ocean fertilization is not effective as a carbon removal strategy, in addition to other significant uncertainties regarding viability that are discussed later in this section.

In 2008, an international moratorium was established under the Convention on Biological Diversity that prohibited ocean fertilization activities except for small-scale research studies (CBD 2008). However, in 2012 a private individual with a history of testing CO_2 removal techniques intentionally added more than 110 metric tons of iron (in the form of iron sulfate and iron oxide) to seawater west of Haida Gwaii, off the coast of British Columbia, with the stated intent of increasing salmon stocks (Biello 2012; Batten and Gower 2014). This event was not approved by any oversight body and was extremely controversial, being viewed by many as a direct breach of the moratorium. Of note, the Haida community of Old Massett, an Indigenous community, decided to sponsor these activities in their coastal waters with the intention of restoring depleted salmon runs and potentially receiving financial returns from carbon credits (Lezaun 2021).

While there was evidence of a large phytoplankton bloom after the application of iron, and the following year saw a record salmon harvest, it is unclear whether salmon stocks increased as a direct result of the iron fertilization or whether any carbon sequestration resulted. Outside of the uncertain scientific outcome, the event served as a flashpoint for many scientists and environmental advocates, prompting backlash and renouncement of iron fertilization as a technique (Piper 2019). Because iron fertilization requires comparatively little material to be added to induce significant change, it could be a particularly efficient means of carbon removal if viable and could be a way for climate-vulnerable communities, such as the Haida community of Old Massett, to take independent action at minimal cost. Conversely, because iron fertilization requires very small amounts of infrastructure and funding—which could potentially be supplied by an individual or small team without appropriate safeguards or scientific understanding as highlighted by this incident—the need for strong international and national governance frameworks is especially relevant.

Serious scientific concerns about the risks of iron fertilization persist today, with the controversial Haida Gwaii incident highlighting risks related to insufficient governance and the risk of deployment by individual actors (Piper 2019). However, the National Academies identified iron fertilization as one of two biotic ocean CDR approaches that are most suitable for further research, and work on a variation of ocean fertilization is actively emerging (NASEM 2021; see Box 2).

Carbon Removal Potential

It is well established that iron fertilization increases photosynthetic uptake of CO_2; however, its effectiveness as a carbon removal strategy depends on how much of that carbon is exported to the deep ocean for long-term storage and whether atmospheric CO_2 is then absorbed into CO_2-depleted surface waters before the seawater subducts away from the surface, which remains highly uncertain (NASEM 2021; NOAA 2010).

In the 13 experiments on artificial iron fertilization, varying amounts of iron sulfate were added via ships (Yoon et al. 2018). The amount of carbon reaching the subsurface ocean compared with total carbon captured from the air was different in each study, ranging from 8 to 50 percent (Yoon et al. 2018). Additionally, no experiments to date have been long enough to track how much carbon is permanently sequestered in the deep ocean; of the studies conducted, the duration of observation ranged from 10 to 40 days (Underwood 2020; NASEM 2021).

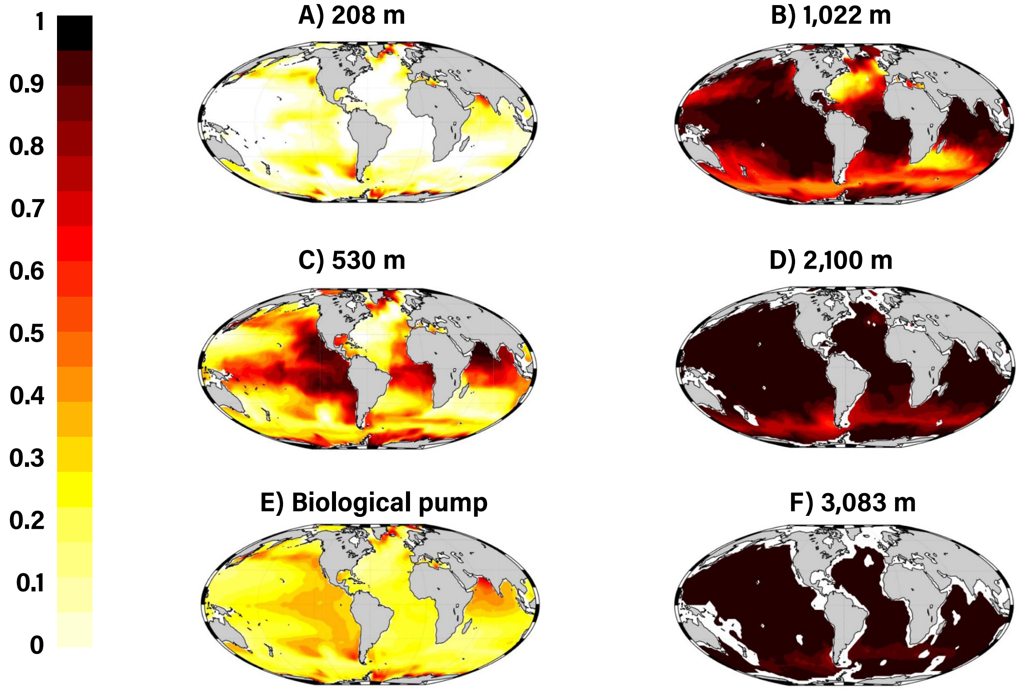
The technical potential for carbon removal via iron fertilization is estimated to be high: Based on modeling, GESAMP (2019) estimates up to 1 billion metric tons of carbon per year (GtC/yr; or 3.7 $GtCO_2/yr$) could be captured if 10 percent of the ocean surface is used, and the Royal Society (2018) also estimates an upper limit of 1 GtC/yr based on modeling of continuous iron application to all suitable areas of the ocean. More recently, the National Academies estimated a carbon dioxide removal potential of 0.1–1.0 $GtCO_2/yr$ with medium confidence (NASEM 2021). It noted a wide range of estimates of theoretical carbon removal scale in earlier studies, from a fraction of 1 GtC/yr to up to 3–5 GtC/yr (a fraction of 3.7 $GtCO_2$/yr up to 18.3 $GtCO_2$/yr). The surveyed modeling efforts use a diversity of modeling assumptions, which leads to the wide range of scale estimates, indicating a high level of uncertainty. Furthermore, the modeling in these evaluated studies often does not consider practical constraints for engineering large-scale deployment (NASEM 2021).

Modeling of macronutrient (nitrogen and phosphate fertilization) shows high theoretical potential; the practical scale will depend on the capacity to increase industrial production of fixed nitrogen and phosphate, and the willingness to dedicate that resource to carbon removal as opposed to terrestrial food production or other uses (Harrison 2017).

Recent modeling suggests that ocean CDR approaches that rely on increased primary productivity and the biological pump for sequestration will likely have low permanence, with 70 percent of captured carbon cycling back to the surface within 50 years (Siegel et al. 2021; see Figure 10). But, the amount of time that carbon is sequestered is expected to vary by location, with the Atlantic and Southern Ocean basins (the latter being a major area of iron fertilization experiments) expected to have shorter sequestration times and the Pacific and Indian Oceans expected to have considerably longer sequestration times (Siegel et al. 2021). If it is assumed that iron fertilization does in fact effectively remove carbon from the atmosphere, modeling indicates that once started, iron fertilization must be performed continuously for its carbon sequestration benefits to be maintained; otherwise, much of the sequestered carbon returns to the atmosphere on decadal timescales (Aumont and Bopp 2006; Gattuso et al. 2021).

Natural sources of iron to the ocean include dust deposits from the Sahara and other deserts, hydrothermal vents, and volcanos (Underwood 2020). Recent work has shown that in addition to natural sources, anthropogenic sources like burning of fossil fuels add iron as well and anthropogenic sources are likely to be a more dominant source of iron to the ocean than previously believed (Conway et al. 2019). Decisions about deployment of iron fertilization should be made knowing that inadvertent iron fertilization may already be occurring at potentially large scales.

FIGURE 10 | Fraction of Carbon Retained after 50 Years under Different Scenarios



Notes: Abbreviation: m = meter. Image E shows the fraction of carbon dioxide retained after 50 years for a biological pump enhancement case compared with the injection of biomass at varying depths.

Source: Siegel et al. 2021.

Cost of Deployment

A wide range of price estimates has been put forth for iron fertilization. Early estimates posited costs of only a few dollars per metric ton of CO_2 removed. However, a 2008 study pointed out that evidence from real-world fertilization events implies that the efficiency of iron fertilization was previously overestimated and that presented costs were therefore too low; the study determined that the cost to sequester carbon via iron fertilization is more realistically between $8 and $80/t$CO_2$ (Boyd 2008). Costs for carbon accounting would be additional to this, including tracking impacts on carbon fluxes outside of the boundaries of iron fertilization application (NASEM 2021).

In terms of how the estimated costs of iron fertilization and macronutrient fertilization compare, a normalized assessment by the National Academies indicates the following material costs (that is, only the cost of materials and not other important costs like transport, loading, addition to the ocean, and monitoring): $48/t$CO_2$ with nitrogen, $2/t$CO_2$ with phosphorus, and <$0.4/t$CO_2$ with iron (NASEM 2021). As can be seen from these values, iron fertilization has a significant advantage in terms of raw material costs because small amounts of material are needed and because the amount of iron needed takes up a proportionately smaller amount of the existing markets for these raw materials.

However, although macronutrient fertilization has the disadvantage of requiring much larger amounts of materials, some research has found that the efficiency (amount of carbon stored relative to the amount of carbon fixed) of nitrogen fertilization in areas with excess phosphate is considerably more efficient than iron fertilization (Harrison 2017). It should be noted that the regions of the ocean where macronutrient fertilization may be feasible are both easier to access and larger than the regions of the ocean where iron fertilization may be viable (NASEM 2021; Harrison 2017; Pitchford and Brindley 1999), which could lend a cost advantage to nitrogen and phosphorus fertilization over iron fertilization if ocean fertilization proves to be a viable ocean CDR approach.

The way nutrients are applied will also influence cost. While previous iron fertilization experiments have delivered iron to seawater by ship, a recent proposal envisions dispersing biogenic iron dust into the air, to be carried by wind over large areas (Emerson 2019), with potential implementation costs that are even lower than those for ship-based distribution.

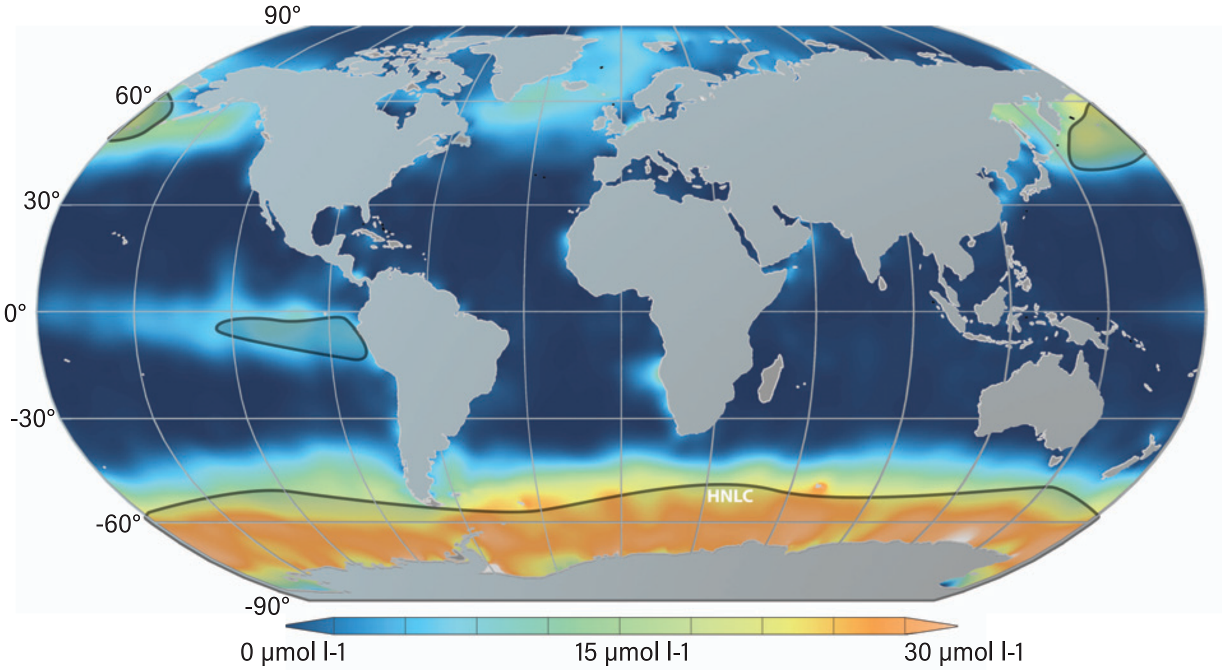
Finally, the cost of monitoring, which is especially important given the potential ecological impacts of ocean fertilization, must not be overlooked and could add significantly to the costs. Although official estimates of monitoring costs for this approach are not available, the National Academies points out that iron fertilization experiments or small-scale demonstration pilots could be similar in cost to previous National Aeronautics and Space Administration studies that tracked the fate of carbon in the ocean (NASEM 2021). These projects had budgets of $15 million to $20 million per field site, with field sizes of 10,000 km^2 over the course of one month.

Geographic Relevance

Foundational research has shown that iron levels and phytoplankton growth are connected in high-nutrient, low-chlorophyll (HNLC) waters (NASEM 2021), which includes three major ocean regions: the Southern Ocean, the North Pacific, and the Equatorial Pacific (GESAMP 2019; see Figure 11). The National Academies identifies the Southern Ocean as the prime candidate region for iron fertilization (NASEM 2021). These HNLC regions have relatively high amounts of macronutrients like nitrates and phosphates but lack the vital micronutrient iron. As a result, they have naturally low primary productivity and phytoplankton growth could be prompted by iron addition.

Of note, the Southern Ocean is also in direct contact and proximity to upwelling water masses near Antarctica, meaning any exported carbon could rapidly be moved back to the surface, reducing permanence (NASEM 2021). The Southern Ocean is also difficult to access, whereas areas suitable for macronutrient fertilization with nitrogen and phosphorus are easier to access and are also more plentiful (Harrison 2017; NASEM 2021). About 70 percent of the ocean is viable for macronutrient fertilization based on low macronutrient concentrations, while approximately 20 percent of the ocean is an HNLC area where iron fertilization is viable (Pitchford and Brindley 1999; Harrison 2017). This location consideration could give macronutrient fertilization an advantage relative to iron fertilization; iron fertilization is preferable largely because of the small amounts of iron needed.

FIGURE 11 | Promising Regions for Iron Fertilization



Notes: Abbreviation: unit = micromoles per liter of surface nitrate. High-nutrient, low-chlorophyll regions, where iron fertilization could spur phytoplankton growth, are shown in orange and outlined in black.

Source: Bristow et al. 2017.

Risks

Ocean fertilization intentionally causes ecological impacts in the form of increased phytoplankton growth, which changes the structure and functioning of marine ecosystems (NOAA 2010). Potential negative ecological impacts include the following:

- Reduced oxygen in the water column as phytoplankton decay takes up oxygen, which can lead to the creation or expansion of dead zones
- Changes in ecological community composition, including the possibility of toxic diatom blooms, which can lead to changes in ecological services and impacts on higher levels of the food chain, as phytoplankton are at the base of the ocean food chain (NASEM 2021; Karl et al. 2001)
- Nutrient depletion, which could lead to impacts like long-term reductions in the amount of biological productivity and export of carbon (Gnanadesikan et al. 2003)
- Reduction in light penetration
- Production of chemical pollutants, such as nitrous oxide, methane, isoprene, and various halocarbons (IPCC 2011; NASEM 2021; NOAA 2010)
- Increased pH in surface water, which could temporarily reduce ocean acidification there, but it could also increase acidity in deeper ocean waters with possible negative impacts on marine life (NASEM 2021)

A possible, but uncertain, impact of ocean nutrient fertilization is local increases in fish stocks (NASEM 2021). However, fertilization in one region may cause productivity to collapse in other locations; in addition, when fertilization ceases, overall global biological productivity could become lower than would have been the case without fertilization (NOAA 2010).

Despite this uncertainty, there is commercial interest in this area. For example, Canadian organization Oceaneos Marine Research Foundation is investigating and developing ocean fertilization with the goal of increasing fish stocks (Oceaneos n.d.). There has been concern that the foundation grew out of the for-profit company Oceaneos Environmental Solutions, which was trying to patent iron fertilization technology and has ties to the controversial Haida Gwaii iron fertilization incident (Tollefson 2017).

Encompassing many of these discussed impacts, a recent study indicated that ocean fertilization could present negative impacts to six Sustainable Development Goals (SDGs) and mixed negative/positive impacts to six SDGs. Examples of negative impacts include substantial energy requirements for iron sulfate production, transport, and distribution; unintended effects on ocean biogeochemistry, including increased greenhouse gas emissions; and risk of conflict if marine resources are significantly affected or changes are incorrectly attributed to an ocean fertilization application. Mixed impacts include negative or positive impacts to fisheries, the need for sizable transportation and distribution infrastructure, and algal production that could either revitalize or harm ocean ecosystems (Honegger et al. 2021a).

Of importance, the Southern Ocean—the most promising location for iron fertilization—is an understudied area of the ocean (Evans 2018). A lack of basic knowledge about the natural conditions, variability, and organisms as they currently exist in this part of the ocean will make it challenging for scientists to credibly compare research findings against informed baselines.

It is likely that impacts of ocean fertilization would emerge over long time frames and in locations far away from the site of application. For example, the possible impact of nutrient depletion could result in nutrient-depleted water recirculating to locations thousands of kilometers away and many years after any monitoring of original iron fertilization occurred (Powell 2008). This time and spatial gap makes it difficult to attribute negative or positive ocean changes to specific fertilization activities. This gap also commits humanity to the potential negative impacts of ocean fertilization should they occur, as the effects may happen years after application and thus would preclude the possibility of ceasing application.

Research Priorities

Three major uncertainties must be further researched to understand the viability and impacts of ocean fertilization as an ocean CDR approach:

- The factors that control the amount of carbon exported to the deep ocean and seabed and the timescales of subsequent storage
- Whether the ocean absorbs atmospheric CO_2 after photosynthesis reduces surface water CO_2 concentration or if instead surface water subduction prior to uptake prevents additional atmospheric carbon from being absorbed by the ocean
- The ecological impacts, which of these impacts are of most concern, and the expected magnitude of each impact (while existing field studies have documented some ecological changes like diatom blooms and greenhouse gas creation, further study and focus on ecological impacts is needed)

Iron fertilization is a risky ocean CDR approach, but global companies are already suggesting ocean fertilization to enhance fisheries. And, because the cost of entry is low for individuals or small organizations to implement iron fertilization, this specific version of ocean fertilization is prone to irresponsible deployment. In addition to the vital role that responsible governance will need to play in managing potential ocean fertilization, these features also mean that investment in additional ocean fertilization research could be merited, even if only to regulate misuse and avoid deployment outside of high-quality, transparent, regulated studies (NASEM 2021). If so, priority research items include the following:

- Identifying the efficiency of CDR at scale and the ecological impacts of iron fertilization field experiments
- Identifying whether it is possible to increase the bioavailability of iron and ease of iron delivery
- Understanding the impact of delivering iron continuously or in pulses
- Monitoring sequestration of carbon, with a focus on permanence and durability of storage (NASEM 2021)

BOX 2 | Ocean Fertilization Using Artificial Whale Excrement

A type of nutrient fertilization framed as "artificial whale feces" or "marine biomass regeneration" involves using a mix of iron, nitrates, silicates, and phosphates to emulate the fertilizing effect of whale feces. In December 2021, an Australian researcher team known as WhaleX dispersed a mix of nutrients about 10 kilometers off the coast of Sydney and are planning further experiments along whale migration routes. The scale of these experiments has not yet been announced, so it is unclear whether they would be considered "genuine scientific research" under the London Protocol. The team acknowledges that much more research is needed to understand the environmental impacts of this process.[a] A coalition of six universities and research centers has announced similar experiments, which include plans to conduct tests off the west coast of India in the Arabian Sea.[b]

Notes:

[a] *Readfearn 2021.*

[b] *Vaughan 2022; McKie 2022.*

3.4 ARTIFICIAL UPWELLING

How It Works

Deep ocean water, particularly in polar regions, has higher concentrations of nutrients compared with surface water. Artificial upwelling pumps this water to the surface to stimulate growth of phytoplankton, which consume these nutrients and fix carbon dioxide via photosynthesis. Then, similar to the processes described above for ocean fertilization, some fraction of the carbon fixed by phytoplankton would be exported to the deep ocean for permanent storage by the biological carbon pump (GESAMP 2019). Various iterations of the concept have been proposed, all involving large pumps of some sort (often vertical pipes), powered by wave energy, offshore wind energy, or, in earlier iterations, salinity differentials or injected air. Artificial upwelling has also been proposed to enhance fish stocks, support seaweed cultivation by providing nutrients, and weaken hurricanes by cooling surface water (GESAMP 2019).

Carbon Removal Potential

There is significant uncertainty around the scale potential of artificial upwelling: Modeling efforts point to a theoretical scale of billions of metric tons per year with tens of millions of pumps installed across the global ocean, but also suggest that widespread deployment of ocean pumps would be a costly and ineffective way to achieve large-scale carbon removal (NASEM 2021). More recent modeling research shows that artificial upwelling would be able to provide 0.15 $GtCO_2$/yr of removal with upwelling pipes up to 500 meters long, and up to 0.18 $GtCO_2$/yr if upwelling pipe length is not limited (Koweek 2022). Artificial upwelling is not expected to provide large-scale carbon removal, mostly because upwelled water brings CO_2 to the surface, which is then outgassed. Some models also predict that the majority of carbon removal associated with artificial upwelling would occur on land as a result of reduced soil respiration from cooler air temperatures adjacent to upwelled waters (Oschlies et al. 2010), which would result in a suite of other impacts that would need to be considered.

Real-world trials have not provided proof of concept that artificial upwelling can result in carbon sequestration. Various iterations of the concept have been proposed, and a few trials at sea or in mesocosms (outdoor experiments in enclosed areas meant to mimic the natural environment) have been conducted (e.g., near Hawaii; Qingdao, China [Box 3]; Sagami Bay, Japan; and the Canary Islands). While these studies demonstrated increased phytoplankton production, none tracked carbon sequestration (Fan et al. 2016; White et al. 2010; NASEM 2021; Ortiz et al. 2022). Recent modeling suggests that around 70 percent of carbon sequestered through processes that increase primary production and rely on the biological pump to sequester embodied carbon (i.e., artificial upwelling and iron fertilization) will circulate that carbon back to the ocean surface within 50 years (Siegel et al. 2021).

Artificial upwelling has also been proposed for applications outside of carbon removal. It could provide additional nutrients for aquaculture or seaweed cultivation; enable energy generation using the temperature differential between surface and deep water; or cool down surface water, potentially reducing storm intensity or mitigating coral reef bleaching (NASEM 2021). Given challenges with monitoring carbon sequestration and scaling to levels that result in meaningful sequestration, artificial upwelling may prove less applicable for direct, large-scale CDR, and more for supporting macroalgae or other applications.

Cost of Deployment

Costs per metric ton of CO_2 removed are uncertain. Demonstration-scale research projects would likely cost tens of millions of dollars, and the National Academies estimates costs of \$100–\$150/tCO_2 with low confidence (NASEM 2021). Costs for monitoring carbon sequestration in the deep ocean and ancillary impacts would be additional.

Geographic Relevance

This approach could be applied to many regions of the ocean but is likely best in mid- and low-latitude waters where nutrients are depleted at the surface (GESAMP 2019). The logistics of establishing and maintaining upwelling infrastructure would also determine possible locations, as would the use of offshore wind energy to power upwelling systems.

Risks

Artificial upwelling is meant to increase phytoplankton production at the surface, which necessarily affects ecosystem structure and function. It can result in nutrient depletion, reduced light penetration, and reduced oxygen concentration in the water, all of which could negatively impact other species living in the area. It also presents uncertainties associated with the infrastructure and engineering requirements to upwell large amounts of seawater, regional impacts of cooling surface water (e.g., on weather systems and crop production), and the potential for upwelled waters to bring carbon from deeper waters to the surface (“outgassing”), which could reduce or even negate the carbon removal benefit of the process.

Depending on the infrastructure used—many proposals involve vertical plastic pipes—there could be adverse impacts on ocean biota and interference with other uses of the ocean such as shipping. If renewable energy were used to power it, that infrastructure would have impacts related to construction.

While upwelling is ongoing, it would result in a net cooling of surface waters and net warming of subsurface waters. However, modeling has shown that once stopped, more heat is brought to the surface than would have happened in the absence of upwelling (Oschlies et al. 2010).

Research Priorities

More work is needed to optimize materials, engineering, and infrastructure to carry out upwelling, including consideration of durability in the open ocean, energy source, and other design questions like the optimal upwelling rate to induce primary productivity. Controlled field experiments would then be needed to demonstrate proof of concept, including technology readiness and durability, and to develop a better understanding of ecological and environmental impacts and relative amounts of upwelled carbon. Monitoring and verification approaches will need to be developed and improved to track additionality of sequestration, nutrient movement, ecological responses, and the impacts of air-sea CO_2 exchange (NASEM 2021). Siting assessments will also be needed to understand where upwelling infrastructure would conflict with other ocean uses, such as shipping lanes.

