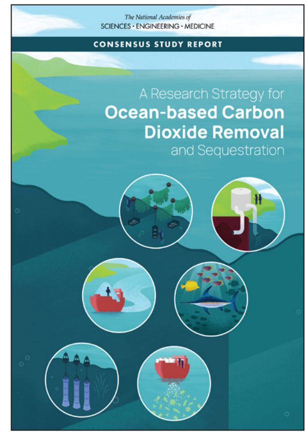

A RESEARCH STRATEGY FOR OCEAN-BASED CARBON DIOXIDE REMOVAL AND SEQUESTRATION

As of 2021, atmospheric carbon dioxide (CO_2) levels have reached historically unprecedented levels, higher than at any time in the past 800,000 years. The increase in CO_2 emissions from human activities such as fossil fuel burning, agriculture, and historical land-use change greatly exceeds the ability of nature to remove CO_2 from the atmosphere. Worldwide efforts to reduce emissions by creating a more efficient, carbon-free energy system may not be enough to stabilize the climate and avoid the worst impacts of climate change. Carbon dioxide removal (CDR), should be researched responsibly with climate justice and the precautionary principle in mind to determine whether this technology can help to meet, in a timely way, the global goal of limiting warming to well below 2° C, compared to pre-industrial levels, as established by the Paris Agreement. An underlying question is whether ocean CDR technology will fit into policy frameworks that help the world get to net-zero CO_2 emissions by 2050, and/or contribute to draw down of legacy carbon in the atmosphere thereafter.

In 2019, the National Academies published a report that laid out a research agenda for advancing the understanding of a variety of land- and coastal-based CDR approaches and specifically, for assessing their benefits, risks, and sustainable scale potential. The study found that, to meet climate goals, some form of CDR will likely be needed to remove roughly 10Gt CO_2/yr by mid-century and 20Gt CO_2/yr by the end of the century (where 1 Gt is a billion metric tonnes). To help meet that goal, the report identified four land-based CDR approaches ready for large-scale deployment: afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and storage, based on the potential of each approach to remove carbon at costs below \$100/t of CO_2. This new report builds on the 2019 report to assess what is currently known about the benefits, risks, and potential for responsible scale-up of six specific ocean-based CDR strategies that include both ecological and technological concepts which were specified by the sponsor, ClimateWorks Foundation. This report starts with the recognition that the present state of knowledge on ocean CDR approaches is inadequate, especially considering the complex interactions of ocean physics, chemistry, and biology, as well as environmental and social impacts. It describes the research needed to advance understanding of those approaches and address knowledge gaps. The resulting research agenda is meant to provide an improved and unbiased knowledge base for the public, stakeholders, and policymakers to make informed decisions on the next steps for ocean CDR, as part of a larger climate mitigation strategy; it is not meant to lock in or advocate for any approach. Lastly, research on ocean CDR will greatly benefit from full lifecycle analyses, together with targeted studies on the interactions and trade-offs among all the solutions that are currently in play to address human disruption of the climate.

This report is science research strategy focused. It acknowledges that there is little social license, and often much opposition to the approaches that constitute geoengineering. It is important that any research done does not cause unintended and potentially irreversible harm to natural systems and coastal communities even where the law allows small scale scientific studies conducted in a controlled setting. In the current dearth of governance of ocean CDR, a Code of Conduct for research should be developed, and governance development should precede any deployment.

OCEAN CARBON DIOXIDE REMOVAL STRATEGIES ASSESSED

The ocean covers 70% of the Earth's surface; it includes much of the global capacity for natural carbon sequestration. The ocean holds great potential for uptake and longer-term sequestration of human-produced CO_2 for several reasons: (1) the ocean acts as a large natural reservoir for CO_2, holding roughly 50 times as much inorganic carbon as the preindustrial atmosphere; (2) the ocean already removes a substantial fraction of the excess atmospheric CO_2 resulting from human emissions; and (3) there are several physical, geochemical, and biological processes that are known to influence air-sea CO_2 gas exchange and ocean carbon storage. It may be possible to enhance the ocean's capacity for natural carbon with the ocean-based CDR approaches examined in this report (see Figure 1):