BOX 3 | Artificial Upwelling Demonstration in Qingdao, China

China's first artificial upwelling demonstration project, located in the waters of Aoshan Bay in Qingdao, operated between 2018 and 2020. The project used artificial upwelling to increase the production of kelp (large brown seaweeds) and other macroalgae.

Upwelling moves nutrients that are found in deeper waters to the surface where they spur growth of phytoplankton and algae, which take up dissolved carbon dioxide in seawater through photosynthesis. These nutrients are concentrated in sediment at the bottom of the bay and not normally available to organisms at the surface. Upwelling also helps alleviate offshore eutrophication, caused by excess nutrients from agricultural runoff and other sources, which causes hypoxia and other negative ecological impacts.

The researchers found that the average weight of kelp near the upwelling area was more than four times the weight of kelp far from the upwelling area. Based on the existing kelp aquaculture area in China, this could increase yields by around 290,000 metric tons and remove nitrogen and phosphorus by around 4,900–6,400 metric tons and 700–1,000 metric tons, respectively.[a]

China is one of the world's major seaweed aquaculture countries and, with the development of aquaculture technology over the past three decades, the area and yield of kelp culture in China have steadily increased. However, with the expansion of the aquaculture area and its increasing density, water exchange capacity has weakened and nutrient supplementation has become limited, resulting in large-scale disease and death of kelp. Because of the weak water exchange capacity in aquaculture areas, the nutrients in the sediments cannot be resuspended effectively through natural processes to be used by kelp and cause eutrophication. Hence, artificial upwelling has been tested as a potential solution to support large-scale seaweed farming in China.[b]

The project, led by Zhejiang University, is in cooperation with Xiamen University, Hangzhou Dianzi University, and Shandong University. It has been listed as a marine carbon sink program by the IPCC.

Notes:

[a] Fan et al. 2019.

[b] Fan et al. 2019.

CHAPTER 4:

Abiotic Approaches to Ocean-Based Carbon Removal

Whereas biotic approaches leverage the ability of photosynthesizing organisms to uptake and store carbon dioxide as biomass, abiotic approaches seek to reduce atmospheric carbon levels by manipulating chemical and physical properties of the ocean.

4.1 ALKALINITY ENHANCEMENT

How It Works

Adding alkaline materials (e.g., silicate and carbonate minerals) to the ocean can reduce atmospheric CO_2 concentrations and address ocean acidification (Lenton et al. 2018; NASEM 2021), and is referred to as ocean alkalinity enhancement (OAE). Several methods have been proposed to add alkalinity to the ocean. Broadly, they mimic and accelerate the natural process of rock and mineral weathering that already consumes around 1.1 $GtCO_2$/yr (Bach et al. 2019).

When alkaline minerals are added to the ocean, they lead to the conversion of some dissolved CO_2 in surface water into dissolved bicarbonate and carbonate ions. Once dissolved CO_2 is consumed in this reaction, additional CO_2 from the atmosphere is absorbed into the ocean to replace it, leading to net removal of CO_2 from the atmosphere. The bicarbonate and carbonate ions from this reaction increase seawater pH, helping to counteract ocean acidification—a serious negative impact of climate change (NASEM 2021).

Alkalinity can be added by ship, plane, and shoreline applications and must dissolve into the seawater for the relevant chemical reactions to occur. This means that alkaline minerals must be ground into very small particles that sink slowly; this dissolution can occur in the open ocean, on exposed shorelines, in chemical reactors on land, or on ships (NASEM 2021). Because dissolution rates are slow, grinding to a small size increases the speed of dissolution but also requires energy. Coastal application is advantageous because waves grind down the particles, reducing the energy input needed, at the cost of increased monitoring requirements.

Many sources of alkalinity have been proposed, including carbonate minerals, silicate minerals, alkaline mineral derivatives, or even alkaline industrial waste (NASEM 2021). The silicate mineral olivine is of particular interest because it converts a large amount of CO_2 to bicarbonate by weight compared with other minerals: 1 $GtCO_2$ for every 1–2 Gt of reactive rock, including energy used for mining, grinding, and distribution (Moosdorf et al. 2014; see Box 4). However, new research indicates that olivine addition may be a less efficient CDR option than previously believed due to the formation of secondary minerals and the buffering capacity of seawater (Fuhr et al. 2022).

Preliminary research on topics like the efficacy and impacts of OAE is underway. Much of this research is based on modeling, but there have been some experimental efforts, such as the work by Gore et al. (2019) to treat calcifying algae with elevated alkalinity seawater, and at-sea microcosm experiments by Subhas et al. (2022).

Some oyster farmers have been successfully using alkaline materials like sodium carbonate to help balance pH levels in overly acidic waters, which has helped those growers recover nearly 75 percent of losses (NOAA n.d.b). While not intended for carbon removal, alkalinity application by oyster farmers is demonstrating the benefits of regional OAE application for calcifying organisms. Similarly, there is evidence that restoring pH to pre-industrial levels through alkalinity enhancement would benefit coral reefs (Albright et al. 2016).

Several companies are developing alkalinity enhancement approaches (Box 4).

Carbon Removal Potential

Published estimates of global carbon removal potential show a wide range, from 0.1 to 1.0 $GtCO_2$/yr (GESAMP 2019; NASEM 2021). If applied globally, sequestration could exceed 1 $GtCO_2$/yr (NASEM 2021).

The potential of alkalinity enhancement is largely dependent on accessing, transporting, and applying suitable materials in such a way that the energy requirements do not exceed the amount of carbon that is sequestered. The mining effort needed to provide alkaline material sufficient to sequester several billion metric tons of CO_2 would be on a par with the current global cement industry, which mines roughly 7 Gt of material each year (Bach et al. 2019). Applying 1 Gt/yr of alkaline material would take 100 bulk carriers (300,000 dry weight tonnage), approximately 4 percent of global shipping capacity (Renforth et al. 2013).

Regional, rather than global, application of OAE could lead to more efficient carbon removal, as regional responses to OAE are affected by differing background concentrations of dissolved inorganic carbon and total alkalinity (Burt et al. 2021).

Additionally, global GHG emissions can impact the efficacy of OAE. Modeling simulations have shown that OAE is most effective in lower-emission scenarios, and that greater amounts of OAE are required to achieve the same warming and acidification reductions in high-emission scenarios (Lenton et al. 2018).

Cost of Deployment

The National Academies estimates a cost of \$100–\$150/ tCO_2 (NASEM 2021); it is likely that there will be additional costs for environmental impact and efficacy monitoring. The carbon accounting to determine overall efficacy will be most challenging in cases where alkalinity is added in mineral form or without grinding to ensure full dissolution (NASEM 2021).

Geographic Relevance

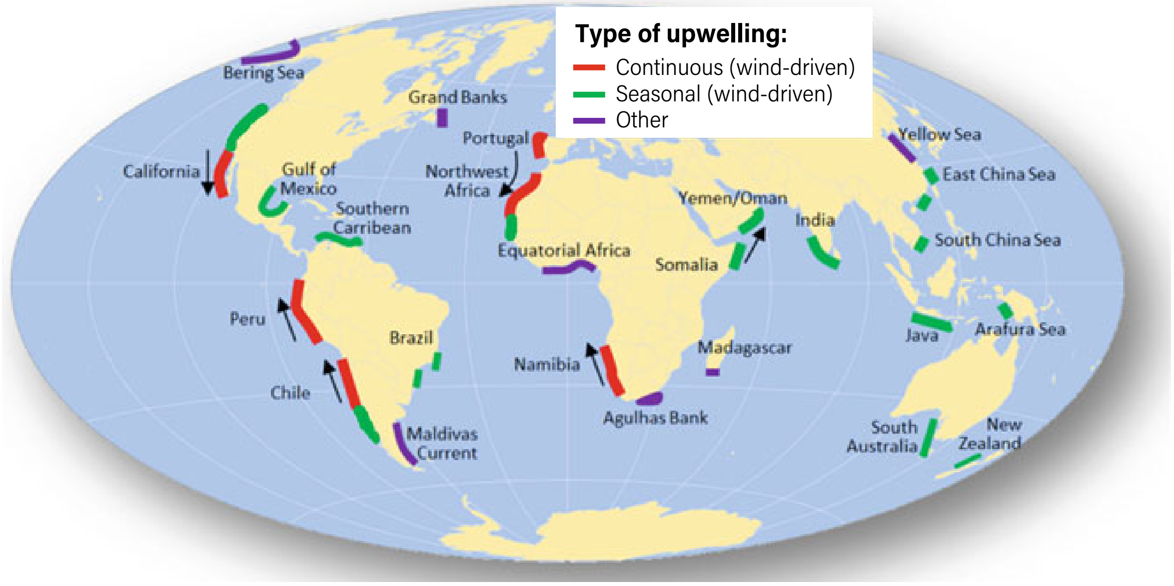
There is not yet a consensus on where it is best to add alkalinity. However, a variety of criteria for identifying ideal locations has been considered in the literature to date.

Some modeling work has found that location is a key element to achieving stabilizing levels of atmospheric carbon dioxide via global implementation of OAE (González and Ilyina 2016). Other modeling work has found that the global carbon removal impact of alkalinity enhancement depends only weakly on the locations where alkalinity is added (Lenton et al. 2018). Sites with high upwelling velocities will likely be desirable, as this could prevent or delay mineral particles sinking to depth (NASEM 2021; see Figure 12). If carbonate minerals are used, they can be applied only in areas where the surface water is not already saturated with carbonate, which is largely in the Arctic (Harvey 2008). Because OAE directly reduces the concentration of dissolved CO_2 in ocean surface waters rather than the atmosphere, it relies on air-sea gas exchange to remove atmospheric CO_2. This occurs at different timescales in different locations in the ocean (see Section 2, Ocean Science Concepts). If alkalinity-enhanced surface water subducts faster than this timescale, the overall efficacy of OAE is reduced, suggesting that locations with rapid rates of air-sea gas exchange are also preferable for deployment.

Alkalinity enhancement could offer co-benefits in some locations. For example, it could be possible to maximize acidity reduction benefits to coral reefs by making choices based on currents and other local conditions near reefs (Gagern et al. 2019). There may also be benefits to adding alkalinity in upwelling regions where cold water with high concentrations of CO_2 rises to the ocean's surface, because this could help limit natural outgassing of CO_2 from seawater (Gagern et al. 2019; see Section 2, Ocean Science Concepts).

Finally, optimal locations of application will be affected by logistical constraints like the availability of alkaline materials across the mining, crushing, and transportation processes and access to shipping and port infrastructure (NASEM 2021).

FIGURE 12 | Major Coastal Upwelling Regions



Source: Kämpf and Chapman 2016.

Risks

Ocean chemistry is relatively well understood, but the ecological impacts of large-scale OAE are still poorly understood.

Ecological impacts:

Despite the carbon removal potential of OAE, deployment will necessarily cause some level of disruption to ocean biogeochemistry with mixed positive and negative ecological impacts (Ferrer González 2017). Enhancing ocean alkalinity would impact ecology by locally raising pH (increasing alkalinity) and altering the saturation state of aragonite (see Section 2, Ocean Science Concepts).

OAE is expected to benefit marine calcifiers such as shellfish and corals by reducing local ocean acidification and making more carbonate ions available for calcifiers to build carbonate-based shells. However, OAE perturbations could potentially give calcifiers an advantage over non-calcifiers (Bach et al. 2019). This could lead to changes in the composition of the food web and biogeochemical fluxes like carbon export (Bach et al. 2019). If large amounts of alkalinity are applied in locations with limited circulation, OAE could raise local pH levels *above* those of pre-industrial levels with uncertain impacts on marine life (Burns and Corbett 2020). Lower concentrations of dissolved CO_2 in the water could temporarily shift where photosynthesizing organisms like phytoplankton are able to grow, with significant uncertainty about whether this would reduce overall productivity (Bach et al. 2019). Recent preliminary at-sea microcosm experiments do not show evidence of impacts on the ability of calcifiers to form calcium carbonate, but may indicate some impacts on net primary productivity (Subhas et al. 2022).

OAE can also alter species composition. For example, the annual spring bloom of phytoplankton is typically dominated by large species. This pattern could be disrupted if smaller species better suited for low CO_2 concentrations perform better in areas of lower dissolved CO_2 concentration (Bach et al. 2019).

Minerals used for OAE could introduce trace metals into the ocean ecosystem. The range of possible trace metals is diverse and dependent on the source of alkalinity used, and could be fertilizing (e.g., iron) or toxic (e.g., cadmium, nickel, chromium) to marine organisms (Bach et al. 2019; Burns and Corbett 2020). The potential for unintentional iron fertilization and its ancillary impacts, along with negative ecosystem and biogeochemical impacts from toxic metals, will need to be carefully considered when selecting alkalinity sources. Additionally, grazers like zooplankton, fish larvae, and echinoderms (e.g., starfish, sand dollars, sea urchins) may consume mineral particles with potentially damaging impacts (NASEM 2021).

Other risks:

Expanded mining activities, processing, and transportation of minerals will have environmental and social impacts that must be included on a life-cycle basis in the overall efficacy assessment of OAE. Large-scale deployment could also require adaptation or expansion of existing ship fleets and infrastructure for storage at ports (NASEM 2021).

Under certain conditions, the addition of alkalinity can cause precipitation of solid calcium carbonate, which also releases CO_2, diminishing the effectiveness of OAE. Modeling has found that ceasing regional OAE application results in a rapid shift back to acidic conditions (Feng 2016), in some cases with acidification rates and warming outpacing those expected in a high-emission "business-as-usual" scenario (RCP 8.5), posing risks to biological systems sensitive to rapid environmental changes (González et al. 2018). As such, any large-scale deployment would need a long-term plan regarding the phase-out of alkalinity enhancement application, including consideration of whether termination effects negate the benefits of alkalinity enhancement application.

Key Research Priorities

- Most information about alkalinity enhancement is based on modeling, so small-scale, contained, at-sea trials will be particularly useful to understand the ecological impacts, efficacy, and feasibility of OAE deployment (NASEM 2021).
- Continued modeling and laboratory-based research is needed to supplement and guide at-sea experiments. These should focus on enhancing mineral dissolution rates, understanding ecological impacts of elevated and variable pH levels (complementing previous acidification studies), and identifying optimal sourcing and treatment of alkaline materials.

- Engineering, materials supply, transportation, and cost questions must be addressed if OAE will be deployed at larger scales. There are questions particular to each application method and alkalinity source. Understanding holistic supply chain impacts, including environmental impacts and greenhouse gas emissions, will also be necessary.

BOX 4 | Vesta: Foundational Research, Participatory Governance, and Community Engagement with Coastal Olivine Application in the Northern Caribbean

Vesta is a U.S.-based company working on carbon removal by applying olivine sand to beaches. This approach has several advantages compared with other types of alkalinity enhancement. Olivine converts a large amount of CO_2 to bicarbonate by weight relative to other alkaline materials and coastal application reduces the energy needs for grinding olivine minerals into the necessary small sizes for dissolution in ocean water. Additional energy needs come from the transportation of olivine to the application sites, but olivine can be found all over the world, offering opportunities to reduce transportation costs.

While this specific approach is beneficial in many ways, it is not without challenges, such as the need to monitor, verify, and report the impacts of alkalinity enhancement application. The theoretical chemistry behind olivine alkalinity enhancement is well understood, but technical barriers like slow dissolution rates make it difficult to monitor the impact of olivine application.

Vesta is working to address remaining knowledge gaps in reaction rates, sediment transportation, impacts to species distribution and diversity, and how various marine species respond to olivine placement. Part of its work to address these knowledge gaps at pilot sites in the Dominican Republic has involved partnerships with local researchers.[a] A shoreline restoration project using olivine is underway in New York for which data will be collected for two years.[b]

In addition to working to advance the scientific understanding behind this approach, Vesta has conducted community engagement in the Dominican Republic where it is planning to add olivine to beaches. It has utilized a participatory governance approach, including a local female leadership team and a steering committee made up of local government entities, NGOs, and academic institutions.[c]

Applying olivine sand has benefits beyond possible carbon removal, as it can help prevent coastal erosion and enhance coastal resilience. From a governance perspective, Vesta has been able to move forward via permitting for coastal protection (i.e., beach nourishment), rather than through currently unclear permitting for carbon dioxide removal approaches.[d] This highlights how permitting specific to proposed ocean CDR approaches is needed, as some approaches can be legally implemented via other avenues.

Notes:

[a] *Hilser et al. 2022.*

[b] *Finn 2022.*

[c] *Hilser et al. 2022.*

[d] *Vesta, personal communication, 2022.*

4.2 ELECTROCHEMICAL TECHNIQUES

How It Works

Because the dissolution of minerals in seawater is relatively slow, some researchers have proposed methods that use electricity to accelerate reactions that ultimately remove CO_2 from seawater. These methods require an electrochemical cell, which typically contains electrodes (which when charged results in a positively charged anode and a negatively charged cathode), a permeable separator, and a liquid (seawater) (NASEM 2021). The anode will attract bases while the cathode will attract acids, resulting in an "acid stream" and a "base stream." These acid and base streams are used to chemically manipulate the concentrations of CO_2 in seawater and, through air-sea gas exchange upon release of seawater back into the ocean, in the atmosphere. Two major approaches exist for reducing atmospheric CO_2 concentrations with electrochemistry:

- Creating alkalinity as a variation of ocean alkalinity enhancement
- Extracting CO_2 from seawater

Creating alkalinity

For approaches that rely on OAE, electrochemical reactions are used to create more alkaline seawater. As discussed in the previous section about alkalinity enhancement, more alkaline seawater results in CO_2 removal and storage as dissolved bicarbonate.

In one version of electrochemical alkalinity enhancement, reactions at the cathode result in a more alkaline solution. This alkaline solution is discharged into the ocean, in turn increasing ocean alkalinity (NASEM 2021). In a second version of electrochemical alkalinity enhancement, the formation of solid metal hydroxide residues from seawater is promoted. These residues are alkaline, so when added to the ocean they increase alkalinity (NASEM 2021). In both versions, electrochemical reactions create a base stream that is ultimately added to the ocean as a source of alkalinity. An acid stream is also produced, and must be neutralized through a reaction with silicate rocks or disposed of in some other fashion (NASEM 2021).

Extraction of CO_2

Extraction of CO_2 from seawater is analogous to methods that directly remove CO_2 from the atmosphere (NASEM 2021), such as direct air capture (see Box 5). CO_2 extraction approaches can occur through a base or acid process.

In the acid process, acidic liquid from the anode is added to seawater, which shifts the equilibrium of the carbonate system in seawater toward CO_2. That CO_2 is then released from the water as a gas and can be collected and stored (NASEM 2021; de Lannoy et al. 2018; Eisaman et al. 2018).

The base process results in two forms of carbon storage. Basic liquid produced at the cathode is added to seawater where it shifts the carbonate system toward higher concentrations of bicarbonate and/or carbonate ions. In this condition, the carbonate can precipitate as a solid, and then the solid carbonate is collected as one form of removed carbon. The precipitation of carbonate then shifts the equilibrium of the carbonate system toward CO_2, which can then be vented as a gas as a second form of removed carbon, similar to the acid process described above (NASEM 2021; de Lannoy et al. 2018; Eisaman et al. 2018).

In both the acid and base processes, the acidic and basic streams from the electrodes are recombined and discharged back into the ocean (NASEM 2021).

These CO_2 extraction systems do not store carbon in the form of dissolved bicarbonate as is the case with alkalinity enhancement. As such, these systems must be coupled with another form of storage, such as geologic storage of released CO_2 gas, to create a full carbon removal system.

Hybrid approaches

Hybrid electrochemical approaches that result in both increases in ocean alkalinity and the removal of CO_2 from seawater are also possible (NASEM 2021).

These electrochemical processes are based on well-understood chemistry and a history of commercial deployment but have not been adapted for CDR outside of a small lab scale (NASEM 2021).

Carbon Removal Potential

The National Academies estimates that carbon removal potential is on the scale of 0.1–1.0 $GtCO_2$/yr (NASEM 2021).

The potential scale of these concepts is limited by some of the same factors as the alkalinity enhancement approaches already discussed, such as the local and global ecological impacts of increasing alkalinity at specific sites. In addition to the barriers facing OAE scaling, electrochemical techniques also face limits from the availability of low-carbon electricity and the need to move large volumes of seawater through an electrolyzer.

Cost of Deployment

Electrochemical reaction processes are capital and energy intensive and, as such, costs for electrochemical ocean CDR are expected to be high. Estimated costs range from \$150 to \$2,500/tCO_2 removed (Rau 2008; NASEM 2021). The National Academies estimates that costs for the OAE approach could range between \$150 and \$700/tCO_2 removed (NASEM 2021). Costs may decline with additional research, development, and demonstration or, where applicable, from the sale of useful byproducts like hydrogen and chlorine (Rau et al. 2013; NASEM 2021; Rau 2008). Additional costs will come from carbon accounting and monitoring for environmental impacts.

One of the largest expenses of this approach will be the electrolyzer at roughly 30–50 percent of the capital cost (NASEM 2021).

In addition to the large capital cost of the electrolyzer, all these concepts require a low- or zero-carbon source of electricity to result in net carbon removal. Estimates for electricity needs range from 0.8 to 8.8 megawatt hours per metric ton of carbon dioxide (MWh/tCO_2) (Rau et al. 2013; NASEM 2021)—8.8 MWh of electricity is roughly the annual electricity use for one home in the United States (EPA 2015). Electricity could come from a variety of sources, including solar, nuclear, geothermal, wind (with offshore wind being of particular interest), ocean thermal energy conversion, or potentially fossil fuel with carbon capture and sequestration. To date, there has been no systematic analysis or comparison of the costs, potential scale, or life-cycle impacts of these electricity sources for ocean carbon removal.

Geographic Relevance

A number of factors will inform the siting of electrochemical projects, including access to seawater, low-carbon energy availability, infrastructure to supply raw materials and dispose of waste, and labor (NASEM 2021). However, it is not yet clear how to optimize siting based on these factors.

Risks

Ecosystem risks are similar to the risks discussed in the previous section about OAE. Additionally, the engineered manipulation of large volumes of seawater could have deleterious effects on ocean biota. Environmental risks in the ocean may be constrained to the immediate locations where effluent is discharged (NASEM 2021). Effluent will eventually mix into the ocean and become less concentrated.

In addition to ocean ecosystem impacts, environmental impacts will arise from the industrial inputs and outputs at an electrochemical facility. The substantial electricity demands may generate social impacts (NASEM 2021). It will also be necessary to safely manage, treat, and transport waste and byproducts resulting from electrochemical ocean CDR. Byproducts from some processes will be substantial; for example, about one metric ton of waste chlorine gas, which is highly toxic, is produced per metric ton of CO_2 removed with some seawater or brine electrochemical reactions. It is possible that some excess chlorine gas could be put to use, but the global chlorine market is relatively small (60–70 Mt/yr) so this will not be feasible at climate-relevant scales (NASEM 2021). It is also likely that an industrial-scale plant would produce wastewater that requires treatment, but this has yet to be explored in the literature (NASEM 2021). Alternatively, some byproducts could produce revenue streams, such as the hydrogen produced at the cathode of some electrochemical approaches (NASEM 2021). It may also be possible to recover useful elements such as silica, aluminum, and iron (in the brine resulting from crushed rocks neutralizing excess acid) along with precipitated minerals, for which niche high-value markets exist (NASEM 2021).

Key Research Priorities

In addition to the research priorities outlined for ocean alkalinity enhancement, research must be conducted to understand the feasibility and optimization of the additional infrastructure and engineered components that are required for electrochemical CDR facilities.

Areas that require research include the following:

- Engineering feasibility of large-scale applications
- Life-cycle assessments of the whole processes for electrochemical CDR, including factors such as energy used for water pumping, extracted CO_2 compression, transportation, and storage/utilization
- Optimal sources of energy to power electrolysis
- Optimization of hydrogen utilization
- Understanding the necessary waste disposal needs, such as for wastewater and chlorine gas

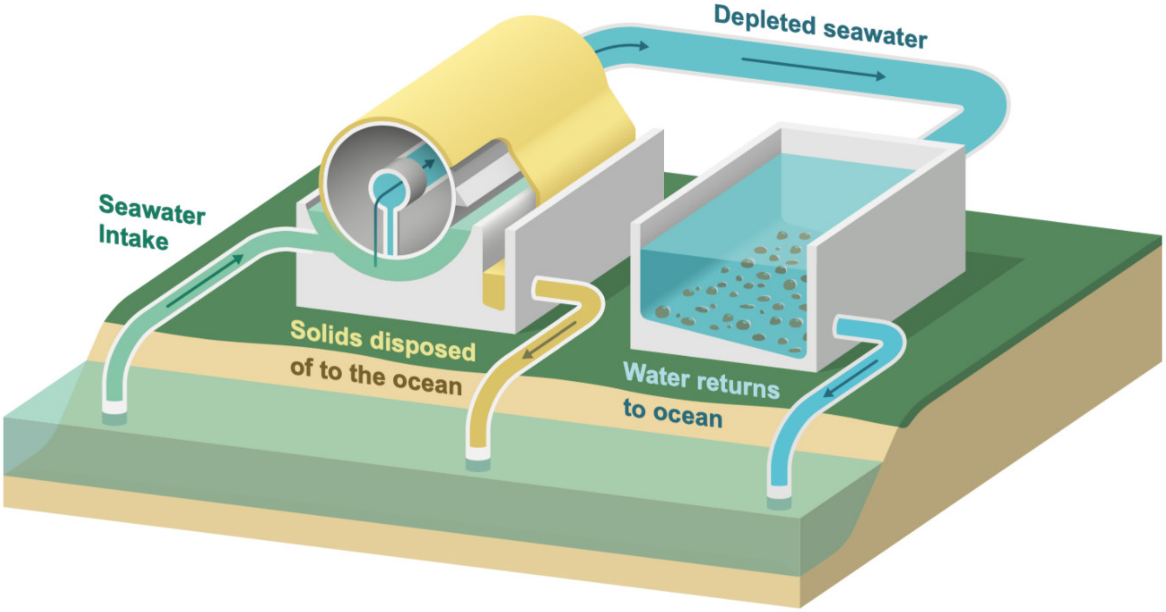
The National Academies lays out further research priorities, including initiating demonstration projects, improving membrane and electrode materials, coupling whole rock dissolution to electrochemical reactors and systems, and developing further hybrid approaches (NASEM 2021).

BOX 5 | Single-Step Storage and Sequestration of CO_2 via Electrolysis of Seawater in Los Angeles, United States

A research team at the University of California, Los Angeles, Institute for Carbon Management has developed a version of electrochemical carbon removal that durably stores carbon dioxide as solid minerals. A recent grant from the Chan Zuckerberg Initiative will allow the team to build and operate a demonstration facility in the Port of Los Angeles.[a]

The approach uses a flow reactor, which is a system that continuously takes in inputs and puts out products (Figure B5.1). Seawater is taken into the system through a mesh that electrically charges the water, which in turn makes the water alkaline. Then, in a process like seashell formation, calcium and magnesium react with the carbon dioxide dissolved in the seawater. After this reaction occurs, the seawater is depleted of CO_2 and is returned to the ocean, where it can take up more carbon dioxide. In addition to CO_2-depleted seawater, the outputs of this reaction are the minerals limestone and magnesite, along with hydrogen, which can be used as a clean fuel.[b]

Figure B5.1. Illustration of Seawater Electrolysis System



The approach involves single-step carbon sequestration and storage in contrast with CDR methods that produce pure CO_2 gas that must be compressed for sequestration.[c] This method is also characterized by the lack of a membrane for electrolysis.[d]

Notes:

[a] *Wei-li Lee 2022.*

[b] *Lewis 2021.*

[c] *Lewis 2021.*

[d] *La Plante et al. 2021.*

Source: La Plante et al. 2021.

4.3 ARTIFICIAL DOWNWELLING

How It Works

Artificial downwelling involves accelerating natural currents that carry carbon-rich surface water into the deep ocean in the Arctic and Antarctic. These currents move dissolved carbon to deeper water, where CO_2 solubility is higher, resulting in a net flux of carbon from the surface to the deep (referred to as the "solubility pump"). At the surface, these waters would be replaced by warmer surface waters from lower latitudes that cool and take up more CO_2 in the process. Various proposals for artificial downwelling involve removing heat from the ocean, which accelerates movement of warmer waters to higher latitudes where they cool and absorb carbon, or using pipes—either attached to the seabed or floating—outfitted with pumps to move water to depth.

Modeling of this approach indicates it would not be a competitive means for carbon sequestration due to impracticalities and costs (Zhou and Flynn 2005).

Downwelling has also been proposed for non-CDR uses including reducing eutrophication and hypoxia by moving oxygen-depleted surface water to depth.

Carbon Removal Potential

Carbon removal potential appears low compared with other proposed concepts. Modeling based on Zhou and Flynn's work shows that between 2020 and 2100 1.4 $GtCO_2$ cumulatively, or around 18 $MtCO_2$/yr on average, could be stored in the North Atlantic Deep Water region, where currents are naturally downwelled, if waters in that region are continuously cooled by 1°C (Lenton and Vaughan 2009). Real-world tests have not proved that artificial downwelling results in carbon sequestration (NASEM 2021).

Cost of Deployment

The few modeling studies that have been done show that costs would be very high—on the order of thousands of dollars per metric ton of carbon dioxide removed (Zhou and Flynn 2005). The minimal literature available on artificial downwelling appears to dismiss it due to high expected costs for cooling large amounts of ocean water (Lenton and Vaughan 2009). Monitoring for environmental impacts and carbon sequestration would require additional costs.

Geographic Relevance

Artificial downwelling would be most applicable where major downwelling currents are located, such as the North Atlantic Deep Water near Greenland and the Antarctic Bottom Water (Zhou and Flynn 2005).

Risks

Artificial downwelling would cool surface waters and warm subsurface waters, which could reverse once the downwelling effort stops, and would impact marine ecosystems. Warmer subsurface waters could reduce net carbon flux to the deep ocean (NASEM 2021). Any infrastructure needed for the process could also pose pollution risks and disrupt marine life or other ocean uses like shipping. Changes in surface water temperature could also affect weather patterns. Overall, because artificial downwelling has not been tested, and remains theoretical, environmental impacts are uncertain.

Research Priorities

There is uncertainty about the efficacy of this approach in storing additional carbon, so at-sea tests would be needed to test carbon removal efficacy.

The few modeling studies that have been conducted have shown very high costs per metric ton of CO_2 and little evidence of permanent storage of carbon (Zhou and Flynn 2005). The National Academies does not prioritize artificial downwelling for research funding (NASEM 2021).

TABLE 1 | Overview of Ocean CDR Approaches

OCEAN CDR APPROACH	COASTAL BLUE CARBON RESTORATION	SEAWEED CULTIVATION	OCEAN FERTILIZATION	ARTIFICIAL UPWELLING	ALKALINITY ENHANCEMENT	ELECTRO-CHEMICAL TECHNIQUES	ARTIFICIAL DOWNWELLING
HOW IT WORKS	Storage of organic carbon in coastal sediment	Embodied carbon in seaweed can be sunk for sequestration in deep ocean water or seafloor sediment; other end uses such as food or biofuel (with minimal carbon removal)	Addition of nutrients (e.g., iron, nitrogen, phosphorus) to nutrient-depleted areas to promote phytoplankton growth; some fraction of this moves to the deep sea for storage where it is sequestered	Upwelling nutrient-rich deep water to the surface spurs phytoplankton blooms; some fraction of this is exported to the deep sea for storage in seabed sediment	Addition of alkaline materials to react with dissolved CO$_2$, which stores carbon as bicarbonate and carbonate ions and results in additional uptake of atmospheric CO$_2$ into the ocean	Using electricity to remove CO$_2$ from seawater, or producing alkalinity for a variant of alkalinity enhancement.	Accelerating natural currents that carry carbon-rich surface water into the deep ocean by cooling surface water or pumping it to depth
CARBON REMOVAL POTENTIAL	0.2–0.33 GtCO$_2$/yr by 2050;[a] maximum potential estimates are closer to 0.8 GtCO$_2$/yr;[b] protecting existing ecosystems could avoid an additional estimated 0.25–0.76 GtCO$_2$/yr[c]	Estimated to be >0.1 GtCO$_2$/yr but <1.0 GtCO$_2$/yr[f]	Wide range based on modeling of theoretical potential—the National Academies estimates 0.1–1 GtCO$_2$/yr with medium confidence;[k] experiments performed to date have shown increased primary productivity, but the necessary transfer of organic matter from the surface to the deep ocean and a corresponding uptake of atmospheric carbon into the ocean has not been verified[l]	Estimated up to 0.18 GtCO$_2$/yr;[n] may be more useful in combination with seaweed cultivation than for dedicated CDR	Uncertain; estimates vary widely from as little as 0.1 GtCO$_2$/yr up to 1.0 GtCO$_2$/yr[p]	Uncertain; estimates vary from 0.1 GtCO$_2$/yr to 1.0 GtCO$_2$/yr[r]	Uncertain but estimated to be 1.4 GtCO$_2$ cumulatively from 2020 to 2100, or 0.018 GtCO$_2$/yr on average through 2100[t]
COST OF DEPLOYMENT	$10/tCO$_2$[d] to more than $500/tCO$_2$;[e] variable depending on ecosystem type, location, and other factors	$65/tCO$_2$ to more than $3,000/tCO$_2$ depending on species, cultivation method, geography, and other factors;[g] the United States Department of Energy is aiming to reach ≤$80/tCO$_2$[h]	Estimated to be $8–$80/tCO$_2$[m]	Uncertain; estimated to be $100–$150/tCO$_2$ with low confidence, excluding monitoring costs[o]	Estimated to be $100–$150/tCO$_2$, not including the additional monitoring costs that would be required[q]	Expected to be high as electrochemical processes are capital and energy intensive; estimated costs range from $150 to $2,500/tCO$_2$ removed[s]	The few modeling studies that have been done show that costs would be very high—on the order of thousands of dollars per metric ton of carbon removed[u]
RISKS AND CO-BENEFITS, IF APPLICABLE	Risks are minimized if native coastal wetland species are used and restoration sites are appropriately selected; significant co-benefits for ecosystem functioning, coastal climate resilience, and livelihoods	Nutrient depletion and diversion from other habitats; competition for light; changes in oxygen, CO$_2$, pH levels; introduction of non-native species; competition for space; durability of infrastructure—potential co-benefits include reduced acidification in surface waters and uptake of excess nutrients	Risks include ecological impacts like reduced oxygen, nutrient depletion, and reduced light, which can change ecosystem composition, and changes to populations of grazer and predator marine organisms; a potential co-benefit is increased fish stocks	Similar risks to ocean fertilization, along with potential for outgassing of CO$_2$ from the deep ocean, use of plastic pipes that could interfere with ocean biota, and increased heat at the surface once upwelling stops; a potential co-benefit is increased fish stocks	Changes to biogeochemistry and food systems, changes to the species composition and growing locations of phytoplankton, introduction of trace minerals; expanded mining and possible termination shock if application suddenly ceased are also risks—a potential co-benefit is locally reduced acidification	Risks are similar to those of alkalinity enhancement, with additional risk from manipulating large volumes of seawater and from effluent discharge; further risks include mining for material inputs and safely managing chemical byproducts like chlorine gas and hydrogen	Cooler surface waters and warmer subsurface waters can alter weather patterns, reduce net carbon flux, and impact ecosystems

TABLE 1 | Overview of Ocean CDR Approaches (Cont'd)

OCEAN CDR APPROACH	COASTAL BLUE CARBON RESTORATION	SEAWEED CULTIVATION	OCEAN FERTILIZATION	ARTIFICIAL UPWELLING	ALKALINITY ENHANCEMENT	ELECTRO-CHEMICAL TECHNIQUES	ARTIFICIAL DOWNWELLING
GEOGRAPHIC RELEVANCE	Coastal areas, particularly areas where these coastal ecosystems used to exist, with variation by ecosystem type (mangroves in lower latitudes and seagrasses and salt marshes at higher latitudes)	Suitability depends on nutrient availability at cultivation site, which includes significant area at high latitudes as well as some midlatitude locations[i]	The largest opportunity for iron fertilization is in the Southern Ocean—roughly 20% of the ocean is suitable for iron fertilization based on where iron is a limiting nutrient; roughly 70% of the ocean is suitable for macronutrient fertilization, based on where they are limiting nutrients to primary production	Likely best in mid- and low-latitude waters where nutrients are depleted at the surface	No consensus exists yet, but possible criteria for selecting a location include season, upwelling velocity, and the possibility of providing co-benefits; carbonate minerals can be added only to locations that are not already saturated with carbonate	Multiple criteria could inform optimal siting, including ocean access, energy availability, synergies with existing infrastructure like desalination plants and/or infrastructure to transport and sequester CO_2	Most applicable where major downwelling currents are located, such as the North Atlantic Deep Water near Greenland and the Antarctic Bottom Water
INTERNATIONAL LEGAL FRAMEWORK	N/A; applied within national jurisdictions	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS[j] ▪ Potential concerns under UNCLOS of introduction of alien and new species ▪ Small-scale scientific research studies permitted under CBD within coastal waters ▪ Large-scale, commercial deployment could contravene the nonbinding ban on climate geoengineering under CBD	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Nonbinding ban on ocean fertilization and climate geoengineering under CBD except for small-scale scientific research ▪ Non-legally binding Assessment Framework for Scientific Research under London Convention ▪ Amendment to London Protocol (not in force)	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Considerations for equipment and installation in shipping paths under UNCLOS ▪ Nonbinding ban of geoengineering under CBD except for small-scale scientific research	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Nonbinding ban of geoengineering under CBD except for small-scale scientific research ▪ General provisions of the London Convention and London Protocol, potential permit requirements.	▪ Same as that for alkalinity enhancement	▪ "No-harm" rule under customary international law ▪ General obligation to protect and preserve the marine environment and employ "appropriate scientific methods" under UNCLOS ▪ Considerations for equipment and installation in shipping paths under UNCLOS ▪ Nonbinding ban of geoengineering under CBD except for small-scale scientific research

TABLE 1 | Overview of Ocean CDR Approaches (Cont'd)

OCEAN CDR APPROACH	COASTAL BLUE CARBON RESTORATION	SEAWEED CULTIVATION	OCEAN FERTILIZATION	ARTIFICIAL UPWELLING	ALKALINITY ENHANCEMENT	ELECTRO-CHEMICAL TECHNIQUES	ARTIFICIAL DOWNWELLING
RESEARCH PRIORITIES	▪ Improving the understanding of carbon accumulation as climate changes ▪ Improving the mapping of blue carbon ecosystems and their sequestration potential ▪ Reducing uncertainty in carbon accounting across ecosystems and locations ▪ Reducing uncertainty around GHG emission rates following disturbance	▪ Optimization of near-shore and open ocean cultivation and harvest ▪ Better understanding of ecological impacts ▪ Field studies to better understand air-sea CO_2 equilibrium ▪ Improved MRV, including in deep ocean water and the ocean floor for sunk biomass ▪ Optimal end uses for cultivated biomass	▪ Factors that control the amount of carbon exported to the seabed ▪ Ecological impacts ▪ Impact of air-sea CO_2 equilibrium time ▪ Optimal locations for and methods of application	▪ Optimization of materials, engineering, and design to effectively upwell ocean water, with attention to durability in the open ocean and other design questions like upwelling rate and energy source ▪ Small-scale field tests for proof of concept and to better understand ecological impacts ▪ Improved monitoring and verification capacity to be able to accurately quantify carbon removal	▪ Small-scale, contained trials to understand the ecological impacts, efficacy, and feasibility of alkalinity enhancement deployment in different geographies and conditions ▪ Addressing engineering, materials supply, transportation, and cost questions, including holistic supply chain impacts	▪ Engineering feasibility of large-scale applications ▪ Holistic life-cycle assessments ▪ Optimal sources of energy ▪ Understanding the disposal or utilization needs of byproducts like chlorine gas and hydrogen	▪ At-sea tests would be needed to test carbon removal efficacy and understand environmental impacts

Notes: Abbreviations: GtCO$_2$/yr = billion metric tons of carbon dioxide per year; tCO$_2$ = metric tons of carbon dioxide; N/A = not applicable; GHG = greenhouse gas; CO$_2$ = carbon dioxide; pH = potential of hydrogen; UNCLOS = United Nations Convention on the Law of the Sea; MRV = measurement, reporting, and verification; CBD = Convention on Biological Diversity; OAE = ocean alkalinity enhancement; London Convention = Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter; London Protocol = Protocol to the London Convention.

[a] *Hoegh-Guldberg et al. 2019.*

[b] *NASEM 2019; Griscom et al. 2017.*

[c] *Hoegh-Guldberg et al. 2019.*

[d] *NASEM 2019.*

[e] *Taillardat et al. 2020.*

[f] *NASEM 2021.*

[g] *Milledge and Harvey 2016; van den Burg et al. 2016; Bjerregaard et al. 2016.*

[h] *von Keitz 2020.*

[i] *See Figure 9.*

[j] *UN 1982.*

[k] *NASEM 2021.*

[l] *Yoon et al. 2018.*

[m] *Boyd 2008; NASEM 2021.*

[n] *Koweek 2022.*

[o] *NASEM 2021.*

[p] *NASEM 2021.*

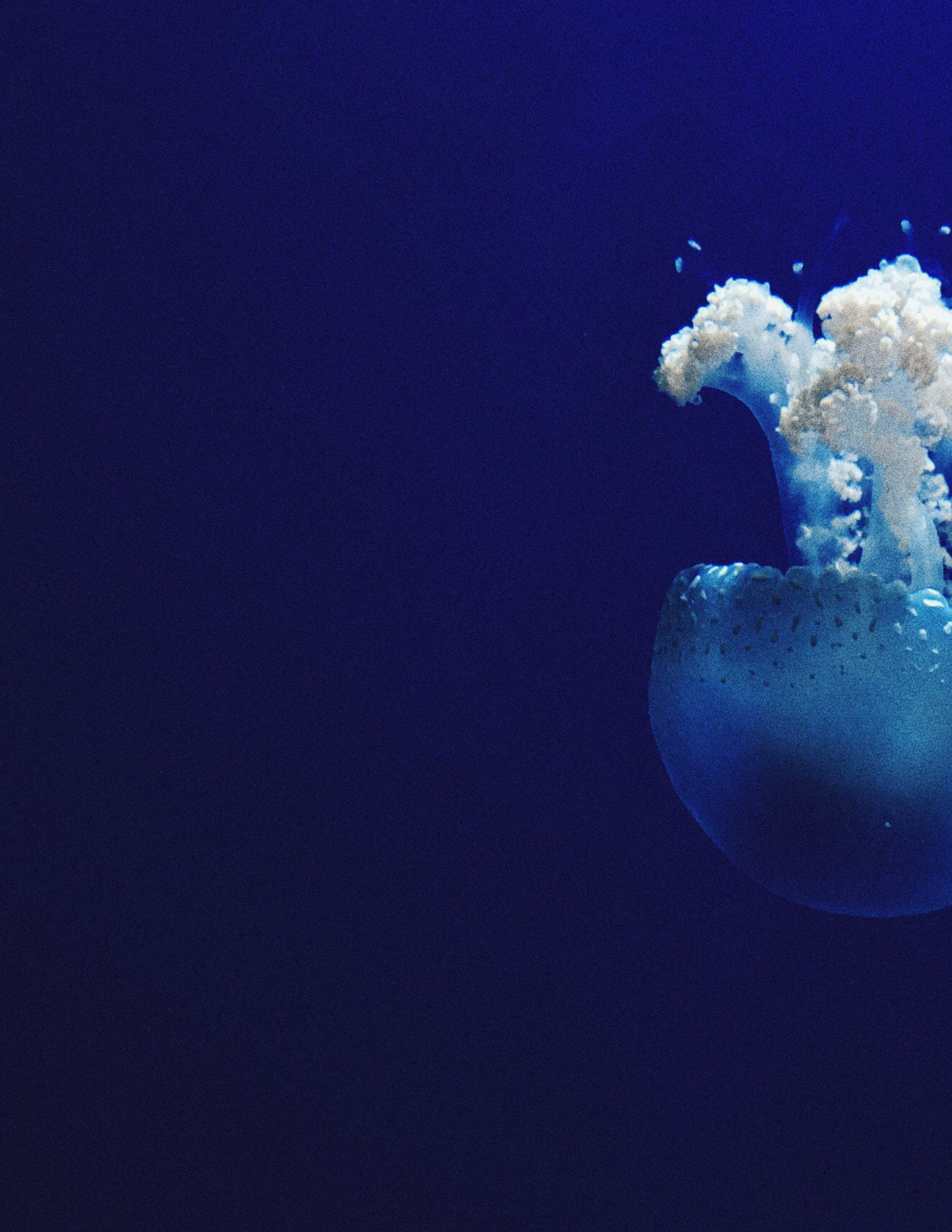
[q] *NASEM 2021.*

[r] *NASEM 2021.*

[s] *Rau 2008; NASEM 2021.*

[t] *Lenton and Vaughan 2009.*

[u] *Zhou and Flynn 2005.*



CHAPTER 5:

Governance Considerations

Even if application occurs within national waters, the impacts of ocean CDR are likely to be transboundary and global in nature (to varying extents) due to ocean currents and weather patterns or could remain undetected and unmonitored in the high seas. This is why ocean CDR has such a fundamentally different risk matrix than land-based carbon dioxide removal, and why governance of ocean CDR is more complicated.

Even if ocean CDR approaches are implemented entirely within national waters, the impacts are likely to be transboundary and global in nature (to varying extents) due to ocean currents and weather patterns.

Ocean CDR operates within a complex and fragmented national and international governance regime that will need to be clarified and strengthened to ensure a responsible, equitable and fair governance regime for research and potential future deployment. This section looks at the current international legal framework that could apply to ocean CDR, first for areas beyond national jurisdiction and then for areas within national jurisdiction, and then provides additional governance considerations for undertaking responsible development and deployment, including safeguards for prevention of harm; stakeholder engagement; equitable benefit sharing; and MRV.

5.1 Legal Framework

International and national legal frameworks determine whether a particular ocean CDR approach can be undertaken in a given area, and under what conditions. Determining the legal framework that applies to each ocean CDR approach is therefore a necessary precondition to both research and commercial deployment at any scale.

While there are many international agreements that govern activities in the ocean, none directly address ocean CDR research or deployment, as CDR had not yet been proposed when these agreements were developed. As a result, a patchwork of existing governance frameworks could be applied with varying levels of clarity and a high degree of uncertainty. This lack of clarity and uncertainty is a risk for undertaking necessary research for ocean CDR, as outlined in previous sections, and future large-scale deployment.

The following agreements under international law have application to at-sea testing and research and commercial deployment by virtue of their applicability to marine activities such as pollution, dumping, or impacts to marine biodiversity: United Nations Convention on the Law of the Sea (UNCLOS), the CBD, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention), and the Protocol to the London Convention (London Protocol) (See Table 2 for a high-level summary of each). The nature, method of application, and location of the ocean CDR approaches influence the application of each.

In addition to determining the potential application of binding provisions under these frameworks, there is another layer of complexity as a result of a series of later decisions and resolutions passed to address ocean CDR under these frameworks that although are not binding are highly persuasive and act as a deterrent to conducting any research at scale or commercial deployment.

Where an ocean CDR approach takes place within ocean maritime boundaries provides the foundation for any assessment of what legal framework applies to that approach (Box 6).

TABLE 2 | Summary of International Frameworks That Apply to Activities Undertaken in the Ocean

AGREEMENT	YEAR OF ADOPTION	NUMBER OF PARTIES	PURPOSE	RELEVANT PROVISIONS FOR OCEAN CDR APPROACHES
United Nations Convention on the Law of the Sea	1982; entered into force 1994	167 countries + European Union (United States is not a party)	Establishes a legal framework for all use and management activities in the ocean, including regulating marine pollution and defining marine scientific research	Part XIII on Marine Scientific Research
Convention on Biological Diversity	1992; entered into force 1993	195 countries + European Union (United States is not a party)	Conservation of biological diversity and sustainable use of its components	Articles 1, 2, 3, and 7 Article 14(d) CBD Decision IX/16 requests that states "ensure that ocean fertilization activities do not take place until there is adequate scientific basis on which to justify such activities." The exceptions to this request are "small-scale scientific research studies in coastal waters" (nonbinding) CBD Decision X/33 (w) calls on parties and other governments to ensure that no climate-related geoengineering activities take place until a series of conditions are met, constituting for most governments a de facto moratorium (nonbinding) Decision X/33 was reaffirmed by the CBD COP in 2012 and again in 2016
London Convention	1972; entered into force 1975	87	Promoting the effective control of all sources of pollution of the marine environment Parties must prohibit dumping of listed substances	Article III(1)(a) and (b) Article IV Resolution LC-LP.1 (2008) to exclude legitimate scientific research on ocean fertilization from the definition of "dumping." Ocean fertilization activities other than legitimate scientific research should not be allowed and should be considered as contrary to the aims of the convention and protocol and not qualify for any exemption from the definition of dumping in Article III.1(b) of the convention and Article 1.4.2 of the protocol Scientific research proposals assessed on a case-by-case basis using the Assessment Framework for Scientific Research Involving Ocean Fertilization (nonbinding) in Resolution LC-LP.2 (2010)
London Protocol	1996	53 (United States is not a party)	Protect and preserve the marine environment from all sources of pollution Parties must prohibit dumping of all substances except those listed	Article 1, 3, and 4 Resolution LP.4(8) (2013) amends the protocol to specifically govern marine geoengineering; LP.4(8) amendment provides a detailed framework for marine geoengineering governance that has capacity to adapt to future scientific and technological developments; this amendment has yet to enter into force and therefore is not yet legally binding on parties

Notes: Abbreviations: CBD = Convention on Biological Diversity; COP = Conference of the Parties to the United Nations Framework Convention on Climate Change.