- **Nutrient Fertilization**: Addition of nutrients (e.g., iron, phosphorus, or nitrogen) to the surface ocean to stimulate production of marine phytoplankton and, consequently enhance uptake of CO_2 through photosynthesis. Through marine food webs, some of the phytoplankton organic carbon is carried to the bottom of the ocean where it can be stored for a century or longer.
- **Artificial Upwelling and Downwelling**: Artificial upwelling involves the use of pipes and pumps to bring up deep, cold, nutrient-rich water to increase phytoplankton production in the surface waters. Like nutrient fertilization, this can enhance uptake of CO_2 through photosynthesis. Artificial downwelling is the downward transport of surface water, which might be a means to increase ventilation to counteract the formation of "dead zones" in coastal regions and could also be a means to carry carbon into the deep ocean.
- **Seaweed Cultivation**: Large-scale seaweed farming can act as a CDR approach by removing CO_2 from the atmosphere through photosynthesis; the seaweed is then transported into the deep sea or into sediments where the carbon can be sequestered.
- **Recovery of Ocean and Coastal Ecosystems**: Recovery of the marine ecosystem can enhance the natural biological uptake of carbon dioxide through protection and restoration of coastal ecosystems, such as kelp forests and free-floating Sargassum, and through the recovery of fishes, whales, and other animals in the oceans.
- **Ocean Alkalinity Enhancement**: Enhancing surface water uptake of CO_2 from the atmosphere by altering seawater chemistry. This can be accomplished by raising the alkalinity, or pH, of the seawater through various mechanisms such as enhanced mineral weathering and electrochemical or thermal reactions.
- **Electrochemical Approaches**: Direct removal of CO_2 from seawater or increasing the pH of seawater, and thus increasing seawater's capacity for uptake of CO_2, by passing an electric current through the water to induce water splitting, or electrolysis.

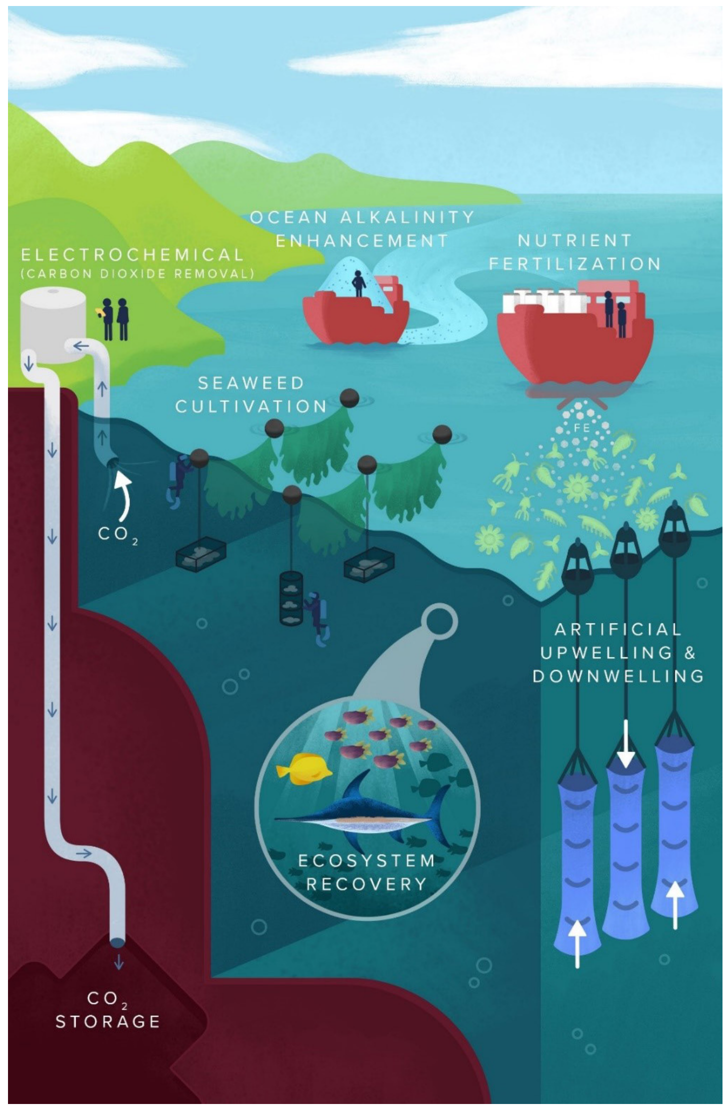

FIGURE 1 Ocean-based CDR approaches explored in this report

The potential for each of the six ocean CDR approaches as a viable path forward (within a larger climate mitigation strategy) was assessed based on information from the published literature, presentations at public workshops and meetings held to inform this study, and the expertise and judgment of the report's authoring committee. Each strategy was given a ranking of low, medium, or high, along with a level of certainty, where appropriate, for each of the following factors: knowledge base, efficacy, durability, scale, monitoring and verification, viability and barriers, and governance and social dimensions.

RESEARCH RECOMMENDATIONS

Expanded research, including in the field, is needed to assess the benefits, risks, and sustainable scale potential for ocean-based CDR techniques. Additionally, research on ocean CDR would greatly benefit from targeted studies on the interactions and tradeoffs between ocean CDR, terrestrial CDR, greenhouse gas abatement and mitigation, and climate adaptation, including the potential of deterring mitigation efforts to reduce emissions.