Sources: London Convention 1972; London Protocol 1996; CBD 1992; UN 1982.

BOX 6 | Ocean Maritime Boundaries

UNCLOS establishes a comprehensive regulatory framework for use of the ocean to ensure the conservation and equitable use of resources and the marine environment and the protection and preservation of the living resources of the ocean.

UNCLOS has 168 parties, the most notable exception being the United States based on strong opposition concerning exploitation of natural resources on the seabed beyond national jurisdiction. However, the United States has recognized certain provisions of UNCLOS as expressions of customary international law, and therefore has integrated legal entities created by the convention into its national law, such as the exclusive economic zone, or EEZ.

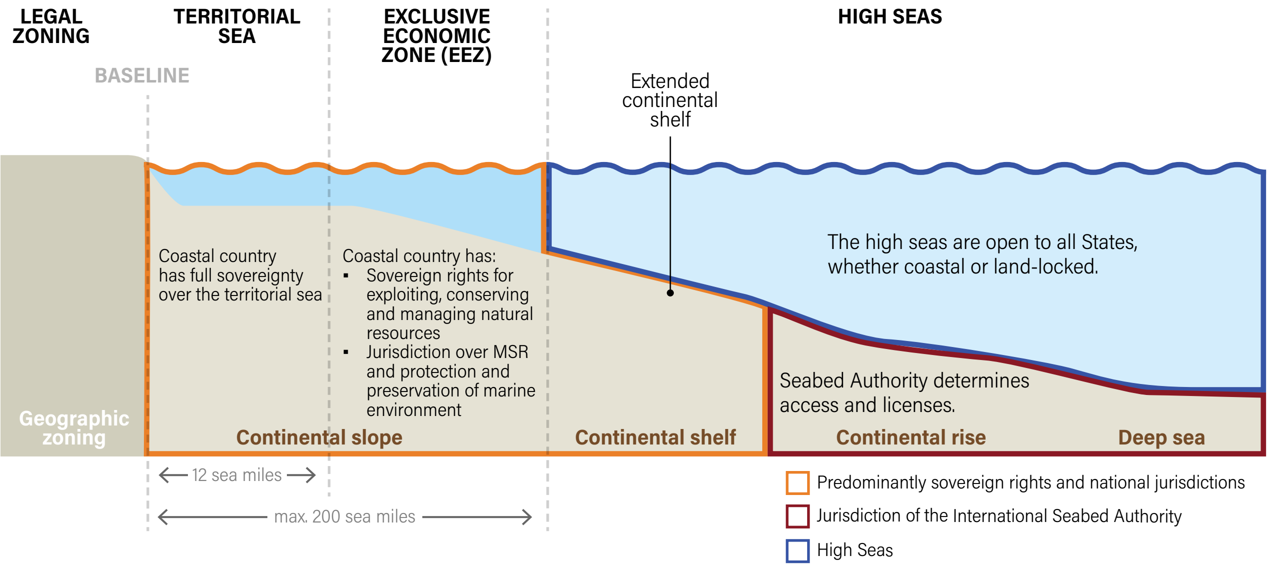
UNCLOS establishes the following boundaries (see Figure B6.1):

Territorial sea: Countries have full sovereignty over their territorial sea, which generally extends 12 nautical miles from the coast, meaning that activities in that area are subject to that state's domestic laws and regulations.

Exclusive economic zone: Countries have sovereign rights to "explore, exploit, conserve, and manage natural resources" in the water column and underlying continental shelf of their EEZs, which extend 200 nautical miles from the shore.

High seas: The high seas extend beyond the territorial sea and EEZ of a country and are open to access by all countries, but activities there are subject to regulations in UNCLOS. In some cases, other regional treaties like the Lima Convention or the Barcelona Convention may apply.

Figure B6.1. Illustration of Ocean Maritime Boundaries



Note: Abbreviations: MSR = marine scientific research.

Source: Authors.

Figure Source: Adapted from (Bähr, 2017).

In this report, ocean CDR approaches undertaken in the waters beyond national jurisdiction refer to those conducted in the high seas, or the water column beyond the national jurisdiction of the EEZ, and ocean CDR approaches undertaken within national waters mean those conducted within the EEZ and territorial sea.

BOX 7 | Ocean Carbon Removal and Environmental Law Principles

Environmental law, including the legal frameworks governing the ocean, has been shaped by a set of principles and concepts defined in Our Common Future (1987)[a] and the Earth Summit's Rio Declaration (1992),[b] outlined below.

Precautionary principle (or precautionary approach): No single articulation of the precautionary principle has emerged as a norm under customary international law and therefore articulations vary from instrument to instrument, as does the threshold of harm. However, its core components include the need for environmental protection, the presence of potential environmental risk or damage, and the assertion that a lack of scientific certainty should not be used to avoid taking action to prevent that damage. One of the more controversial components of the principle places the burden of proof on the party seeking to conduct an action—they must prove the proposed activity is not harmful. The European Commission has defined the precautionary principle[31] in terms of risk management and recommends that decisions taken on the basis of the precautionary principle be proportionate, nondiscriminatory, consistent with other measures, based on an assessment of costs and benefits, and subject to regular scientific review and risk assessment so as to identify and assess areas of scientific uncertainty.

Neither the London Convention nor the London Protocol includes an explicit articulation of the threshold of harm. The precautionary principle may impact how treaties are interpreted and applied and is therefore relevant for carbon removal approaches that are not explicitly regulated (e.g., alkalinity enhancement, enhanced upwelling and downwelling); however, the precautionary principle alone would not be sufficient to safeguard against harm or govern the deployment of these approaches. It will also apply in the absence of a treaty, or where the country undertaking the carbon removal activity is not a party under an existing treaty. It also informs national policy and law and may therefore have specific application in some country contexts.

The precautionary principle could be used to limit deployment of ocean CDR approaches given the uncertain risks to ocean ecosystems and therefore human health. However, as climate impacts increase in severity, some legal academics have argued that an application of the precautionary principle to small-to-moderate-scale field tests would support such field tests and associated research, because of the need to balance the potential risks of these tests with the risks from unabated climate change.[c]

Polluter pays principle: Application of the polluter pays principle (PPP) means that polluters bear the costs of their pollution, including the cost of measures taken to prevent, control, and remedy pollution and the costs it imposes on society. By applying the principle, polluters are incentivized to avoid environmental damage and are held responsible for the pollution that they cause. It is also the polluter, and not the taxpayer, who covers the cost of remediation. Application of this principle to ocean CDR should result in clear liability and a responsibility to remediate any damage. However, despite its potential to be applied to many global environmental issues, the PPP is still not recognized as a customary international norm.[d] The PPP has been discussed predominantly in the context of international climate change law, although it is not expressly mentioned in the UNFCCC, the Kyoto Protocol, or the Paris Agreement.

There is no universally agreed-on definition of the Ecosystem Approach (EA) in international law

Ecosystem approach: The ecosystem approach has received little attention compared with the precautionary approach and there remains no agreed-on definition for it, but it has been adopted and operationalized through the CBD and underpins much of the latest thinking on conservation and use of the ocean and marine ecosystems. The ecosystem approach is a strategy for integrated land, water, and resource management under the Convention on Biological Diversity that prioritizes conservation, sustainability, and equity.[e] Given that scientific understanding of marine ecosystems is incomplete, the ecosystem approach has been closely associated with the precautionary principle in its application to the ocean. Outside of the CBD, the practical application of the ecosystem approach remains unclear, but it should form the basis for any governance regime that covers ocean CDR to ensure any deployment of ocean CDR does not endanger marine life or the ecological relationship as a whole among the marine living resources in the area. The application of the ecosystem approach in the Convention on the Conservation of Antarctic Marine Living Resources is a good example of this.

Notes:

[a] *UN 1987.*

[b] *UN 1992.*

[c] *Reynolds and Fleurke 2013.*

[d] *Heine et al. 2020.*

[e] *CBD 2021.*

Ocean CDR in Waters beyond National Jurisdiction

United Nations Convention on the Law of the Sea

Ocean CDR approaches are not explicitly addressed in UNCLOS. However, the general provisions of UNCLOS and the obligations they give rise to—particularly those related to protection of the marine environment, marine scientific research, and dispute resolution—will apply to the deployment of any ocean CDR approach.

Under UNCLOS, all parties[2] have the freedom to conduct marine scientific research (MSR) in the high seas provided it is conducted for peaceful purposes and employs "appropriate scientific methods."[3] Parties may also conduct MSR in the EEZ of other states subject to their authorization (with a presumption that such authorization will be granted).[4] UNCLOS doesn't have a specific definition of activities that fall within MSR, and there is no commonly accepted definition of "scientific research" in international law to interpret this term.[5]

In addition, there is a general obligation on all parties to UNCLOS to protect and preserve the marine environment (Part XII of UNCLOS).[6] This includes an obligation to adopt measures to prevent, reduce, and control pollution of the marine environment and introduction of alien and new species.[7] Part XV of UNCLOS establishes rules for the resolution of disputes among parties arising out of the interpretation or application of UNCLOS.

UNCLOS does not distinguish between basic research, conducted solely for the purpose of increasing scientific knowledge, and more applied research, conducted to inform or facilitate commercial activities (Webb et al. 2022).

Convention on Biological Diversity

In addition to UNCLOS, the CBD also contains provisions of general application to ocean CDR approaches in areas beyond national jurisdiction. These include identification and monitoring under Article 7 (for activities likely to have a significant adverse impact on the conservation and sustainable use of biodiversity) and environmental impact assessments under Article 14.

The parties to the CBD[8] adopted nonbinding Decision IX/16 C, which requests that states "ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities … with the exception of small scale scientific research studies within coastal waters."[9] In October 2010, the parties to the CBD adopted a further decision, X/33, which broadened the scope of the 2008 ban on commercial ocean fertilization to include "climate-related geoengineering activities."[10] The CBD defines geoengineering as "deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts," which would include carbon removal as well as solar radiation management, which is more often classified as geoengineering.[11] Decision X/33 also creates an exception for small-scale scientific research carried out in a controlled setting in accordance with Article 3 of the CBD, and only if it is justified by the need to gather specific scientific data and is subject to a thorough prior assessment of the potential impacts on the environment. The parties to the CBD adopted Decision XI/20 on climate-related geoengineering in 2012, reaffirming paragraph 8(w) of Decision X/33 and noting that there is no single geoengineering approach that currently meets basic criteria for effectiveness, safety, and affordability. The parties also "noted" the lack of science-based, global, transparent, and effective control and regulatory mechanisms for geoengineering, and the need for taking a precautionary approach. The parties further noted that effective control and regulatory mechanisms would be most necessary for those activities that have a potential to cause significant adverse transboundary effects, and those deployed in areas beyond national jurisdiction and the atmosphere. The parties reaffirmed the subsequent decisions again in 2016 through Decision XIII/14.[12]

Given the nonbinding nature of the CBD decisions, a state cannot be found to breach them; however, the decision remains the most universal statement (taken by consensus of 196 governments) on climate geoengineering and is therefore still highly persuasive. It remains a clear signal from the international community that research and field testing that isn't considered "small scale" or in a "controlled setting" should not proceed. Given the nonbinding nature of these decisions and objective of the CBD, the CBD's capacity to govern ocean fertilization activities could be limited (Nguyen 2021).

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 and the Protocol to that Convention

The London Convention[13] and London Protocol[14] are two international frameworks that have particular application to ocean CDR approaches that involve the addition of materials into the ocean (e.g., ocean fertilization and alkalinity enhancement).

The purpose of the protocol is similar to that of the convention, but the protocol is more restrictive: Application of a "precautionary approach" is included as a general obligation (see Box 8) and a "reverse list" approach is adopted, prohibiting all dumping unless explicitly permitted in Annex 1.[15] The nature of the substances employed in ocean CDR is therefore extremely important to assess against Annex 1 in the London Convention and Protocol. Note, the two instruments operate in parallel, with the protocol being the operative instrument where a state is party to both instruments.[16]

Shortly after the initial decision under the CBD in 2008, the parties to the London Convention and Protocol passed a resolution agreeing that ocean fertilization was within the scope of the London Convention and Protocol but noting that "knowledge on the effectiveness and potential environmental impacts of ocean fertilization is currently insufficient to justify activities other than legitimate scientific research" and excluded ocean iron fertilization research from constituting dumping for the purposes of the protocol.[17] In 2010, the parties adopted *An Assessment Framework for Scientific Research Involving Ocean Fertilization* (LC-LP.2 2010) as a tool for assessing proposed activities on a case-by-case basis to determine if the proposed activity constitutes legitimate scientific research that is not contrary to the aims of the London Convention or Protocol.[18] Neither of these resolutions is legally binding, however (Brent et al. 2019).

To address this, in 2013, an amendment to the London Protocol was passed that would ban ocean fertilization except for "legitimate scientific research" and "other activities."[19] It also established a framework for the London Protocol to govern other marine geoengineering activities in the future. The amendments define marine geoengineering as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe." However, to date only six parties have accepted the amendment, so it is not in force (two-thirds, or 35 out of the 53 parties, are needed). However, this amendment is designed to protect the marine environment from geoengineering approaches, not to proactively govern research or commercial deployment of geoengineering approaches. Despite being an amendment that specifically addresses these approaches and potentially a first step toward a more comprehensive treatment of all ocean CDR under the London Protocol, it is still only an amendment to an existing treaty and its capacity to provide a comprehensive governance framework for ocean CDR approaches will therefore be limited by the aims, scope, and membership of the London Protocol (Brent at al. 2019).

This complex patchwork of resolutions and decisions under the CBD and London Convention and Protocol has led to differing perspectives among governments and organizations and a general reluctance to reopen the issue at the international level.

The following is a discussion of the potential application of these provisions under the existing international legal regime for the purposes of "scientific research," including at-sea tests, for the ocean CDR approaches in areas beyond national jurisdiction (noting that any application would need to be assessed against each agreement on a case-by-case basis):

- **Seaweed cultivation and deep-sea disposal:** Provided the general obligations under UNCLOS are met, at-sea tests for floating seaweed farms would likely be permitted as marine scientific research. However, depending on the type of seaweed being tested and whether it is found naturally in those waters, Articles 194 and 196 regarding the introduction of alien and new species would need to be considered. The provisions of Section XII establish a due-diligence standard, based on conduct, not results. So, if reasonable efforts are made to preclude invasives, and reasonable notification effectuated, it might not contravene Articles 194 and 196. In terms of the CBD, it would also likely be permitted if the general obligations were complied with (Webb et al. 2021). However, when considering the nonbinding decisions, in particular nonbinding Decision X/33 adopted in 2010 (and affirmed in subsequent Decisions XI/20 and XIII/4), the definition of the ban on all "climate geoengineering" could include large-scale seaweed cultivation and any deep-sea disposal for the purposes of mitigating climate change. As discussed above, the decision's impact is limited because it is nonbinding, and merely "invites" countries to "consider" the guidelines provided (Webb et al. 2021). It would likely not be affected by either the London Convention or Protocol provided sinking of seaweed and addition of nutrients, if applicable, are not considered dumping (Silverman-Roati et al. 2021). For the London Convention, it would depend on whether the placement of seaweed and nutrients is considered not contrary to the aims of the convention and would likely trigger risk assessment requirements. In terms of the London Protocol, organic material of natural origin is included in Annex 1 and therefore could be permitted subject to a permit even if it was considered to be dumping. Further legal analysis and consensus among experts are required.

- **Artificial upwelling and downwelling:** The general provisions of UNCLOS will be applicable, particularly those for the protection of the marine environment, marine scientific research, and dispute resolution, but legal scholars have concluded that "projects aimed at demonstrating or testing ocean CDR techniques would qualify if conducted 'in situ' in the ocean" (NASEM 2021), which would include artificial upwelling and downwelling. According to Proelss and Hong (2012), projects that involve the temporary installation of pipes in the ocean to determine the feasibility and efficacy of artificial upwelling and downwelling would likely be considered MSR under UNCLOS. So, too, would other activities aimed at identifying areas suitable for artificial upwelling and downwelling (e.g., the collection and testing of samples to assess water temperature, density, and nutrient concentration and the in situ measurement of wave, wind, and other meteorological conditions) (Webb et al. 2022). Unlike other forms of ocean CDR, artificial upwelling and downwelling research may require the installation of pipes and pumps, both of which would likely be considered "installations" and/or "equipment" for the purposes of UNCLOS and would need to be deployed outside of shipping routes (as per Article 261). In terms of the CBD, small-scale scientific research would also likely be permitted if the general obligations were complied with (Webb et al. 2022). However, nonbinding Decisions X/33, XI/20, and XIII/4 under the CBD would apply to any large scale of commercial deployment of artificial upwelling and downwelling due to the expansion of the ban to climate geoengineering.[20] The 2013 amendment to the London Protocol is unlikely to apply to any large scale of commercial deployment of artificial upwelling (and downwelling), as this involves the transfer of water and nutrients from one part of the ocean to another, rather than the introduction of new matter (Salomon and Markus 2018). This also means, arguably, that the provisions of the London Convention would also not apply. However, some legal scholars have argued that the installation of pipes could constitute dumping.[21] If it were considered dumping, parties could permit the project, at least in some circumstances (Webb et al. 2022). Further legal analysis is required.

- **Alkalinity enhancement:** Field tests, such as the placement of lime for ocean alkalinity enhancement, would be permissible in the open ocean for the purposes of marine scientific research under UNCLOS (subject to the general obligations as discussed above). In terms of the CBD, provided the general obligations are met, alkalinity enhancement would be permissible, even if those tests affected biodiversity (Webb et al. 2021). There is increasing consensus that alkalinity enhancement would constitute "geoengineering" for the purposes of nonbinding Decisions X/33, XI/20, and XIII/4 under the CBD although the same caveats apply regarding the non-binding nature of this decision and exception for small-scale scientific research (Webb and Gerrard 2021). Ocean alkalinity enhancement is therefore likely to be treated similarly to ocean fertilization for the purposes of the London Convention and London Protocol, unless it could be clearly distinguished from ocean fertilization and therefore considered to be in alignment with the aims of the London Convention and Protocol and subject to the dumping exemption (Brent et al. 2019). Based on the experience of ocean fertilization (and particularly the parties' decision that it presents such a significant risk to the marine environment that it would be contrary to the aims of both the London Convention and Protocol), parties could decide to regulate the addition of alkalinity to the ocean in a similar fashion to ocean fertilization (Renforth and Henderson 2017). This would be based on the 2013 amendment to the London Protocol,[22] which enabled regulation of ocean fertilization activities and other marine geoengineering activities in the future, potentially including the addition of alkalinity to the ocean.[23] For alkalinity enhancement to be regulated under the London Protocol, it would need to fall within the definition of "marine geoengineering" as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe."[24] This point requires further consideration and exploration by legal experts. It may largely be a moot point given the amendment is not in force. However, some contracting parties, such as Germany, are already implementing the amendment within their national waters (BMUV 2018). Until the amendment enters into force, alkalinity enhancement activities will be subject to the general requirements of the London Convention and Protocol. Webb et al. (2021) concluded that alkalinity enhancement projects could likely be permitted by parties to the London Convention, but not by parties to the London Protocol due to the "reverse list" under the London Protocol. Smaller-scale research activities may be permitted, so long as they do not risk harming the marine environment (Brent et al. 2019).

- **Ocean fertilization:** Field tests, such as the placement of iron sulfate for ocean fertilization, would be permissible in the open ocean for the purposes of marine scientific research under UNCLOS. However, the potential for iron fertilization to use nutrients and therefore decrease primary production in downstream regions could be argued as violating the "no-harm" rule under customary international law (see discussion in next section). Due to the reverse list under the London Protocol, large-scale activities are most likely prohibited under the London Protocol. Smaller-scale research activities may be permitted under both the London Convention and Protocol, so long as they do not risk harming the marine environment (Brent et al. 2019). However, the various nonbinding prohibitions under the CBD, London Convention, and London Protocol would apply and clearly prohibit large-scale research or commercial deployment of ocean fertilization. The 2008 resolution indicates that "ocean fertilization activities other than legitimate scientific research" ("non-research projects") do not qualify for the dumping exemption because they are "contrary to the aims of the Convention and Protocol." The parties have agreed that ocean fertilization research projects should be assessed on a case-by-case basis according to the agreed Assessment Framework.[25]

In addition to international instruments, specific sectoral or regional instruments are relevant and generally contain stricter environmental standards. An example is the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention), which established detailed rules for transboundary environmental impact assessments. Its rules are relevant to carbon removal activities that will likely have transboundary impacts on other states' territories. However, only Canada and European states have ratified or assented to it.

Regional seas agreements also provide states with additional obligations for high seas marine environmental protection (e.g., the OSPAR Convention for the North-East Atlantic and Arctic region and the Noumea Convention for the South Pacific). These agreements contain rules potentially applicable to carbon removal activities, including broad rules for environmental protection, application of the precautionary principle, control of pollution from marine dumping, environmental impact assessment, and the prevention of transboundary harm. Parties to regional seas agreements will therefore have additional obligations under international law if they wish to conduct carbon removal activities within the relevant high seas areas.

Of particular note is the Antarctic Treaty System; namely, the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol). The Madrid Protocol established a framework for environmental protection of the Antarctic continent and the Southern Ocean below 60 degrees south latitude. It aims to comprehensively protect the Antarctic environment and contains an obligation to limit activities from having adverse impacts on "the Antarctic environment and dependent and associated ecosystems" (SAT 1991). More specifically, parties to the Madrid Protocol must prevent their activities from negatively affecting Antarctic climate and weather patterns, air and water quality, fauna and flora populations, and threatened species. States within the Madrid Protocol also have an obligation to avoid "significant changes in the atmospheric, terrestrial (including aquatic), glacial or marine environment" (SAT 1991). The Madrid Protocol also establishes detailed procedures for environmental impact assessment.

Ocean CDR in Waters within National Jurisdiction

For ocean CDR activities within a country's national jurisdiction (e.g., EEZ), national laws and governance frameworks (including permits and licenses for operation) will apply and in most cases determine whether research activities or commercial deployment can proceed and under what conditions. It is beyond the scope of this assessment to provide a detailed analysis of what domestic laws might apply to ocean CDR approaches across all countries; however, it is important to note that the same challenges that pertain to determining the application of international laws are likely to apply in national waters also. Most, if not all, countries will have a similar patchwork approach to ocean CDR unless domestic laws have been enacted to specifically respond to ocean CDR research or deployment.

Countries that are a party to the UNCLOS, CBD, London Convention, and London Protocol have an obligation to either apply the instruments domestically or adopt other measures to implement these treaties domestically. Additionally, principles of customary international law also apply in national jurisdictions.

Under customary international law,[26] all countries are obligated to prevent activities under their jurisdiction (within 200 nautical miles) from causing significant harm to the territory of other countries and areas beyond the individual jurisdiction and control of countries, such as the high seas. This is known as the no-harm rule under international law. Countries have a considerable amount of discretion in how they decide to interpret their obligations under the no-harm rule. A further limitation is that the no-harm rule can be triggered only by risks of harm above the threshold level of "significant" transboundary harm.[27] Potentially relevant factors for assessing severity of harm for marine geoengineering activities may include the vulnerability of the environment likely to be affected, the physical and/or temporal scale over which impacts are likely to be felt, and the irreversibility of the impacts (Brent et al. 2019). The no-harm rule is therefore more likely to apply to large-scale field tests and full-scale deployment activities than to small-scale research activities (Brent et al. 2019).

The no-harm rule has been incorporated into binding international agreements, including the CBD and UNFCCC. Countries that are a party to these agreements have an obligation to either apply the instruments domestically or adopt other measures to implement these treaties domestically. The prevention of transboundary harm under customary international law includes harm to the high seas and other areas beyond national jurisdiction (Reichwein et al. 2015; Saxler et al. 2015; Reynolds 2018).

Particularly relevant to questions of potential deployment of ocean CDR within national waters is a specific exception under the CBD for small-scale scientific research studies within coastal waters. Such studies should be authorized only if justified by the need to gather specific scientific data, be subject to a thorough prior assessment of the potential impacts on the marine environment, be strictly controlled, and not be used for generating and selling carbon offsets or any other commercial purposes.

In addition, all parties to UNCLOS when exercising their rights to exploit ocean resources within their national jurisdictions remain subject to the general obligation to protect and preserve the marine environment.[28] UNCLOS also requires that countries shall have due regard to the rights and duties of other states under the convention.[29] This general obligation will be triggered by any transboundary harm created by deployment of ocean CDR approaches within national waters.

If ocean CDR approaches are found to involve pollution of the marine environment, UNCLOS requires the party under whose jurisdiction it occurs to do the following:

- Take all necessary measures to minimize the adverse impacts of the project and ensure that it does not cause damage to other states or their environment
- Notify affected countries and competent international authorities of any imminent or actual damage from the project
- Study the risks and effects of the project and publish the results of that study

5.2 ADDITIONAL GOVERNANCE CONSIDERATIONS

One of the main concerns regarding the ability of the current international legal framework to govern ocean CDR approaches is that the focus is on the prohibition of harm, rather than also on proactively managing how ocean CDR approaches are developed and deployed within a robust governance framework that considers the full life cycle of an ocean CDR project.

For a robust governance framework, the following additional considerations must be addressed:

- Ensuring ocean CDR that takes place in national waters does so within strong national and local sustainable ocean management frameworks
- Ensuring appropriate codes of conduct and safeguards are put in place for at-sea research demonstrations and for commercial deployment
- Ensuring broad and inclusive stakeholder engagement
- Resolving who decides when/if/under what conditions (e.g., level of scientific uncertainty) to move from research to deployment
- Reaching consensus on the balance between the potential for harm to the ocean environment and benefits of deployment
- Resolving equity issues around intellectual property and commercialization of deployment in the high seas, including benefit sharing

Each of these considerations plays out differently when considering the global and local implications of ocean CDR, but these governance considerations should not be seen as necessarily limiting the use of ocean CDR. The failed 2012 Haida Gwaii iron fertilization experiment was designed to evade requirements under Canadian and international law and, as a result, it has been argued that this contributed to the international backlash that is still responsible for the lack of global discussion and consensus on a way forward (Burns and Corbett 2020). Lessons should be learned through this experience, with robust and inclusive governance providing an opportunity for legitimate and necessary scientific research to proceed.

Sustainable Ocean Management Frameworks

The impacts of ocean CDR approaches are unlikely to occur in just the ocean. For example, undertaking ocean alkalinity enhancement at scale will require extensive land-based infrastructures for the extraction, processing, and transportation of the required materials. Adverse environmental impacts of mining include ground vibration from blasting; noise pollution; poor soil and air quality as a result of dust; low quality and quantity of surface water and groundwater; air and water pollution, both on and off the mine site; an increase in truck traffic transporting mineral, sedimentation, and erosion; and land subsidence. All these factors directly impact wildlife habitats; forestland and recreational land; human habitats; physical, mental, and social wellness; food security; and cultural and aesthetic resources (Sengupta 2021). Accordingly, governance of this CDR approach must extend beyond the national and international frameworks for the use of the ocean and also consider its land-based impacts. While the scale of coastal and inshore infrastructure will vary for different ocean CDR approaches, none of them will take place exclusively in the ocean without any land-based infrastructure associated with operations.

Appropriate governance frameworks will therefore be required to manage possible conflicts over competing uses within national waters if ocean CDR approaches are deployed—for example, with macroalgae cultivation, it is possible that conflicts with the local fishing industry or companies doing oil and gas exploration could arise and ecological issues could go undetected through a lack of monitoring and/or standards.

One possible way to do this would be to consider ocean CDR proposals and permits within existing frameworks for marine spatial planning (MSP) or integrated ocean management (IOM) and their associated decision-making frameworks (see Box 8). These tools operate at the ecosystem level, taking into account land-sea interactions, and providing a framework for understanding the tensions and potential conflicts as well as potential synergies between uses of the marine space (Winther et al. 2020). Often, these planning and governance tools include specific mandates for transparency, participation, and accountability (e.g., the European Union's Marine Spatial Planning Directive).

BOX 8 | Frameworks to Support Ocean Management and Inclusive Decision-Making Processes for Maritime Resources

Sustainable ocean plans aim to guide public and private sector decision-makers on how to sustainably manage a nation's ocean area under national jurisdiction to advance long-term economic and social development by protecting the natural marine ecosystems that underpin that development.[a]

Integrated ocean management (IOM) aims to support a sustainable ocean economy that uses ocean resources in ways that preserve the health and resilience of marine ecosystems and improve livelihoods and jobs, balancing protection and production to achieve prosperity. To achieve this goal, IOM brings together relevant actors from government, business, and civil society and across sectors of ocean industry. IOM promotes environmentally sound economic development, protects coastal and marine habitats and biodiversity, provides ecosystem services, and balances conflicting interests through spatial planning. IOM is a dynamic process, building on existing initiatives and bringing industries and sectors together, whether under the umbrella of marine spatial planning, ecosystem-based management, or others.[b]

Integrated coastal zone management, or integrated coastal management, is "the process of managing the coast and nearshore waters in an integrated and comprehensive manner with the goal of achieving conservation and sustainable use."[c]

Marine spatial planning is used to create geospatial plans that identify what spaces of the ocean are appropriate for different uses and activities. These plans have similarities with sustainable ocean economy plans, which describe how to sustainably use the ocean and its resources to advance economic and social development. Marine spatial planning aims to create a framework for the ocean that minimizes conflict among economic sectors and maintains "good environmental status" of the ocean through the identification of ocean spaces that are appropriate for different uses and activities. MSP is increasingly seen as a practical way to establish a framework for the use of marine space by many types of users and stakeholders, and to balance demands for development with the need to protect marine ecosystems and achieve social and economic objectives in an open and planned way. MSP is widely used for setting targets for and implementing ecosystem-based management.[d]

Adaptive ocean management is "a systematic process for continually improving management policies and practices toward defined goals by learning from the outcomes of previous policies and practices."[e] It recognizes the inherent variability and dynamic nature of the ocean in terms of its bio-chemo-physical properties and social and economic factors in addition to scientific uncertainties. By scheduling periodic reviews of and updates to management plans, in addition to adding ad hoc opportunities for responding to unexpected events, adaptive ocean management acknowledges that changes in conditions and knowledge are likely.

Notes:

[a] Hanson et al. 2022.

[b] Winther et al. 2020.

[c] Katona et al. 2017.

[d] Katona et al. 2017.

[e] Katona et al. 2017.

[e] CBD 2021.

Stakeholder Engagement

To enable informed discussions on the future of ocean CDR, public education and outreach will be critical to building public acceptance and enabling an informed debate. The potential risks and consequences of deployment must be clearly and quantifiably weighed against the risks and consequences of not utilizing ocean CDR approaches (and therefore relying on other emissions reduction strategies and technologies). This dialogue needs to include the marine science, management, and ocean conservation communities, where there currently can be a relatively low level of awareness and understanding of the issues and opportunities surrounding ocean CDR (EFI 2020).

National and international legal frameworks, while critical to responsible development, will tend to devolve key decisions—such as defining what constitutes "legitimate scientific research" or calculating the relevant "environmental risks"—to technical experts, and offer limited opportunities for public consultation and review (Lezaun 2021).

While ocean CDR approaches could have global climate benefits, the ocean CDR approaches examined in this report, if deployed, are all also expected to have significant site-specific impacts that will affect coastal communities and local marine environments most immediately. Identifying the local environmental, social, and economic impacts is a necessary precondition for determining the communities and ecosystems that will be most directly affected by their deployment.

It will be important to ensure that adequate and inclusive stakeholder engagement processes begin well before pilots and research programs are initiated. These processes could be relevant to either ocean CDR approaches in national waters or development aspects that are taking place along the coast to support deployment in the high seas (e.g., additional mining for alkalinity enhancement or ocean fertilization). Responsible deployment of ocean CDR must include engagement with those potentially affected by the project to inform them of expected impacts and gather input on project design and potential benefits, and explore potential options for project co-development or co-ownership, if applicable. Lezaun (2021) argues that the potential global benefit from CDR should not come at the expense of important local considerations. An example of this is the controversial iron fertilization activities in Haida Gwaii. Although the deployment of iron fertilization in Haida Gwaii violated international law and could have had damaging ecological effects from a poorly understood and risky technology, the activities did have support from local stakeholders. The decision by the Haida community of Old Massett to sponsor iron fertilization was driven by a host of complex considerations, including a desire to replenish depleted salmon runs and the prospect of direct financial returns through the sale of carbon credits (Lezaun 2021). Ensuring these viewpoints are part of any global discourse on the risks and benefits of ocean CDR approaches must be part of governance efforts in the future.

Measurement, Reporting, and Verification

Robust MRV of ocean CDR application is necessary to understand how much net carbon is sequestered, whether carbon sequestration is durable, and who is credited with the resulting carbon removal. In the context of ocean CDR, "measurement" refers to the measurement and tracking of short- and long-term carbon sequestration. The "M" can also stand for "monitoring" of impacts more broadly, which is addressed below. "Reporting" refers to governments and companies sharing the observations from this measurement, ideally transparently and through a standardized data format. In turn, these data are used for "verification" in which the measured amount of sequestered carbon is confirmed for the purposes of assigning credit to companies or countries responsible for the ocean CDR application in question.

Without sufficient MRV, it will be unclear if or to what extent investments in ocean CDR are resulting in carbon sequestration, ensuring permanence, and avoiding double-counting or issues of leakage (displacement of emitting activities that can partially or wholly cancel out climate benefits). Reliable MRV is required for both voluntary and compliance carbon markets to function in a credible manner. Companies or individuals can use voluntary carbon markets to invest in carbon removal, while compliance markets could provide a means for governments to include more types of carbon removal into their portfolios of climate action to meet national climate commitments. As such, development of effective MRV is a precondition to effective and responsible ocean CDR development.

While possible synergies with ocean, environmental, and climate observing systems not intended for ocean carbon removal could aid in MRV efforts (NASEM 2021), significant challenges currently exist for MRV across all ocean CDR approaches.

Measurement and verification are usually more difficult in the ocean compared to on land because of the size, interconnectedness, and continual movement of the ocean. While remote sensing can enable low-cost monitoring of some relevant aspects of ocean ecosystems, it is limited in the detail and types of information it can provide. Modeling and simulation may also be able to improve MRV capabilities, but the relevant models are challenging to calibrate and maintain, and in most cases are not fully developed. The gold standard of measurement—physical in situ sampling of sea water and direct measurement of key ecosystems at high spatial and temporal rates—is usually prohibitively expensive in ocean environments because of the costs of access and data transmission.

Carbon accounting (the process of estimating the net impact on GHG emissions considering all aspects of a project life cycle) is difficult for a variety of technical reasons, such as tracking additional sequestration that may occur outside of a project boundary; quantifying changes to other ocean systems such as primary productivity that may impact emissions; and estimating emissions due to the energy, materials, or equipment that are used in a project (NASEM 2021). In addition to the technical challenges of MRV, there is also a need to develop a transparent and standardized platform or integrate with existing platforms for countries or companies to report collected data, which will in turn facilitate the ability to verify carbon removal efficacy. Any carbon removal that occurs in the ocean may impact global GHG concentrations, but will not have a clear home in national or corporate accounting frameworks when it takes place outside the traditional boundaries of GHG emissions inventories.

These challenges mean MRV efforts are currently costly, to the extent that MRV may be a significant fraction of overall costs for pilots or deployment (NASEM 2021). Developing the technologies to enable MRV along with a transparent, standardized platform for reporting and verification would help resolve uncertainty about the viability of proposed ocean CDR approaches and help enable viable projects to eventually earn credits in voluntary or compliance carbon markets.

Among the seven ocean CDR approaches discussed in this report, coastal blue carbon restoration has the most developed carbon accounting guidance. The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement)* allows countries to include wetlands in their NDCs and provides the methodological guidance needed (in line with other land-based sources and sinks of emissions) (IPCC 2013), but more technical support and national capacity-building effort is needed to enable countries to do so. However, despite the guidance, countries still face multiple challenges in terms of ensuring reliable accounting of these ecosystems, including high variability in carbon burial rates; errors in determining carbon burial rates; lateral carbon transport; fluxes of methane and nitrous oxide; carbonate formation and dissolution; vulnerability to future climate change; and vulnerability to non-climatic factors (Williamson and Gattuso 2022).

More national-level research and data are needed to enable countries to move from using the default method (Tier 1)—minimum evidence required for inventory inclusion—to the most detailed and accurate method (Tier 3)—developing country-specific emissions factors or employing modeling approaches. The *Wetlands Supplement* covers all three blue carbon ecosystems discussed in this report—mangrove forests, tidal marshes, and seagrass meadows—as well as constructed wetlands for wastewater treatment, and reflects their statuses with clear links between specific anthropogenic activities and increased emissions or sequestration of GHGs. However, the *Wetlands Supplement* does not offer guidance on how future climate impacts will alter the accounting methods it relies on. Future revisions will need to incorporate greater guidance on climate variability and the associated impacts on sequestration and storage rates.

Despite these challenges, the restoration of coastal blue carbon ecosystems is highly advantageous for climate adaptation, coastal protection, food provision, and biodiversity conservation. Such action can therefore be societally justified in many circumstances, based on the multiple benefits that such habitats provide at the local scale (Williamson and Gattuso 2022).

In general, measurement is concerned with quantifying the net amount of carbon that is removed, taking into account all impacts that could increase emissions (such as generating energy that is consumed by the CDR approach). Monitoring is also critical for understanding which ocean CDR approaches are viable for development and deployment, and generally focuses on determining what, if any, ecological impacts result from CDR activities. In some cases, measurement and monitoring will be related, such as scenarios in which ecological impacts lead to increased or reduced emissions that are not the primary focus of the CDR approach.

Monitoring ocean CDR research and at-sea trials, both small and large scale, and ultimately commercial deployment, will be critical to understanding the impacts of projects, beyond the intended carbon sequestration, and ensuring adequate safeguards are in place. Monitoring includes surveilling ecological and environmental impacts that stem from ocean CDR application. It will be difficult for companies and governments to conduct responsible small-scale trials or any future medium- or large-scale deployment of ocean CDR without reliable monitoring and transparency systems in place.

Monitoring systems must be sufficiently sensitive but also able to withstand harsh environments. They would likely differ based on project size, location in the ocean, and carbon removal approach. Monitoring impacts on marine organisms/ecosystems and regional- or global-scale impacts on carbon storage is particularly challenging (NASEM 2021).

Equitable Benefit Sharing

In addition to managing conflicts and ensuring a broad and inclusive stakeholder engagement process, any decisions made about the management and use of coastal or ocean ecosystems will affect the lives and livelihoods of the communities that live along these coasts as well as those living close to infrastructure needed to carry out these approaches. If one or more ocean CDR approaches successfully reaches the stage of commercial deployment and is deployed on or near the coast, there will still be issues connected to equity even with robust and effective governance structures in place.

Questions regarding benefit sharing will need to be addressed to ensure an equitable playing field; policies supporting coastal carbon projects should have social and economic benefits that are distributed equitably. Furthermore, the pre-existing rights of Indigenous communities and traditional owners should be always respected and, where possible, opportunities for collaboration and co-management explored. Box 9 explains the international governance framework with respect to Indigenous rights in more detail, but national and subnational legislative frameworks may also apply for decisions regarding the use and management of coastal blue carbon.

BOX 9 | Indigenous Peoples

The United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) protects Indigenous Peoples' right to self-determination, including the right to freely pursue their economic, social, and cultural development. UNDRIP requires free, prior, and informed consent before any relocation, such as may come from land use changes, and guarantees Indigenous Peoples' right to participate in decision-making in matters that would affect their rights. They also require free, prior, and informed consent before legislative or administrative measures that may affect them are adopted or implemented.

The International Labour Organization Convention safeguards Indigenous Peoples' right to the natural resources pertaining to their lands. The convention requires special measures for safeguarding the persons, institutions, property, labor, cultures, and environment of the peoples concerned.

Regional instruments such as the American Declaration on the Rights of Indigenous Peoples strongly reflect Indigenous Peoples' rights to territory; to a safe and sustainable environment; to protect the environment; and to manage their lands, territories, and resources in a sustainable way; and to prior, free, and informed consent before being subject to research programs. Indigenous Peoples in the Americas are entitled to prior consent and restitution of compensation for potential damage caused by activities that interfere or restrict their rights.

The implications of pre-existing rights, under subnational, national, regional, or international law, should be considered as part of any proposed carbon removal development.

Source: UN 2007.

Code of Conduct

Significant thought has gone into the elements necessary for effective governance of CDR (Renforth and Henderson 2017). Rayner et al. (2013) laid out a set of five guiding principles (known as the "Oxford Principles") that can apply equally to the further development of ocean CDR approaches:

1. That CDR be regulated as a public good
2. Public participation in decision-making
3. Disclosure of research and open publication of results
4. Independent assessment of impacts
5. Governance before deployment

Building on this framework, Hubert and Reichwein (2015) identified a means to codify norms for conducting further research, focusing on the foundational principles established under treaties (e.g., UNCLOS for ocean-based concepts) and customary international law (e.g., prevention of harm and the precautionary principle), the responsibility of countries to prevent activity without prior assessment of harms, and the responsibility of scientists to design and undertake proportional step-by-step activities to further scientific understanding.

These efforts provide an important foundation for further development to ensure strong governance frameworks can develop alongside efforts to expand understanding and scientific certainty of the application of carbon removal.

As real-world trials will be necessary to fully understand the risks and benefits of various ocean-based carbon removal techniques, governance structures will be necessary to ensure that these trials occur responsibly.

Developing a set of internationally agreed-on principles for ocean CDR or an international code of conduct, including clear safeguards, that could be signed or adopted by all entities engaging in ocean CDR research and commercial deployment—both public and private—could help ensure these happen responsibly.

The Aspen Institute (2021) identifies key questions that should be considered by researchers and practitioners—as well as policymakers, regulators, investors, communities, and others—related to undertaking limited research to test any particular ocean-based CDR technique. These questions are intended to provide the basis for the future development of a fuller code of conduct.

Loomis et al. (2022) recently laid out 15 elements of an ocean CDR research code of conduct based on codes of conduct in other scientific fields (see Figure 13).

Establishing a code of conduct for research could serve as a basis for a code of conduct that includes commercial deployment as well, and represent an important first step toward a new international framework for ocean CDR.

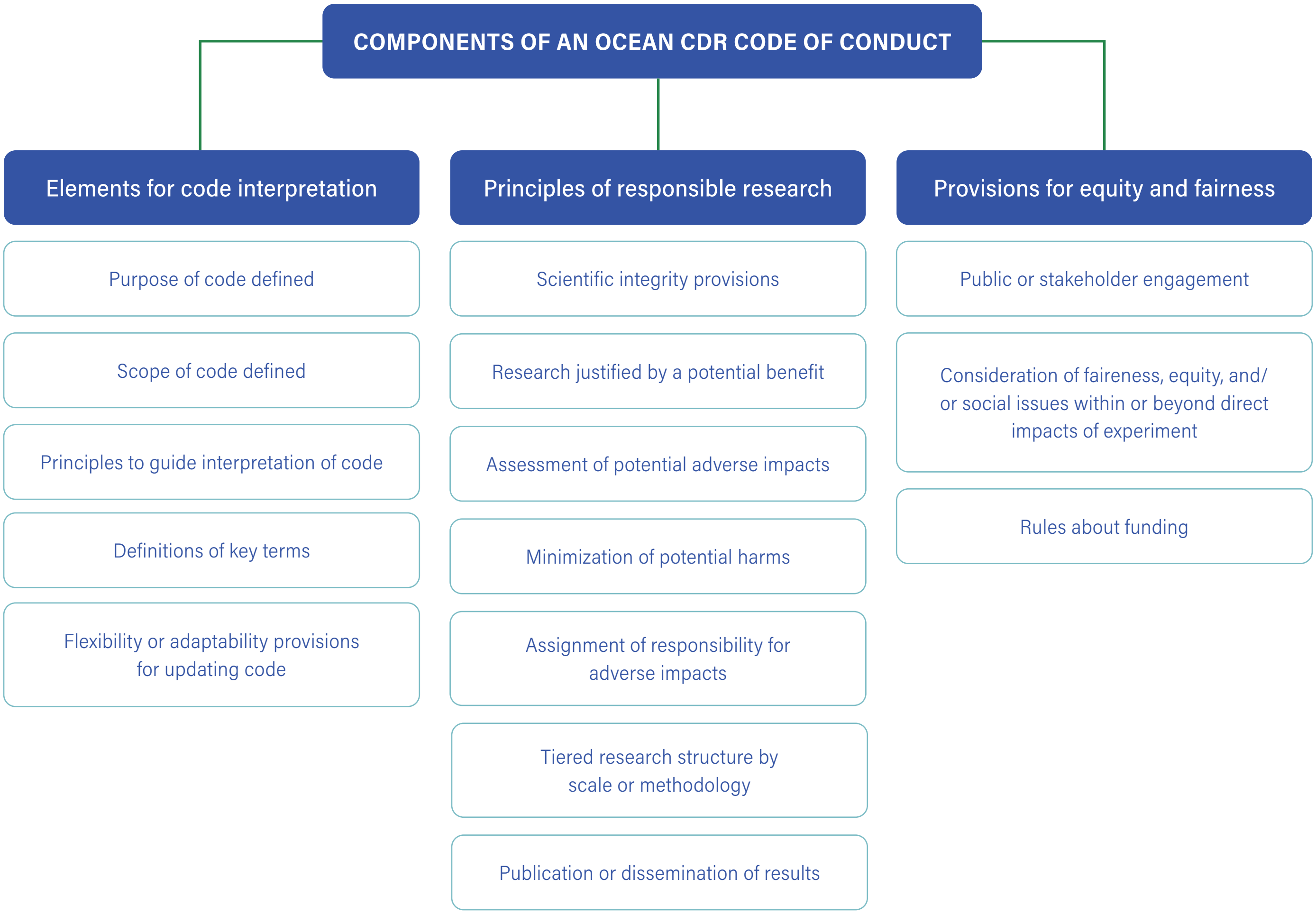
Ultimately, though, a new international framework may be required that is fit for purpose for the upcoming challenges of reducing carbon dioxide emissions through ocean CDR approaches in a manner that is responsible, sustainable, and equitable and that does not unreasonably put the health of the ocean and those that depend on it at risk. The current fragmentation of governance systems and enforcement mechanisms may make it difficult to ensure responsible ocean-based CDR research and to prevent projects for which the negative externalities (e.g., on ecosystems and communities) outweigh the benefits (Aspen Institute 2021). It will also complicate the process of determining who should be the appropriate stakeholders or regulators to decide whether, on balance, a project is net beneficial (Aspen Institute 2021).

Agreeing to a new framework treaty will take a substantial amount of time and global resources given the complexity of the issues involved in ocean CDR approaches, significant negative public perception to overcome, and likely hesitation of political leaders. The slow uptake and ratification of the 2013 amendment to the London Protocol (currently only six parties) is an indication of the potential hurdles to overcome. Many environmental treaty processes take more than five years to complete.[30]

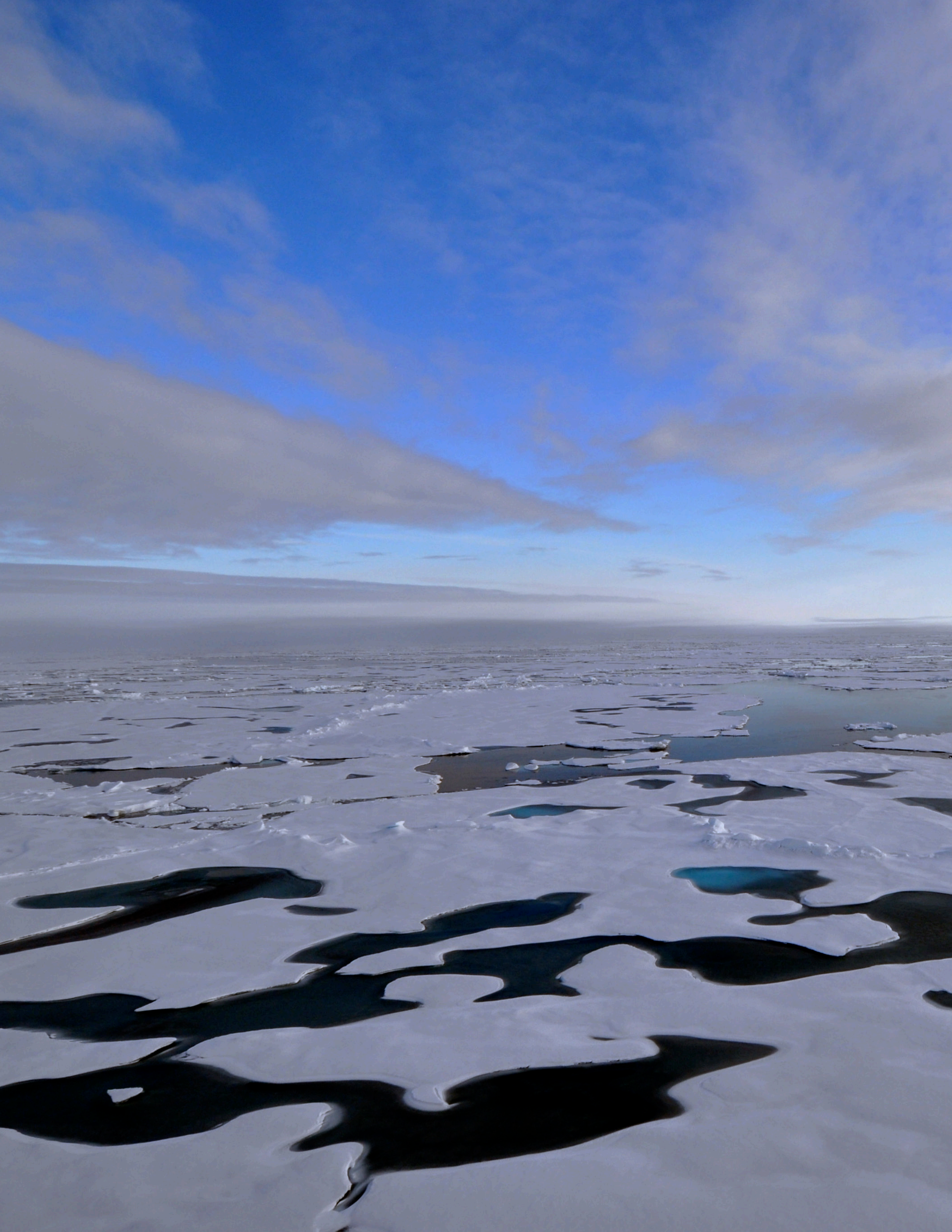
One possible pathway could be to initiate an independent scientific advisory body that draws on the existing GESAMP marine experts and IPCC scientists to represent a balanced and transdisciplinary approach. Recommendations from this body could then inform a multilateral ministerial convened under the auspices of the UNFCCC to lay the foundation for negotiations.