The report identifies the specific research needed to advance understanding of ocean CDR, including foundational research and research needed to better understand the benefits and risks of each of the strategies. The research agenda should be adaptive, meaning that decisions on future investments in research activities will need to take into account new findings on the efficacy and durability of a technique, whether the social and environmental impacts outweigh benefits, or face social and governance challenges; showstoppers can be anticipated for approaches that exhibit diminishing CDR potential as research progresses.

Recommendation 1 - Ocean CDR Research Program Goals: To inform future societal decisions on a broad climate response mitigation portfolio, a research program for ocean CDR should be implemented, in parallel across multiple approaches, to address current knowledge gaps. The research program should not advocate for or lock in future ocean CDR deployments but rather provide an improved and unbiased knowledge base for the public, stakeholders, and policymakers. Funding for this research could come from both the public and private sectors, and collaboration between the two is encouraged. The integrated research program should include the following elements:

1. Assessment of whether the approach results in both durable and net atmospheric CO_2 removal, as a primary goal.
2. Assessment of intended and unintended environmental impacts beyond CO_2 removal.
3. Assessment of social and livelihood impacts, examining both potential harms and benefits.
4. Integration of research on social, legal, regulatory, policy, and economic questions relevant to ocean CDR research and possible future deployment with the natural science, engineering, and technological aspects.
5. Systematic examination of the biophysical and social interactions, synergies, and tensions among ocean CDR, terrestrial CDR, mitigation, and adaptation.

Recommendation 2: Common Components of an Ocean CDR Research Program. No single research framework will be adequate for all CDR approaches within a comprehensive research strategy, as knowledge base and readiness levels differ substantially. There are, however, several common components that are relevant to research into any ocean CDR approach.

Implementation of the research program in Recommendation 1 should include several key common components:

1. The development and adherence to a common research code of conduct that emphasizes transparency and open public data access, verification of carbon sequestration, monitoring for intended and unintended environmental and other impacts, and stakeholder and public engagement.
2. Full consideration of, and compliance with, permitting and other regulatory requirements. Regulatory agencies should establish clear processes and criteria for permitting ocean CDR research, with input from funding entities and other stakeholders.
3. Co-production of knowledge and design of experiments with communities, Indigenous collaborators, and other key stakeholders.
4. Promotion of international cooperation in scientific research and issues relating to the governance of ocean CDR research, through prioritizing international research collaborations and enhancement of international oversight of projects (e.g., by establishing an independent expert review board with international representation).
5. Capacity building among researchers in the US and other countries, including fellowships for early career researchers in climate-vulnerable communities and under-represented groups, including from Indigenous populations and the Global South.

Research Priorities

Based on the present state of knowledge, there are substantial uncertainties in all of the ocean CDR approaches evaluated in this report. **The best approach for reducing knowledge gaps will involve**

a diversified research investment strategy that includes both cross-cutting, common components and coordination across multiple individual CDR approaches in parallel.

Amongst the biotic approaches, research on ocean iron fertilization and seaweed cultivation offer the greatest opportunities for evaluating the viability of possible biotic ocean CDR approaches; research on the potential CO_2 removal and sequestration permanence for ecosystem recovery would also be beneficial in the context of ongoing marine conservation efforts.

Out of the abiotic approaches, research on ocean alkalinity enhancement, including electrochemical alkalinity enhancement, have priority over electrochemical approaches that only seek to achieve carbon dioxide removal from seawater (also known as carbon dioxide stripping).

Recommendation 3 – Ocean CDR Research Program Priorities. A research program should move forward integrating studies, in parallel, on multiple aspects of different ocean CDR approaches, recognizing the different stages of the knowledge base and technological readiness of specific ocean CDR approaches. Priorities for the research program should include development of:

1. Overarching implementation plan for the next decade adhering to the cross-cutting strategy elements in Recommendation 1 and incorporating from its onset the common research components in Recommendation 2. Progress on these common research components is essential to achieve as a foundation for all other recommended research.
2. Tailored implementation planning for specific ocean CDR approaches focused on reducing critical knowledge gaps by moving sequentially from lab-scale to pilot-scale field experiments, as appropriate, with adequate environmental and social risk reduction measures and transparent decision-making processes.
3. Common framework for intercomparing the viability of ocean CDR approaches with each other and with other climate response measures using standard criteria for efficacy, permanence, costs, environmental and social impacts, and governance and social dimensions.
4. Research framework including program-wide components for experimental planning and public engagement, monitoring and verification (carbon accounting), and open publicly-accessible data management.
5. Strategy and implementation for engaging and communicating with stakeholders, policymakers, and publics.
6. Research agenda that emphasizes advancing understanding of ocean fertilization, seaweed cultivation, and ocean alkalinity enhancement.

THE COMMITTEE ON A RESEARCH STRATEGY FOR OCEAN CARBON DIOXIDE REMOVAL AND SEQUESTRATION

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2021). The study was sponsored by ClimateWorks Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu or via the Ocean Studies Board web page at http://www.nationalacademies.org/oceanstudiesboard/osb.

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