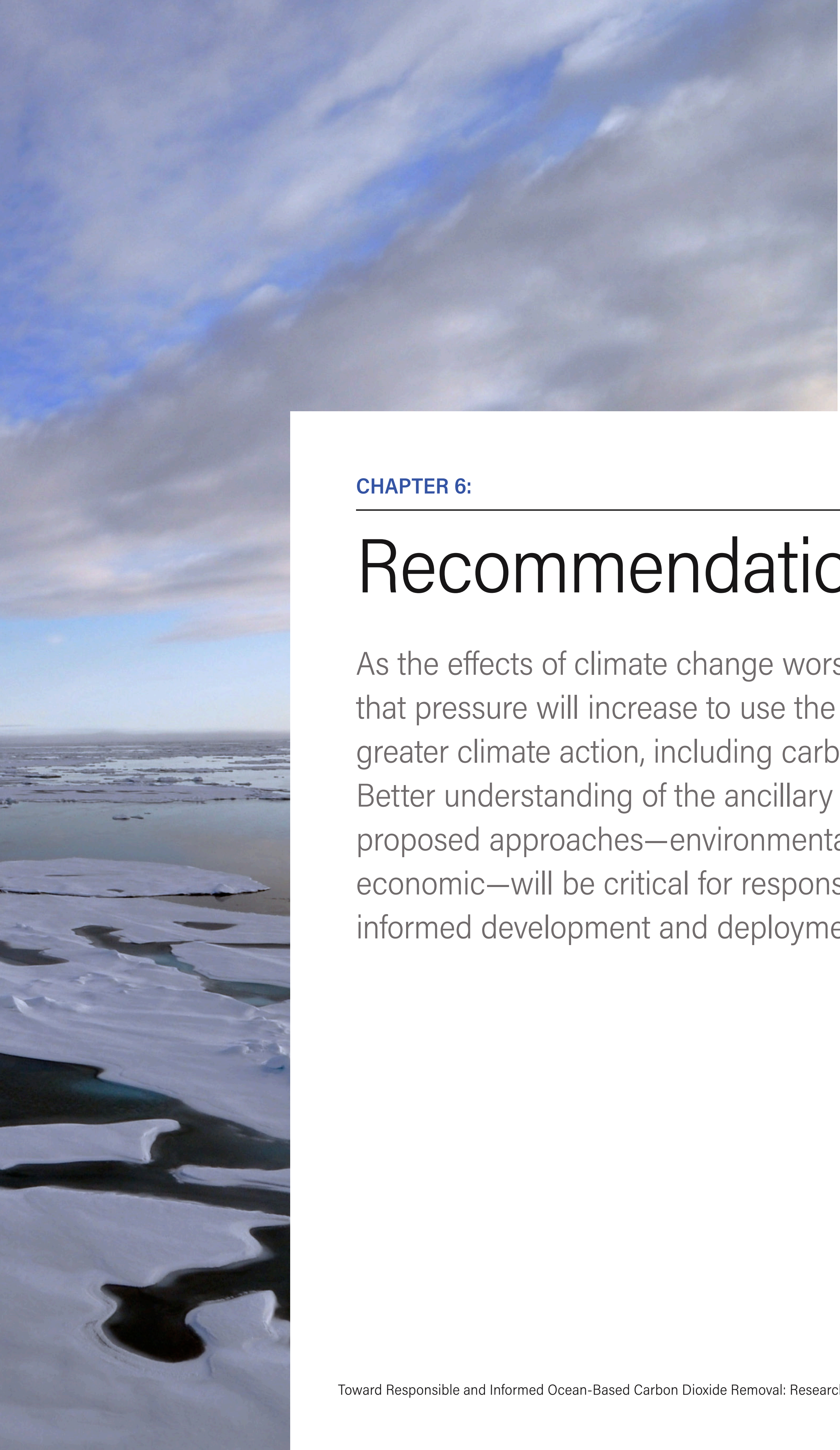
Efforts would need to bring coherence to the existing system and provide for coordination and clear mandates across the existing frameworks.

FIGURE 13 | Components of an Ocean CDR Code of Conduct



Source: Loomis et al. 2022.





CHAPTER 6:

Recommendations

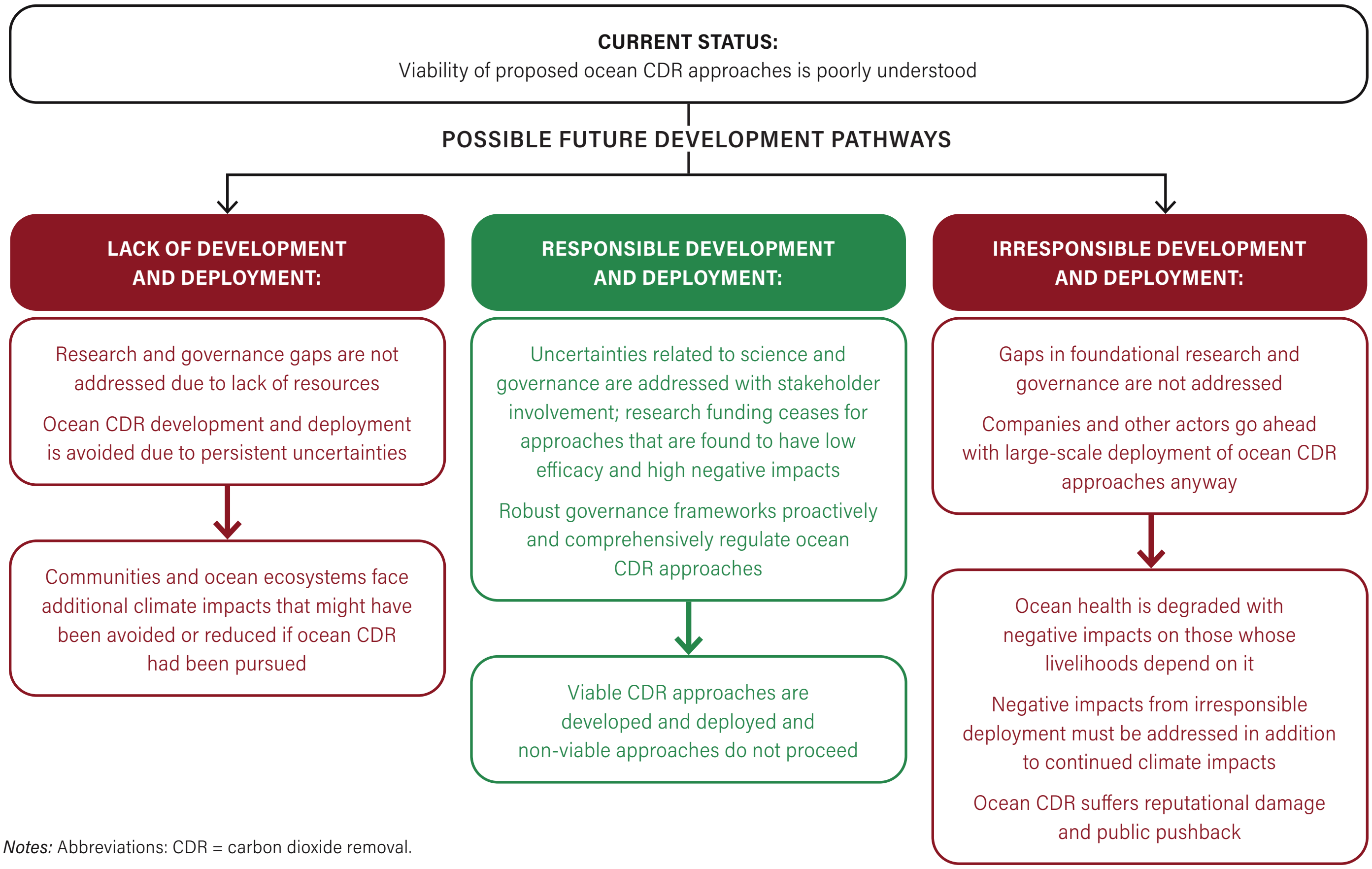
As the effects of climate change worsen, it is likely that pressure will increase to use the ocean for greater climate action, including carbon removal. Better understanding of the ancillary impacts of proposed approaches—environmental, social, and economic—will be critical for responsible and informed development and deployment.

Striking an appropriate balance between the urgency of reducing emissions and using appropriate ocean CDR approaches without causing further harm to ocean systems, ecosystems, and coastal communities will require an iterative and adaptive approach, as proposed by the National Academies (NASEM 2021). Decisions about research investments must adapt based on findings about the efficacy, durability, cost-benefit balance, and social or governance challenges of each approach. This adaptive approach includes ceasing research investment and preventing harmful deployment if an approach is found to be nonviable (NASEM 2021).

Responsible development of ocean CDR requires implementing appropriate governance structures and ensuring equitable outcomes (Figure 14). Each ocean CDR approach is unique, and will likely pose unique opportunities, but also impacts. Clarifying and developing robust governance frameworks at the international and national levels is also vital to providing responsible guardrails on ocean carbon removal development.

To aid in these goals, we propose three key priorities to help advance the informed and responsible deployment of ocean CDR.

FIGURE 14 | The Case for Responsible Deployment of Ocean Carbon Dioxide Removal



CURRENT STATUS:
Viability of proposed ocean CDR approaches is poorly understood

POSSIBLE FUTURE DEVELOPMENT PATHWAYS

LACK OF DEVELOPMENT AND DEPLOYMENT:

Research and governance gaps are not addressed due to lack of resources

Ocean CDR development and deployment is avoided due to persistent uncertainties

Communities and ocean ecosystems face additional climate impacts that might have been avoided or reduced if ocean CDR had been pursued

RESPONSIBLE DEVELOPMENT AND DEPLOYMENT:

Uncertainties related to science and governance are addressed with stakeholder involvement; research funding ceases for approaches that are found to have low efficacy and high negative impacts

Robust governance frameworks proactively and comprehensively regulate ocean CDR approaches

Viable CDR approaches are developed and deployed and non-viable approaches do not proceed

IRRESPONSIBLE DEVELOPMENT AND DEPLOYMENT:

Gaps in foundational research and governance are not addressed

Companies and other actors go ahead with large-scale deployment of ocean CDR approaches anyway

Ocean health is degraded with negative impacts on those whose livelihoods depend on it

Negative impacts from irresponsible deployment must be addressed in addition to continued climate impacts

Ocean CDR suffers reputational damage and public pushback

Notes: Abbreviations: CDR = carbon dioxide removal.

Source: Authors.

Priority One: Resolve uncertainties to understand which approaches are viable for large-scale deployment with minimal negative impact on ocean systems, ecosystems, and coastal communities

1. Increase public, private, and philanthropic funding for collaborative research on ocean CDR, prioritizing the following:

- Improved models for large-scale ocean CDR simulations, including integration with smaller-scale models, to understand the impacts on ocean systems, ecosystems, and coastal communities
- Research, including mesocosm trials and field testing for approaches where uncertainty cannot be resolved in a laboratory setting, to assess efficacy and ecological impacts
- Research on safeguards and emergency measures
- Tracking research and commercial deployment taking place (national, regional, international) in a transparent and accessible public database
- Improved methodologies for MRV, including development or improvement of baselines needed for accounting, as well as monitoring for environmental and ecological impacts
- Understanding social impacts and whether/how ocean CDR could affect other priorities like sustainable development, biodiversity, job provision, and food production
- Capacity development for early-career researchers in climate-vulnerable communities, underrepresented groups, Indigenous Peoples, and the Global South
- Collaborative and co-produced research partnerships with Indigenous and coastal communities

2. Establish an independent interdisciplinary committee, drawing on scientific experts from the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the IPCC, and other groups, to advance consensus on an international research agenda, including what constitutes responsible field tests and priorities for clarifying the international governance framework, building on work done already at the national level.

Priority Two: Improve governance frameworks at the local, national, and international levels to ensure research and small-scale pilots are undertaken responsibly and all stakeholders are informed and included

1. Convene a ministerial dialogue on ocean CDR under the joint auspices of the UNFCCC, CBD, London Convention, and London Protocol to respond to the recommendations from the scientific committee (identified in Priority One), lay the foundation for further discussions, and promote greater coherence across existing international frameworks.
2. Develop an international code of conduct for at-sea research trials and require adherence to this code to receive public and/or philanthropic funding or permits.
3. Ensure national and local regulatory and permitting processes are clear in their application to ocean CDR approaches. Where necessary, develop new regulatory and permitting processes that include robust environmental impact assessments and incentivize research (either for scientific or commercial purposes) for which data are shared transparently.
4. Develop a publicly accessible and transparent platform to share standardized data from research efforts and any at-sea trials.
5. Embed robust, inclusive, and funded community consultation in all nationally and philanthropically funded ocean CDR research and deployment processes and promote use of shared benefits agreements (where relevant).

Priority Three: Lay the foundation for robust governance of large-scale deployment in the future

1. Initiate a process to explore a new agreement or framework to proactively govern ocean CDR deployment, including consideration of the following:

- Which institution (new or existing) will have the mandate to regulate ocean CDR as a cross-cutting issue
- Governance of different jurisdictional zones
- Independent and peer-reviewed assessments of impacts

- Clear thresholds for unacceptable levels of harm or unacceptable levels of uncertainty in terms of achieving sustainable development goals and social, equity, economic, and ecological impacts of deployment
- Stage-gated, science-based decision-making
- Clarity on what constitutes research versus commercial deployment of ocean CDR approaches
- Liability in the event of harm
- Transparency and information-sharing requirements, including data standardization
- Equitable benefit sharing and avoidance of developing countries bearing the burden of research and at-sea testing
- Robust and inclusive stakeholder engagement processes (building on codes of conduct and existing safeguards)
- Obligation to either apply the instrument domestically or adopt other measures to implement the operative provisions domestically

2. Initiate a process to resolve uncertainties related to MRV methodologies; accounting and reporting under the UNFCCC; and use of credits in voluntary carbon markets.

GLOSSARY OF TERMS

adaptive ocean management: A systematic process to improve management policies and practices by learning from the results of previous policies and practices

alkalinity enhancement: Adding alkaline materials to the ocean to mimic natural rock weathering that takes up dissolved CO_2, converts it to bicarbonate and carbonate, and allows atmospheric CO_2 to then be absorbed by ocean water

artificial downwelling: Accelerating natural currents that carry carbon-rich surface water into the deep ocean where temperature is lower and CO_2 solubility is higher

artificial upwelling: Bringing deep, nutrient-rich water up to the surface to stimulate enhanced phytoplankton growth; some fraction of the carbon fixed by phytoplankton is then thought to be exported to the deep ocean for storage while additional atmospheric CO_2 is thought to be drawn into the ocean to compensate for reduced CO_2 levels

Atlantic meridional overturning circulation (AMOC): An important system of ocean currents in the Atlantic that is expected to see reduced strength this century due to climate change

carbon capture and sequestration (CCS): Technologies that capture carbon dioxide at the emission source, such as cement plants, in contrast to carbon removal, which removes CO_2 from the air

carbon dioxide removal (CDR): Approaches or technologies that pull carbon dioxide from the air using natural or engineered processes on land or in the ocean

carbon sink: Natural or artificial reservoirs that store carbon for an indefinite period; the ocean is a critical natural carbon sink

coastal blue carbon: Carbon that is captured and stored by coastal and marine ecosystems including salt marshes, mangroves, and seagrasses

code of conduct: A set of norms and best practices that encourage responsible research among public and private actors

Conference of the Parties (COP): The decision-making body for the United Nations Framework Convention on Climate Change that meets annually; all states that are parties to the convention are represented at COP meetings

Convention on Biological Diversity (CBD): A multilateral treaty adopted in 1992 that focuses on conserving biological diversity and sustainably using its components

customary international law: Rules that come from general principle rather than from written conventions and treaties

ecosystem approach: A strategy for integrated land, water, and resource management under the Convention on Biological Diversity that prioritizes conservation, sustainability, and equity

electrochemical techniques: Ocean CDR approaches that use electricity to accelerate reactions that remove CO_2 from seawater

exclusive economic zone (EEZ): The area extending 200 nautical miles from shore in which countries have sovereign rights to "explore, exploit, conserve, and manage natural resources" in the water column and underlying continental shelf (UN 1982)

gigaton (Gt): A unit equal to one billion metric tons (billion tonnes)

high seas: The area of the ocean extending beyond the territorial and exclusive economic zones of countries, which is open to access by all countries but is subject to the regulations in the United Nations Convention on the Law of the Sea and relevant regional treaties

integrated coastal zone management (ICZM): A participatory and cooperative process of determining societal goals in a given coastal area and managing coastal and nearshore waters in an integrated, iterative, and comprehensive way to achieve conservation and sustainable use of marine resources that balances environmental, social, cultural, and recreational objectives (EEA 2000)

integrated ocean management (IOM): A process that brings together actors across sectors of the ocean industry to support a sustainable ocean economy and use ocean resources in ways that preserve the health and resilience of marine ecosystems and improve livelihoods and jobs

Intergovernmental Panel on Climate Change (IPCC): An intergovernmental body established in 1988 to advance knowledge and understanding of anthropogenic climate change

London Convention: Adopted in 1972, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) requires parties to "promote the effective control of all sources of pollution of the marine environment"; parties must prohibit dumping of listed substances (London Convention 1972)

London Protocol: Adopted in 1996, the Protocol to the London Convention (London Protocol) has a mission to "protect and preserve the marine environment from all sources of pollution"; parties must prohibit dumping of all substances except those listed in the protocol (London Protocol 1996)

long-term strategies (LTSs): Long-term, low-emission development strategies that parties to the Paris Agreement are invited to submit to the United Nations Framework Convention on Climate Change

marine scientific research (MSR): The freedom for all parties of the United Nations Convention on the Law of the Sea to conduct research in the high seas so long as it is conducted for peaceful purposes and employs appropriate scientific methods

marine spatial planning (MSP): The creation of geospatial plans that identify which spaces of the ocean are appropriate for different human uses and activities to minimize conflicts

megaton (Mt): A unit equal to one million metric tons (million tonnes)

mitigation: Approaches or technologies that reduce or avoid emissions

measurement, reporting, and verification (MRV): Quantifying short- and long-term carbon sequestration that stems from ocean carbon dioxide removal application (measurement); sharing the results of this quantification among countries and/or governments as appropriate (reporting); and confirming that the claimed amount of sequestered carbon is assigned to the appropriate company or country (verification)

nationally determined contribution (NDC): Climate plans submitted by parties under the United Nations Framework Convention on Climate Change to reduce emissions in line with the goals of the Paris Agreement and adapt to the impacts of climate change

"no-harm" rule: A rule under customary international law that all countries are obligated to prevent activities under their jurisdictions from causing significant harm to the territories of other countries and to the high seas

nutrient cycling: Movement of nutrients like nitrogen and phosphorus from surface waters to the deep sea and back to surface waters through natural processes and ocean currents

ocean acidification: Decreases in the pH (potential of hydrogen) in the ocean caused by excess absorption of carbon dioxide from the atmosphere, which can cause detrimental impacts to ecosystems

ocean alkalinity enhancement (OAE): See "alkalinity enhancement."

ocean fertilization: The process of adding key nutrients like iron, nitrogen, and phosphorus to areas of the ocean where these nutrients limit primary productivity, thus accelerating fixation of inorganic carbon into biomass; some portion of this biomass sinks to the deep ocean for storage while corresponding oceanic uptake of atmospheric carbon dioxide (CO_2) compensates for some portion of the resulting reduced CO_2 levels in ocean water

polluter pays principle: A principle that has been discussed in international law but is not a customary international norm, and which asserts that polluters should bear the costs of their pollution, including the cost of measures taken to prevent, control, and remedy pollution and the costs it imposes on society

precautionary principle/precautionary approach: A norm under customary international law that generally articulates the need for environmental protection, the presence of potential environmental risk or damage, and the management of risk in the face of scientific uncertainty

primary productivity: Production of biomass (organic matter) from carbon dioxide, sunlight, water, and nutrients by photosynthetic producers (e.g., phytoplankton)

regional seas agreements: Agreements that, in addition to international instruments, provide states with further obligations for high seas marine environmental protection

seaweed cultivation: Growing macroalgae that take up inorganic carbon from seawater during photosynthesis, thus fixing this carbon as biomass; this biomass is then sunk to the bottom of the ocean for permanent sequestration or is harvested and used in products like food, fuel, and fertilizer

stakeholder engagement: Participation of stakeholders in planning and decision-making to incorporate their unique knowledge or preferences in project design or development; effective stakeholder engagement can strengthen social and environmental benefits and help enhance project acceptance or ownership

Sustainable Development Goals (SDGs): A collection of 17 interlinked global goals intended to be achieved by 2030 that have been laid out by the United Nations General Assembly

territorial sea: The area of the ocean that countries have full sovereignty over, which generally extends 12 nautical miles from the coast

United Nations Convention on the Law of the Sea (UNCLOS): A comprehensive regulatory framework regarding use of the ocean that establishes a legal framework for all use and management activities in the ocean, including regulating marine pollution and defining marine scientific research

United Nations Decade of Ocean Science: United Nations–declared decade (2021–2030) to increase scientific understanding of the ocean and convene stakeholders to support efforts to reverse declines in ocean health

United Nations Framework Convention on Climate Change (UNFCCC): A United Nations convention that established an international treaty to combat dangerous human interference with the climate system and stabilize greenhouse gas emissions at safe levels

voluntary carbon market: Markets on which purchasers can buy and suppliers can sell credits representing the reduction or removal of greenhouse gas emissions without regulatory requirements or incentives to do so; in general, these markets are not regulated by governments

X/33: A decision adopted by the parties of the Convention on Biological Diversity that provides a nonbinding ban on all geoengineering activities

ENDNOTES

1. There is currently scientific debate in the research literature about whether macroalgae should be considered a form of “blue carbon” carbon removal, because only a small portion of net primary production may end up buried in sediment (Brent et al. 2019; Krause-Jensen et al. 2018). For the purposes of this report, we address it as a separate carbon removal concept.

2. Unlike customary international law, states must consent to be bound by international agreements by ratifying, accepting, or otherwise expressing consent. The capacity of an international agreement to govern carbon removal is limited to governing actions of states that have consented to be bound by it and whether it has entered into force.

3. Article 240(b), UNCLOS.

4. For more information on the different regimes of MSR in the high seas and exclusive economic zones, see M. Pavliha and N.A. Martinez Gutiérrez, “Marine Scientific Research and the 1982 United Nations Convention on the Law of the Sea,” *Ocean & Coastal Law Journal* 16, no. 1 (2010), http://digitalcommons.mainelaw.maine.edu/oclj/vol16/iss1/4.

5. For further discussion of this issue in the context of whaling, see B. Gogarty and P. Lawrence, “The ICJ Whaling Case: Missed Opportunity to Advance the Rule of Law in Resolving Science-Related Disputes in Global Commons?” *Heidelberg Journal of International Law* 77, no. 1 (2017): 165.

6. Articles 192 and 193, UNCLOS.

7. Articles 194 and 196, UNCLOS.

8. Note that the United States is not a contracting party to the CBD.

9. “Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at Its Ninth Meeting: IX/16. Biodiversity and Climate Change,” 9th Meeting, Agenda Item 4.5, UNEP/CBD/ COP/DEC/IX/16, October 9, 2008, Section C.

10. “Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at Its Tenth Meeting: X/33. Biodiversity and Climate Change,” 10th Meeting, Agenda Item 5.6, UNEP/CBD/ COP/DEC/X/33 October 29, 2010, paragraph 8(w).

11. “Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at Its Tenth Meeting,” UNEP/CBD/COP/DEC/X/33, October 29, 2010.

12. “Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at Its Thirteenth Meeting: XIII/14. Biodiversity and Climate Change,” 13th Meeting, Agenda Item 17, UNEP/CBD/COP/ DEC/XIII/14, December 8, 2016.

13. The objective of the London Convention is to promote the effective control of all sources of marine pollution and take all practicable steps to prevent pollution of the sea by dumping of wastes and other matter. Currently, 87 states are parties to this convention.

14. The London Protocol was agreed to further modernize the London Convention and, eventually, replace it. The protocol entered into force on March 24, 2006, and there are currently 53 parties to the protocol.

15. The following are listed in Annex 1: dredged material; sewage sludge; fish wastes or material resulting from industrial fish processing operations; vessels and platforms or other manmade structures at sea; inert, inorganic geological material; organic material of natural origin; bulky items primarily comprising iron, steel, concrete, and similarly unharmful materials for which the concern is physical impact, and limited to the circumstances where such wastes are generated at locations with no land-based alternatives; carbon dioxide streams from carbon dioxide capture processes for sequestration in subseabed geological formations (London Protocol 1996).

16. 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972, https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/PROTOCOLAmended2006.pdf.

17. Resolution LC-LP.1, 2008, on the Regulation of Ocean Fertilization, adopted October 31, 2008.

18. “Assessment Framework for Scientific Research Involving Ocean Fertilization (Adopted October 14, 2010),” Report of the Thirty-Second Consultative Meeting and the Fifth Meeting of Contracting Parties, 32nd and 5th Meetings, Agenda Item 15, Annex 6, LC 32/15, November 9, 2010.

19. Resolution LP.4(8), 2013.

20. Note that it is unclear whether the earlier 2008 decision would also apply as there is no legal or scientific consensus on whether artificial upwelling or downwelling constitutes “ocean fertilization” for the purposes of the CBD. Within the scientific community, the term *ocean fertilization* is generally used to refer to the addition of nutrients to ocean waters to stimulate the growth of photosynthesizing life, such as plankton, and thereby increase the natural biological pump that transports carbon dioxide from the surface ocean downward. This definition arguably would not encompass artificial upwelling and downwelling because they do not involve the addition of nutrients to ocean waters. See generally, Royal Society and Royal Academy of Engineering, Greenhouse Gas Removal 43 (London: Royal Society, 2018), https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-societygreenhouse-gas-removal-report-2018.pdf.

21. See, for example, Chris Vivian, Remarks at the National Academies of Sciences, Engineering, and Medicine Workshop on Ocean-Based CDR Opportunities and Challenges, February 25, 2021. Slides available at https://www. nationalacademies.org/event/02-25-2021/a-research-strategy-for-ocean-carbon-dioxide-removal-andsequestration-workshop-series-part-4. But see Proelss and Hong (2012) at 380: "Given that the pipes are introduced into the marine environment 'for a purpose other than mere disposal thereof,' their deployment cannot be regarded as dumping."
22. London Protocol Resolution LP.4(8) 2008.
23. London Protocol Resolution LP.4(8) 2008 has yet to enter into force, as it needs to be ratified by two-thirds of contracting parties to the London Protocol.
24. London Protocol Resolution LP.4(8) 2008.
25. Resolution LC-LP.2(2010) on the Assessment Framework for Scientific Research Involving Ocean Fertilization, October 14, 2010.
26. Rules of customary international law are generally binding on all states.
27. See Pulp Mills on the River Uruguay (Argentina v Uruguay) [2010] ICJ Rep 14 at 101.
28. Articles 192 and 193, UNCLOS.
29. Articles 56/2, 87/2, and 142/1, UNCLOS.
30. The process to negotiate the Paris Agreement took five years, from COP17 in 2011, and negotiations that are still underway began in 2015 to establish a new agreement under UNCLOS aimed at conserving marine biodiversity beyond national jurisdiction.
31. Article 191 of the Treaty on the Functioning of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A12016E191.

REFERENCES

Abelson, A., D.C. Reed, G.J. Edgar, C.S. Smith, G.A. Kendrick, R.J. Orth, L. Airoldi, et al. 2020. "Challenges for Restoration of Coastal Marine Ecosystems in the Anthropocene." *Frontiers in Marine Science* 7. https://www.frontiersin.org/articles/10.3389/fmars.2020.544105.

Albright, R., L. Caldeira, J. Hosfelt, and L. Kwaitkowski. 2016. "Reversal of Ocean Acidification Enhances Net Coral Reef Calcification." *Nature* 531: 362–65. https://www.nature.com/articles/nature17155.pdf.

ARPA-E (Advanced Research Projects Agency–Energy, United States). 2017. *Macroalgae Research Inspiring Novel Energy Resources (MARINER) Program Overview*. Washington, DC: U.S. Department of Energy. https://arpa-e.energy.gov/sites/default/files/documents/files/MARINER_ProgramOverview_FINAL.pdf.

Aspen Institute. 2021. *Guidance for Ocean-Based Carbon Dioxde Removal Projects: A Pathway to Developing a Code of Conduct*. Washington, DC: The Aspen Institute. https://www.aspeninstitute.org/wp-content/uploads/files/content/docs/pubs/120721_Ocean-Based-CO2-Removal_E.pdf.

Aumont, O., and L. Bopp. 2006. "Globalizing Results from Ocean In Situ Iron Fertilization Studies." *Global Biogeochemical Cycles* 20 (2). doi:10.1029/2005GB002591.

Bach, L.T., S.J. Gill, R.E.M. Rickaby, S. Gore, and P. Renforth. 2019. "CO_2 Removal with Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems." *Frontiers in Climate* 1. doi:10.3389/fclim.2019.00007.

Bach, L.T., V. Tamsitt, J. Gower, C.L. Hurd, J.A. Raven, and P.W. Boyd. 2021. "Testing the Climate Intervention Potential of Ocean Afforestation Using the Great Atlantic Sargassum Belt." *Nature Communications* 12 (1): 2556. doi:10.1038/s41467-021-22837-2.

Bähr, U. 2017. "Ocean Atlas: Facts and Figures on the Threats to Our Marine Ecosystems." Heinrich Böll Foundation. https://www.boell.de/sites/default/files/web_170607_ocean_atlas_vektor_us_v102.pdf.

Batten, S.D., and J.F.R. Gower. 2014. "Did the Iron Fertilization near Haida Gwaii in 2012 Affect the Pelagic Lower Trophic Level Ecosystem?" *Journal of Plankton Research* 36 (4): 925–32. doi:10.1093/plankt/fbu049.

Bayraktarov, E., M.I. Saunders, S. Abdullah, M. Mills, J. Beher, H.P. Possingham, P.J. Mumby, et al. 2016. "The Cost and Feasibility of Marine Coastal Restoration." *Ecological Applications* 26 (4): 1055–74. doi:10.1890/15-1077.

Berger, M., L. Bopp, D.T. Ho, and L. Kwiatkowski. 2022. "Assessing Global Macroalgal Carbon Dioxide Removal Potential Using a High-Resolution Ocean Biogeochemistry Model." Vienna, Austria: EGU General Assembly 2022, May 23–27, EGU22-469. doi:10.5194/egusphere-egu22-4699.

Biello, D. 2012. "Can Controversial Ocean Iron Fertilization Save Salmon?" *Scientific American*, October 24. https://www.scientificamerican.com/article/fertilizing-ocean-with-iron-to-save-salmon-and-earn-money/.

Bigelow (Bigelow Laboratory for Ocean Sciences). 2018. "Kelp Strengthening Maine's Marine Economy." East Boothbay, Maine: Bigelow Laboratory for Ocean Sciences. https://www.bigelow.org/news/articles/2018-10-15.html.

Bjerregaard, R., D. Valderrama, N. Sims, R. Radulovich, J. Diana, M. Capron, J. Forster, et al. 2016. *Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries*. Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/947831469090666344/pdf/107147-WP-REVISED-Seaweed-Aquaculture-Web.pdf.

BMUV (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, Germany). 2018. "The German Government Implements Additional Provisions of the London Protocol on the Prevention of Marine Pollution." Press Release. Bonn and Berlin: BMUV. https://www.bmuv.de/PM8049-1.

Boehm, S., K. Lebling, K. Levin, H. Fekete, J. Jaeger, R. Waite, A. Nilsson, et al. 2021. *State of Climate Action 2021: Systems Transformations Required to Limit Global Warming to 1.5°C*. Washington, DC: World Resources Institute. https://www.wri.org/research/state-climate-action-2021.

Bopp, L., C. Bowler, L. Guidi, E. Karsenti, and C. de Vargas. 2015. *The Ocean: A Carbon Pump*. Ocean & Climate Platform. http://www.ocean-climate.org/wp-content/uploads/2015/03/ocean-carbon-pump_ScientificItems_BD-2.pdf.

Boyd, P.W. 2008. "Implications of Large-Scale Iron Fertilization of the Oceans." *Marine Ecology Progress Series* 364 (July): 213–18. doi:10.3354/meps07541.

Boyd, P.W., L.T. Bach, C.L. Hurd, E. Paine, J.A. Raven, and V. Tamsitt. 2022. "Potential Negative Effects of Ocean Afforestation on Offshore Ecosystems." *Nature Ecology & Evolution* 6 (6): 675–83. doi:10.1038/s41559-022-01722-1.

Brent, K., W. Burns, and J. McGee. 2019. *Governance of Marine Geoengineering*. Waterloo, Canada: Centre for International Governance Innovation. https://www.cigionline.org/publications/governance-marine-geoengineering.

Bristow, L.A., W. Mohr, S. Ahmerkamp, and M.M.M. Kuypers. 2017. "Nutrients That Limit Growth in the Ocean." *Current Biology* 27 (11): R474–78. doi:10.1016/j.cub.2017.03.030.

Burns, W., and C.R. Corbett. 2020. "Antacids for the Sea? Artificial Ocean Alkalinization and Climate Change." *One Earth* 3 (2): 154–56. doi:10.1016/j.oneear.2020.07.016.

Burt, D.J., F. Fröb, and T. Ilyina. 2021. "The Sensitivity of the Marine Carbonate System to Regional Ocean Alkalinity Enhancement." *Frontiers in Climate* 3. https://www.frontiersin.org/articles/10.3389/fclim.2021.624075.

Campbell, I., A. Macleod, C. Sahlmann, L. Neves, J. Funderud, M. Øverland, A.D. Hughes, et al. 2019. "The Environmental Risks Associated with the Development of Seaweed Farming in Europe—Prioritizing Key Knowledge Gaps." *Frontiers in Marine Science* 6. doi:10.3389/fmars.2019.00107.

Carlton, J.T., J.W. Chapman, J.B. Geller, J.A. Miller, D.A. Carlton, M.I. McCuller, N.C. Treneman, et al. 2017. "Tsunami-Driven Rafting: Transoceanic Species Dispersal and Implications for Marine Biogeography." *Science* 357 (6358): 1402–06. doi:10.1126/science.aao1498.

CAT (Climate Action Tracker). 2021. "Temperatures: Addressing Global Warming." https://climateactiontracker.org/global/temperatures/.

CBD (Convention on Biological Diversity). 2008. "COP Decision." Montreal, Canada: Secretariat of the Convention on Biological Diversity. https://www.cbd.int/decision/cop/?id=11659.

CBD. 2021. "Ecosystem Approach." Montreal, Canada: Secretariat of the Convention on Biological Diversity. https://www.cbd.int/ecosystem/.

CBD. 1992. "Convention on Biological Diversity: Text of the Convention." Secretariat of the Convention on Biological Diversity. https://www.cbd.int/convention/text/.

Conway, T., D. Hamilton, R. Shelley, A. Agulair-Islas, W. Landing, N. Mahowald, and S. John. 2019. "Tracing and Constraining Anthropogenic Aerosol Iron Fluxes to the North Atlantic Ocean Using Iron Isotopes." *Nature Communications* 10 (2628). https://www.nature.com/articles/s41467-019-10457-w.

de Boyer Montégut, C., G. Madec, A.S. Fischer, A. Lazar, and D. Iudicone. 2004. " Mixed Layer Depth over the Global Ocean: An Examination of Profile Data and a Profile-Based Climatology." *Journal of Geophysical Research: Oceans* 109 (C12). doi:10.1029/2004JC002378.

de Lannoy, C.-F., M.D. Eisaman, A. Jose, S.D. Karnitz, R.W. DeVaul, K. Hannun, and J.L.B. Rivest. 2018. "Indirect Ocean Capture of Atmospheric CO_2: Part I. Prototype of a Negative Emissions Technology." *International Journal of Greenhouse Gas Control* 70 (March): 243–53. doi:10.1016/j.ijggc.2017.10.007.

Dickson, A. n.d. *Part 1: Seawater Carbonate Chemistry*. San Diego, California: Scripps Institution of Oceanography, University of California, San Diego. https://www.pmel.noaa.gov/co2/files/dickson_thecarbondioxidesysteminseawater_equilibriumchemistryandmeasurementspp17-40.pdf. Accessed July 8, 2022.

Duarte, C.M., J. Wu, X. Xiao, A. Bruhn, and D. Krause-Jensen. 2017. "Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?" *Frontiers in Marine Science* 4. doi:10.3389/fmars.2017.00100.

EEA (European Environment Agency). 2000. "Integrated Coastal Zone Management." EEA Glossary. https://www.eea.europa.eu/help/glossary/eea-glossary/integrated-coastal-zone-management.

EFI (Energy Futures Initiative). 2020. *Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments*. Washington, DC: Energy Futures Initiative. https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/03/UnchartedWaters_Report_Dec2020.pdf.

Eisaman, M.D., J.L.B. Rivest, S.D. Karnitz, C.-F. de Lannoy, A. Jose, R.W. DeVaul, and K. Hannun. 2018. "Indirect Ocean Capture of Atmospheric CO_2: Part II. Understanding the Cost of Negative Emissions." *International Journal of Greenhouse Gas Control* 70 (March): 254–61. doi:10.1016/j.ijggc.2018.02.020.

Emerson, D. 2019. "Biogenic Iron Dust: A Novel Approach to Ocean Iron Fertilization as a Means of Large Scale Removal of Carbon Dioxide from the Atmosphere." *Frontiers in Marine Science* 6. doi:10.3389/fmars.2019.00022.

EPA (Environmental Protection Agency, United States). 2015. "Greenhouse Gas Equivalencies Calculator." Data and Tools. Washington, DC: EPA. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

EPA. 2021. "Climate Change Indicators: Oceans." Washington, DC: EPA. https://www.epa.gov/climate-indicators/oceans.

Evans, I. 2018. "The Scientists, Robots Cracking the Mysteries of the Southern Ocean." *The New Humanitarian*. https://deeply.thenewhumanitarian.org/oceans/community/2018/01/12/the-scientists-robots-cracking-the-mysteries-of-the-southern-ocean.

Fan, W., Y. Pan, D. Zhang, C. Xu, Y. Qiang, and Y. Chen. 2016. "Experimental Study on the Performance of a Wave Pump for Artificial Upwelling." *Ocean Engineering* 113 (February): 191–200. doi:10.1016/j.oceaneng.2015.12.056.

Fan, W., R. Zhao, Z. Yao, C. Xiao, Y. Pan, Y. Chen, N. Jiao, et al. 2019. "Nutrient Removal from Chinese Coastal Waters by Large-Scale Seaweed Aquaculture Using Artificial Upwelling." *Water* 11 (9): 1754. doi:10.3390/w11091754.

Ferdouse, F., S.L. Holdt, R. Smith, P. Murua, and Z. Yang. 2018. *The Global Status of Seaweed Production, Trade and Utilization*. Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/3/CA1121EN/ca1121en.pdf.

Ferrer González, M. 2017. "Climate Engineering by Enhancement of Ocean Alkalinity: Impacts on the Earth System and a Comparison with Solar Radiation Management." Dissertation. Hamburg, Germany: University of Hamburg. https://ediss.sub.uni-hamburg.de/handle/ediss/7327.

Figuerola, B., A.M. Hancock, N. Bax, V.J. Cummings, R. Downey, H.J. Griffiths, J. Smith, et al. 2021. "A Review and Meta-analysis of Potential Impacts of Ocean Acidification on Marine Calcifiers from the Southern Ocean." *Frontiers in Marine Science* 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.584445.

Finn, L. 2022. "Plans for 1st 'Carbon-Negative' Beach Unveiled in Hamptons." Southampton, New York: *Patch*, July 14. Sec. Community Corner. https://patch.com/new-york/southampton/plans-1st-carbon-negative-beach-unveiled-hamptons.

Friedlingstein, P., M.W. Jones, M. O'Sullivan, R.M. Andrew, D.C.E. Bakker, J. Hauck, C. Le Quéré, et al. 2022. "Global Carbon Budget 2021." *Earth System Science Data* 14 (4): 1917–2005. doi:10.5194/essd-14-1917-2022.

Friess, D.A., K. Rogers, C.E. Lovelock, K.W. Krauss, S.E. Hamilton, S.Y. Lee, R. Lucas, et al. 2019. "The State of the World's Mangrove Forests: Past, Present, and Future." *Annual Review of Environment and Resources* 44 (1): 89–115. doi:10.1146/annurev-environ-101718-033302.

Froehlich, H.E., J.C. Afflerbach, M. Frazier, and B.S. Halpern. 2019. "Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting." *Current Biology* 29 (18): 3087–93.e3. doi:10.1016/j.cub.2019.07.041.

Fuhr, M., S. Geilert, M. Schmidt, V. Liebetrau, C. Vogt, B. Ledwig, and K. Wallmann. 2022. "Kinetics of Olivine Weathering in Seawater: An Experimental Study." *Frontiers in Climate* 4. https://www.frontiersin.org/article/10.3389/fclim.2022.831587.

Gagern, A., G.H. Rau, D. Rodriguez, P. Renforth, W. Burns, and E. Graffy. 2019. *Ocean Alkalinity Enhancement: Current State of Knowledge and Potential Role of Philanthropy*. San Francisco, California: CEA Consulting. https://www.ceaconsulting.com/wp-content/uploads/Ocean-Alkalinity-Enhancement-CEA-proceedings-doc.pdf.

Gallagher, J.B., V. Shelamoff, and C. Layton. 2022. "Seaweed Ecosystems May Not Mitigate CO_2 Emissions." *ICES Journal of Marine Science* 79 (3): 585–92. doi:10.1093/icesjms/fsac011.

Gattuso, J.-P., A.K. Magnan, L. Bopp, W.W.L. Cheung, C.M. Duarte, J. Hinkel, E. Mcleod, et al. 2018. "Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems." *Frontiers in Marine Science* 5. doi:10.3389/fmars.2018.00337.

Gattuso, J.-P., P. Williamson, C.M. Duarte, and A.K. Magnan. 2021. "The Potential for Ocean-Based Climate Action: Negative Emissions Technologies and Beyond." *Frontiers in Climate* 2. https://www.frontiersin.org/article/10.3389/fclim.2020.575716.

GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 2019. *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques*. London: GESAMP. http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques.

Gnanadesikan, A., J.L. Sarmiento, and R.D. Slater. 2003. "Effects of Patchy Ocean Fertilization on Atmospheric Carbon Dioxide and Biological Production." *Global Biogeochemical Cycles* 17 (2). doi:10.1029/2002GB001940.

Goldberg, L., D. Lagomasino, N. Thomas, and T. Fatoyinbo. 2020. "Global Declines in Human-Driven Mangrove Loss." *Global Change Biology* 26 (10): 5844–55. doi:10.1111/gcb.15275.

Gong, H., C. Li, and Y. Zhou. 2021. "Emerging Global Ocean Deoxygenation across the 21st Century." *Geophysical Research Letters* 48 (23): e2021GL095370. doi:10.1029/2021GL095370.

González, M.F., T. Ilyina, S. Sonntag, and H. Schmidt. 2018. "Enhanced Rates of Regional Warming and Ocean Acidification after Termination of Large-Scale Ocean Alkalinization." *Geophysical Research Letters* 45 (14): 7120–29. doi:10.1029/2018GL077847.

González, M.F., and T. Ilyina. 2016. "Impacts of Artificial Ocean Alkalinization on the Carbon Cycle and Climate in Earth System Simulations." *Geophysical Research Letters* 43 (12): 6493–6502. doi:10.1002/2016GL068576.

Gore, S., P. Renforth, and R. Perkins. 2019. "The Potential Environmental Response to Increasing Ocean Alkalinity for Negative Emissions." *Mitigation and Adaptation Strategies for Global Change* 24 (7): 1191–211. doi:10.1007/s11027-018-9830-z.

Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, et al. 2017. "Natural Climate Solutions." *Proceedings of the National Academy of Sciences* 114 (44): 11645–50. doi:10.1073/pnas.1710465114.

Gruber, N., D. Clement, B.R. Carter, R.A. Feely, S. van Heuven, M. Hoppema, M. Ishii, et al. 2019. "The Oceanic Sink for Anthropogenic CO_2 from 1994 to 2007." *Science* 363 (6432): 1193–99. doi:10.1126/science.aau5153.

Hanson, C., N. Frost, M. Potouroglou, E. Hollaway, P. Huagan, and P. Schive. 2022. *100% Sustainable Ocean Management: An Introduction to Sustainable Ocean Plans.* High Level Panel for a Sustainable Ocean Economy. https://oceanpanel.org/wp-content/uploads/2022/06/21_REP_Ocean-SOP_v10.pdf.

Harrison, D.P. 2017. "Global Negative Emissions Capacity of Ocean Macronutrient Fertilization." *Environmental Research Letters* 12 (3): 035001. doi:10.1088/1748-9326/aa5ef5.

Harvey, L.D.D. 2008. "Mitigating the Atmospheric CO_2 Increase and Ocean Acidification by Adding Limestone Powder to Upwelling Regions." *Journal of Geophysical Research: Oceans* 113 (C4). doi:10.1029/2007JC004373.

Heine, D., M.G. Faure, and G. Dominioni. 2020. "The Polluter-Pays Principle in Climate Change Law: An Economic Appraisal." *Climate Law* 10 (1): 94–115. doi:10.1163/18786561-01001004.

Hickey, H. 2018. "Seaweed Fights Ocean Acidification." Seattle: School of Oceanography, College of the Environment, University of Washington. www.ocean.washington.edu/story/Seaweed_Fights_Ocean_Acidification.

Hilser, H., E. Cox, A. Draiby, C. Moreau, L. Hiraldo, N. Walworth, and L. Winks. 2022. "Localized Governance of Carbon Dioxide Removal in Small Island Developing States." Scholarly Paper. Rochester, NY: SSRN. doi:10.2139/ssrn.4114319.

Himes-Cornell, A., L. Pendleton, and P. Atiyah. 2018. “Valuing Ecosystem Services from Blue Forests: A Systematic Review of the Valuation of Salt Marshes, Sea Grass Beds and Mangrove Forests.” *Ecosystem Services* 30 (April): 36–48. doi:10.1016/j.ecoser.2018.01.006.

Hoegh-Guldberg, O., K. Caldeira, T. Chopin, S. Gaines, P. Haugan, M. Hemer, J. Howard, et al. 2019. *The Ocean as a Solution to Climate Change.* High Level Panel for a Sustainable Ocean Economy. http://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf.

Honegger, M., A. Michaelowa, and J. Roy. 2021a. “Potential Implications of Carbon Dioxide Removal for the Sustainable Development Goals.” *Climate Policy* 21 (5): 678–98. doi:10.1080/14693062.2020.1843388.

Honegger, M., M. Poralla, A. Michaelowa, and H.-M. Ahonen. 2021b. “Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies.” *Frontiers in Climate* 3. https://www.frontiersin.org/article/10.3389/fclim.2021.672996.

Hubert, A.-M., and D. Reichwein. 2015. *An Exploration of a Code of Conduct for Responsible Scientific Research Involving Geoengineering.* Potsdam, Germany: Institute for Advanced Sustainability Studies. https://www.insis.ox.ac.uk/sites/default/files/insis/documents/media/an_exploration_of_a_code_of_conduct.pdf.

Hurd, C.L., C.S. Law, L.T. Bach, D. Britton, M. Hovenden, E.R. Paine, J.A. Raven, et al. 2022. “Forensic Carbon Accounting: Assessing the Role of Seaweeds for Carbon Sequestration.” *Journal of Phycology* 58 (3): 347–63. doi:10.1111/jpy.13249.

IPCC (Intergovernmental Panel on Climate Change). 2011. “IPCC Expert Meeting on Geoengineering.” Lima, Peru: IPCC, June 20. https://www.ipcc.ch/publication/ipcc-expert-meeting-on-geoengineering/.

IPCC. 2013. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Geneva: IPCC. https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/.

IPCC. 2018. *Special Report: Global Warming of 1.5C*. Geneva: IPCC. https://www.ipcc.ch/sr15/chapter/chapter-2/.

IPCC. 2019. *The Ocean and Cryosphere in a Changing Climate: A Special Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC. https://www.ipcc.ch/srocc/chapter/chapter-5/.

IPCC. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press.

IPCC. 2022a. *Climate Change 2022: Mitigation of Climate Change*. Geneva: IPCC. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

IPCC. 2022b. *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Geneva: IPCC. https://www.ipcc.ch/report/ar6/wg2/.

Jones, D., T. Ito, Y. Takano, and W.-C. Hsu. 2014. “Spatial and Seasonal Variability of the Air-Sea Equilibration Timescale of Carbon Dioxide.” *Global Biogeochemical Cycles* 28 (11): 1163–78. doi:https://doi.org/10.1002/2014GB004813.

Kämpf, J., and P. Chapman. 2016. “The Functioning of Coastal Upwelling Systems.” In *Upwelling Systems of the World: A Scientific Journey to the Most Productive Marine Ecosystems*, edited by J. Kämpf and P. Chapman, 31–65. Cham, Switzerland: Springer International Publishing. doi:10.1007/978-3-319-42524-5_2.

Karl, D.M., R.R. Bidigare, and R.M. Letelier. 2001. “Long-Term Changes in Plankton Community Structure and Productivity in the North Pacific Subtropical Gyre: The Domain Shift Hypothesis.” *Deep Sea Research Part II: Topical Studies in Oceanography* 48 (8): 1449–70. doi:10.1016/S0967-0645(00)00149-1.

Katona, S., J. Polsenberg, J. Lowndes, B.S. Halpern, E. Pacheco, L. Mosher, A. Kilponen, et al. 2017. “Navigating the Seascape of Ocean Management: Waypoints on the Voyage toward Sustainable Use.” *MarXiv*. doi:10.31230/osf.io/79w2d.

Kim, J.K., C. Yarish, E.K. Hwang, M. Park, Y. Kim, J.K. Kim, C. Yarish, et al. 2017. “Seaweed Aquaculture: Cultivation Technologies, Challenges and Its Ecosystem Services.” *ALGAE* 32 (1): 1–13. doi:10.4490/algae.2017.32.3.3.

Koweek, D. 2022. “Expected Limits on the Potential for Carbon Dioxide Removal from Artificial Upwelling.” *Frontiers in Marine Science* 9. https://www.frontiersin.org/article/10.3389/fmars.2022.841894.

Krause-Jensen, D., and C.M. Duarte. 2016. “Substantial Role of Macroalgae in Marine Carbon Sequestration.” *Nature Geoscience* 9 (10): 737–42. doi:10.1038/ngeo2790.

Krause-Jensen, D., P. Lavery, O. Serrano, N. Marbà, P. Masque, and C.M. Duarte. 2018. “Sequestration of Macroalgal Carbon: The Elephant in the Blue Carbon Room.” *Biology Letters* 14 (6). doi:10.1098/rsbl.2018.0236.

La Plante, E.C., D.A. Simonetti, J. Wang, A. Al-Turki, X. Chen, D. Jassby, and G.N. Sant. 2021. "Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO_2 Management." *ACS Sustainable Chemistry & Engineering* 9 (3): 1073–89. doi:10.1021/acssuschemeng.0c08561.

Lenton, A., R.J. Matear, D.P. Keller, V. Scott, and N.E. Vaughan. 2018. "Assessing Carbon Dioxide Removal through Global and Regional Ocean Alkalinization under High and Low Emission Pathways." *Earth System Dynamics* 9 (2): 339–57. doi:https://doi.org/10.5194/esd-9-339-2018.

Lenton, T., and N. Vaughan. 2009. "The Radiative Forcing Potential of Different Climate Geoengineering Options." *Atmos. Chem. Phys.* 9 (15): 5539–61. https://www.atmos-chem-phys.net/9/5539/2009/acp-9-5539-2009.pdf.

Lewis, W. 2021. "Could the Ocean Hold the Key to Reducing Carbon Dioxide in the Atmosphere?" Los Angeles, California: University of California, Los Angeles, January 12. https://newsroom.ucla.edu/releases/using-seawater-to-reduce-co2-in-atmosphere.

Lezaun, J. 2021. "Hugging the Shore: Tackling Marine Carbon Dioxide Removal as a Local Governance Problem." *Frontiers in Climate.* Sec. Negative Emission Technologies. https://www.frontiersin.org/articles/10.3389/fclim.2021.684063/full.

Loomis, R., S.R. Cooley, J.R. Collins, S. Engler, and L. Suatoni. 2022. "A Code of Conduct Is Imperative for Ocean Carbon Dioxide Removal Research." *Frontiers in Marine Science* 9. https://www.frontiersin.org/article/10.3389/fmars.2022.872800.

London Convention. 1972. "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter." https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC1972.pdf.

London Protocol. 1996. "1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972." https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/PROTOCOLAmended2006.pdf.

Martin, J.H., R.M. Gordon, and S.E. Fitzwater. 1990. "Iron in Antarctic Waters." *Nature* 345: 156–58. https://www.nature.com/articles/345156a0.pdf.

Macreadie, P.I., A. Anton, J.A. Raven, N. Beaumont, R.M. Connolly, D.A. Friess, and J.J. Kelleway. 2019. "The Future of Blue Carbon Science." *Nature* 10 (3998). https://www.nature.com/articles/s41467-019-11693-w.

McKie, R. 2022. "The Squit and the Whale: Can Artificial Faeces Revive the Ocean Ecosystem?" *The Observer*, March 6. Sec. Environment. https://www.theguardian.com/environment/2022/mar/06/the-squit-and-the-whale-can-artificial-faeces-revive-the-ocean-ecosystem.

Mcleod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, et al. 2011. "A Blueprint for Blue Carbon: Toward an Improved Understanding of the Role of Vegetated Coastal Habitats in Sequestering CO_2." *Frontiers in Ecology and the Environment* 9 (10): 552–60. doi:10.1890/110004.

Milledge, J.J., and P.J. Harvey. 2016. "Potential Process 'Hurdles' in the Use of Macroalgae as Feedstock for Biofuel Production in the British Isles." *Journal of Chemical Technology and Biotechnology* 91 (8): 2221–34. doi:10.1002/jctb.5003.

Moore, C.M., M.M. Mills, K.R. Arrigo, I. Berman-Frank, L. Bopp, P.W. Boyd, E.D. Galbraith, et al. 2013. "Processes and Patterns of Oceanic Nutrient Limitation." *Nature Geoscience* 6 (9): 701–10. doi:10.1038/ngeo1765.

Moosdorf, N., P. Renforth, and J. Hartmann. 2014. "Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering." *Environmental Science & Technology* 48 (9): 4809–16. doi:10.1021/es4052022.

Mork, M. 1996. "Wave Attenuation Due to Bottom Vegetation." Bergen, Norway: Geophysical Institute, University of Bergen. https://page-one.springer.com/pdf/preview/10.1007/978-94-009-0253-4_30.

NASA (National Aeronautics and Space Administration). 2010. "What Are Phytoplankton?" NASA Earth Observatory, July 16. https://earthobservatory.nasa.gov/features/Phytoplankton.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: National Academies of Sciences, Engineering, and Medicine. doi:10.17226/25259.

NASEM. 2021. *A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration*. Washington, DC: National Academies of Sciences, Engineering, and Medicine. https://www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration.

Nguyen, A. 2021. "To What Extent Is the Existing International Framework in Environmental Law Equipped to Regulate and Manage the Potential Environmental Impacts of Ocean Fertilisation?" *University of New South Wales Law Journal Student Series*. Sydney: University of New South Wales. http://classic.austlii.edu.au/au/journals/UNSWLawJlStuS/2021/36.html.

NOAA (National Oceanic and Atmospheric Administration). n.d.a. "How Much of the Ocean Has Been Explored?" Ocean Exploration Facts. Washington, DC: NOAA Office of Ocean Exploration and Research. https://oceanexplorer.noaa.gov/facts/explored.html. Accessed July 8, 2022.

NOAA. n.d.b. "Ocean Acidification's Impact on Oysters and Other Shellfish." Washington, DC: NOAA. https://www.pmel.noaa.gov/co2/story/Ocean+Acidification%27s+impact+on+oysters+and+other+shellfish. Accessed December 8, 2021.

NOAA. 2010. *Report to Congress: Ocean Fertilization: The Potential of Ocean Fertilization for Climate Change Mitigation*. Washington, DC: NOAA. https://www.gc.noaa.gov/documents/2010_climate_fert_rept_Congress_final.pdf.

NOAA. 2020. "How Does the Ocean Affect Climate and Weather on Land?" Ocean Exploration Facts. Washington, DC: NOAA Office of Ocean Exploration and Research. https://oceanexplorer.noaa.gov/facts/climate.html.

NOAA. 2021a. "Coastal Blue Carbon." https://oceanservice.noaa.gov/ecosystems/coastal-blue-carbon/.

NOAA. 2021b. "What Is the Global Ocean Conveyor Belt?" https://oceanservice.noaa.gov/facts/conveyor.html.

NOAA. 2021c. "What Percentage of Life Is Estimated to Be in the Ocean?" https://oceanservice.noaa.gov/facts/ocean-human-health.html.

Northrop, E., S. Rufo, G. Taraska, L. Schindler Murray, E. Pidgeon, E. Landis, E. Cerny-Chipman, et al. 2020. "Enhancing Nationally Determined Contributions: Opportunities for Ocean-Based Climate Action" Working Paper. Washington, DC: World Resources Institute. www.wri.org/publication/enhancing-nationally -determined-contributions-opportunities-for-ocean-basedclimate-action.

Oceaneos. n.d. "Oceaneos—Restoring Ocean Life." https://www.oceaneos.org/faq/. Accessed January 25, 2022.

Ortiz, J., J. Arístegui, J. Taucher, and U. Riebesell. 2022. "Artificial Upwelling in Singular and Recurring Mode: Consequences for Net Community Production and Metabolic Balance." *Frontiers in Marine Science* 8. https://www.frontiersin.org/article/10.3389/fmars.2021.743105.

Oschlies, A., M. Pahlow, A. Yool, and R.J. Matear. 2010. "Climate Engineering by Artificial Ocean Upwelling: Channelling the Sorcerer's Apprentice." *Geophysical Research Letters* 37 (4). doi:10.1029/2009GL041961.

Pendleton, L., D.C. Donato, B.C. Murray, S. Crooks, W.A. Jenkins, S. Sifleet, C. Craft, et al. 2012. "Estimating Global 'Blue Carbon' Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems." *PLOS ONE* 7 (9): e43542. doi:10.1371/journal.pone.0043542.

Peng, Q., S.-P. Xie, D. Wang, R.X. Huang, G. Chen, Y. Shu, J.-R. Shi, et al. 2022. "Surface Warming–Induced Global Acceleration of Upper Ocean Currents." *Science Advances* 8 (16): eabj8394. doi:10.1126/sciadv.abj8394.

Pickup, D., and T. Tyrrell. 2020. "Latitudinal Patterns in the Concentrations of Biologically Utilised Elements in the Surface Ocean." *Biogeosciences* Discuss. Preprint. doi:https://doi.org/10.5194/bg-2020-371.

Piper, K. 2019. "The Climate Renegade." *Vox*, May 24. https://www.vox.com/the-highlight/2019/5/24/18273198/climate-change-russ-george-unilateral-geoengineering.

Pitchford, J.W., and J. Brindley. 1999. "Iron Limitation, Grazing Pressure and Oceanic High Nutrient–Low Chlorophyll (HNLC) Regions." *Journal of Plankton Research* 21 (3): 525–47. https://academic.oup.com/plankt/article/21/3/525/1395829.

Powell, H. 2008. "What Are the Possible Side Effects?" *Oceanus* (blog). Woods Hole, Massachusetts: Woods Hole Oceanographic Institution. https://www.whoi.edu/oceanus/feature/what-are-the-possible-side-effects/.

Priede, I.G. 2017. *Deep-Sea Fishes: Biology, Diversity, Ecology and Fisheries*. Cambridge, United Kingdom: Cambridge University Press.

Proelss, A., and C. Hong. 2012. "Ocean Upwelling and International Law." *Ocean Development & International Law* 43 (4): 371–85. https://www.tandfonline.com/doi/abs/10.1080/00908320.2012.726843.

Rau, G.H. 2008. "Electrochemical Splitting of Calcium Carbonate to Increase Solution Alkalinity: Implications for Mitigation of Carbon Dioxide and Ocean Acidity." *Environmental Science & Technology* 42 (23): 8935–40. doi:10.1021/es800366q.

Rau, G.H., S.A. Carroll, W.L. Bourcier, M.J. Singleton, M.M. Smith, and R.D. Aines. 2013. "Direct Electrolytic Dissolution of Silicate Minerals for Air CO_2 Mitigation and Carbon-Negative H_2 Production." *Proceedings of the National Academy of Sciences* 110 (25): 10095–100. doi:10.1073/pnas.1222358110.

Rayner, S., C. Heyward, T. Kruger, N. Pidgeon, C. Redgwell, and J. Savulescu. 2013. "The Oxford Principles." *Climatic Change* 121 (3): 499–512. doi:10.1007/s10584-012-0675-2.

Readfearn, G. 2021. "Can Fake Whale Poo Experiment Net Australian Scientists a Share of Elon Musk's US$100M Climate Prize?" *The Guardian*, December 23. Sec. Environment. https://www.theguardian.com/environment/2021/dec/24/can-fake-whale-poo-experiment-net-australian-scientists-a-share-of-elon-musks-us100m-climate-prize.

Reichwein, D., A.-M. Hubert, P.J. Irvine, F. Benduhn, and M.G. Lawrence. 2015. "State Responsibility for Environmental Harm from Climate Engineering." *Climate Law* 5 (2–4): 142–81. doi:10.1163/18786561-00504003.

Renforth, P., B.G. Jenkins, and T. Kruger. 2013. "Engineering Challenges of Ocean Liming." *Energy* 60 (C): 442–52. https://core.ac.uk/download/pdf/42513977.pdf.

Renforth, P., and G. Henderson. 2017. "Assessing Ocean Alkalinity for Carbon Sequestration." *Reviews of Geophysics* 55 (3): 636–74. doi:10.1002/2016RG000533.

Reynolds, J., and F. Fleurke. 2013. "Climate Engineering Research: A Precautionary Response to Climate Change?" In *Carbon & Climate Law Review*. https://jreynolds.org/wp-content/uploads/2017/09/Reynolds-and-Fleurke-2013-Climate-Engineering-Research-A-Precautionary-Response-to-Climate-Change.pdf.

Reynolds, J.L. 2018. "International Law." In *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, 57–153. Cambridge: Cambridge University Press. doi:10.1017/9781316661864.003.

Ricart, A.M., D. Krause-Jensen, K. Hancke, N.N. Price, P. Masqué, and C.M. Duarte. 2022. "Sinking Seaweed in the Deep Ocean for Carbon Neutrality Is ahead of Science and beyond the Ethics." *Environmental Research Letters* 17 (8): 081003. doi:10.1088/1748-9326/ac82ff.

Rosentreter, J.A., A.N. Al-Haj, R.W. Fulweiler, and P. Williamson. 2021. "Methane and Nitrous Oxide Emissions Complicate Coastal Blue Carbon Assessments." *Global Biogeochemical Cycles* 35 (2): e2020GB006858. doi:10.1029/2020GB006858.

Royal Society. 2018. *Greenhouse Gas Removal*. London: The Royal Society. https://royalsociety.org/~/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf.

Salomon, M., and T. Markus. 2018. *Handbook on Marine Environment Protection*. Cham, Switzerland: Springer Cham. https://link.springer.com/content/pdf/10.1007%2F978-3-319-60156-4.pdf.

SAT (Secretariat of the Antarctic Treaty). 1991. "The Protocol on Environmental Protection to the Antarctic Treaty." https://www.ats.aq/e/protocol.html.

Saxler, B., J. Siegfried, and A. Proelss. 2015. "International Liability for Transboundary Damage Arising from Stratospheric Aerosol Injections." *Law, Innovation and Technology* 7 (1). doi:https://doi.org/10.1080/17579961.2015.1052645.

Schumer, C., and K. Lebling. 2022. "How Are Countries Counting on Carbon Removal to Meet Climate Goals?" *WRI Insights* (blog). Washington, DC: World Resources Institute. https://www.wri.org/insights/carbon-removal-countries-climate-goals.

Sengupta, M. 2021. *Environmental Impacts of Mining: Monitoring, Restoration and Control*. Boca Raton, Florida: CRC Press. https://www.taylorfrancis.com/books/mono/10.1201/9781003164012/environmental-impacts-mining-mritunjoy-sengupta.

Shopify. 2020. "Fighting for the Future: Shopify Invests $5M in Breakthrough Sustainability Technologies." https://news.shopify.com/fighting-for-the-future-shopify-invests-5m-in-breakthrough-sustainability-technologies.

Siegel, D.A., T. DeVries, S.C. Doney, and T. Bell. 2021. "Assessing the Sequestration Time Scales of Some Ocean-Based Carbon Dioxide Reduction Strategies." *Environmental Research Letters* 16 (10): 104003. doi:10.1088/1748-9326/ac0be0.

Sigman, D., and M. Hain. 2012. "The Biological Productivity of the Ocean." *Nature Education Knowledge* 3 (10): 21. https://www.nature.com/scitable/knowledge/library/the-biological-productivity-of-the-ocean-70631104/.

Silverman-Roati, K., M. Gerrard, and R. Webb. 2021. "Removing Carbon Dioxide through Seaweed Cultivation: Legal Challenges and Opportunities." New York, New York: Sabin Center for Climate Change Law, Columbia Law School. https://scholarship.law.columbia.edu/faculty_scholarship/2980.

Stripe. 2021. "Stripe Commits $8M to Six New Carbon Removal Companies." https://stripe.com/newsroom/news/spring-21-carbon-removal-purchases.

Subhas, A.V., L. Marx, S. Reynolds, A. Flohr, E.W. Mawji, P.J. Brown, and B.B. Cael. 2022. "Microbial Ecosystem Responses to Alkalinity Enhancement in the North Atlantic Subtropical Gyre." *Frontiers in Climate* 4. https://www.frontiersin.org/articles/10.3389/fclim.2022.784997.

Taillardat, P., B.S. Thompson, M. Garneau, K. Trottier, and D.A. Friess. 2020. "Climate Change Mitigation Potential of Wetlands and the Cost-Effectiveness of Their Restoration." *Interface Focus* 10 (5): 20190129. doi:10.1098/rsfs.2019.0129.

Taylor, S.F.W., M.J. Roberts, B. Milligan, and R. Ncwadi. 2019. "Measurement and Implications of Marine Food Security in the Western Indian Ocean: An Impending Crisis?" *Food Security* 11 (6): 1395–1415. doi:10.1007/s12571-019-00971-6.

Tollefson, J. 2017. "Iron-Dumping Ocean Experiment Sparks Controversy." *Nature News* 545 (7655): 393. doi:10.1038/545393a.

UN (United Nations). 1982. "United Nations Convention on the Law of the Sea." https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

UN. 1987. *Our Common Future: The World Commission on Environment and Development*. Oxford: Oxford University Press. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

UN. 1992. "Annex 1: Rio Declaration on Environment and Development." In *Report of the United Nations Conference on Environment and Development*. Rio de Janeiro: United Nations. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf.

UN. 2007. "United Nations Declaration on the Rights of Indigenous Peoples." United Nations. https://www.un.org/development/desa/indigenouspeoples/wp-content/uploads/sites/19/2018/11/UNDRIP_E_web.pdf.

Underwood, E. 2020. "The Complicated Role of Iron in Ocean Health and Climate Change." *Smithsonian Magazine*, January 3. https://www.smithsonianmag.com/science-nature/complicated-role-iron-ocean-health-and-climate-change-180973893/.

UoH (University of Hawai'i at Manoa). 2016. "Part 3. Oceanic Carbon and Nutrient Cycling." Honolulu, Hawaii: School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa. https://www.soest.hawaii.edu/oceanography/courses/OCN401/401_Fall2016/20_Oceans-3_102716_KF.pdf.

UoM (University of Maine). 2018. "Attenuating Waves with Kelp Farms." *Aquaculture Research Institute* (blog). Orono, Maine: University of Maine. https://umaine.edu/aquaculture/project/attenuating-waves-kelp-farms/.

Ustick, L.J., A.A. Larkin, C.A. Garcia, N.S. Garcia, M.L. Brock, J.A. Lee, N.A. Wiseman, et al. 2021. "Metagenomic Analysis Reveals Global-Scale Patterns of Ocean Nutrient Limitation." *Science* 372 (6539): 287–91. doi:10.1126/science.abe6301.

van den Burg, S., A.P. van Duijn, H. Bertelings, M. van Krimpen, and M. Poelman. 2016. "The Economic Feasibility of Seaweed Production in the North Sea." *Aquaculture Economics & Management* 20 (3). https://www.tandfonline.com/doi/full/10.1080/13657305.2016.1177859.

Vaughan, A. 2022. "Scientists Want to Restore the Oceans with Artificial Whale Poo." *New Scientist*, February 22. https://www.newscientist.com/article/2309262-scientists-want-to-restore-the-oceans-with-artificial-whale-poo/.

Vesta. n.d. "Introduction." https://www.vesta.earth/science#Introduction. Accessed March 17, 2022.

von Keitz, M. 2020. "State of Macroalgae Science and Technology." Webinar. Hosted by Ocean Visions. October.

Wahl, M., S.S. Covachã, V. Saderne, C. Hiebenthal, J.D. Müller, C. Pansch, and Y. Sawall. 2018. "Macroalgae May Mitigate Ocean Acidification Effects on Mussel Calcification by Increasing pH and Its Fluctuations." *Limnology and Oceanography* 63 (1): 3–21. doi:10.1002/lno.10608.

Waycott, M., C.M. Duarte, T.J.B. Carruthers, R.J. Orth, W.C. Dennison, S. Olyarnik, A. Calladine, et al. 2009. "Accelerating Loss of Seagrasses across the Globe Threatens Coastal Ecosystems." *Proceedings of the National Academy of Sciences* 106 (30): 12377–81. doi:10.1073/pnas.0905620106.

Webb, R., and M. Gerrard. 2021. "The Legal Framework for Offshore Carbon Capture and Storage in Canada." New York, New York: Sabin Center for Climate Change Law, Columbia Law School. https://climate.law.columbia.edu/sites/default/files/content/Webb%20%26%20Gerrard%20-%20Offshore%20CCS%20in%20Canada.pdf.

Webb, R., K. Silverman-Roati, and M. Gerrard. 2021. "Removing Carbon Dioxide through Ocean Alkalinity Enhancement and Seaweed Cultivation: Legal Challenges and Opportunities." New York, New York: Sabin Center for Climate Change Law, Columbia Law School. https://scholarship.law.columbia.edu/faculty_scholarship/2739.

Webb, R., K. Silverman-Roati, and M. Gerrard. 2022. "Removing Carbon Dioxide through Artificial Upwelling and Downwelling: Legal Challenges and Opportunities." New York, New York: Faculty Scholarship, Columbia Law School. https://scholarship.law.columbia.edu/faculty_scholarship/3337.

Wei-li Lee, C. 2022. "UCLA Engineering Receives $21 Million Pledge from Chan Zuckerberg Initiative." Los Angeles, California: University of California, Los Angeles, February 10. https://newsroom.ucla.edu/releases/institute-carbon-management-chan-zuckerberg-initiative.

White, A., K. Björkman, E. Grabowski, R. Letelier, S. Poulos, B. Watkins, and D. Karl. 2010. "An Open Ocean Trial of Controlled Upwelling Using Wave Pump Technology." *Journal of Atmospheric and Oceanic Technology* 27 (February). doi:10.1175/2009JTECHO679.1.

Williamson, P., and J.-P. Gattuso. 2022. "Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, with Questionable Climatic Cost-Effectiveness." *Frontiers in Climate* 4. https://www.frontiersin.org/articles/10.3389/fclim.2022.853666.

Winther, J.-G., M. Dai, F. Douvere, L. Fernandes, P. Halpin, and A. Hakon. 2020. *Integrated Ocean Management*. High Level Panel for a Sustainable Ocean Economy. https://oceanpanel.org/blue-papers.

Wu, J., D.P. Keller, and A. Oschlies. 2022. "Carbon Dioxide Removal via Macroalgae Open-Ocean Mariculture and Sinking: An Earth System Modeling Study." *Earth System Dynamics Discussions*, January, 1–52. doi:10.5194/esd-2021-104.

Xiao, X., S. Agustí, Y. Yu, Y. Huang, W. Chen, J. Hu, C. Li, et al. 2021. "Seaweed Farms Provide Refugia from Ocean Acidification." *Science of the Total Environment* 776 (July): 145192. doi:10.1016/j.scitotenv.2021.145192.

XPrize. 2022. "Xprize and the Musk Foundation Award $15M to Prize Milestone Winners in $100M Carbon Removal Competition." https://www.xprize.org/prizes/elonmusk/articles/xprize-and-the-musk-foundation-award-15m-to-prize-milestone-winners-in-100m-carbon-removal-competition.

Yoon, J.-E., K.-C. Yoo, A.M. Macdonald, H.-I. Yoon, K.-T. Park, E.J. Yang, H.-C. Kim, et al. 2018. "Reviews and Syntheses: Ocean Iron Fertilization Experiments—Past, Present, and Future: Looking to a Future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) Project." *Biogeosciences* 15 (19): 5847–89. doi:https://doi.org/10.5194/bg-15-5847-2018.

Zhou, S., and P. Flynn. 2005. "Geoengineering Downwelling Ocean Currents: A Cost Assessment." *Climatic Change* 71: 203–20. http://www.homepages.ed.ac.uk/shs/Hurricanes/Flynn%20downwelling.pdf.

ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

OUR CHALLENGE

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

OUR VISION

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Photo Credits

Cover, Samuele Giglio; Pg. ii, KC Welch; Pg. 2, Sandy Millar; Pg. 4, Thomas Bonometti; Pg. 6, Joshua J Cotten; Pg. 10, Thomas Bonometti; Pg. 14, Kalen Kemp; Pg. 15, Joshua J Cotten; Pg. 17, Jim Bread; Pg. 18, Jea Beller

WORLD
RESOURCES
INSTITUTE

10 G Street, NE
Washington, DC 20002
WRI.ORG