Ocean-Based Carbon Dioxide Removal: A New Frontier in the Blue Economy

Antonius Gagern  
Additional Ventures, Washington, DC

Justin Manley  
Just Innovation Inc., Boston, Massachusetts

Lydia Kapsenberg  
CEA Consulting, San Francisco, California

Abstract

The ocean is a key facet of climate stability and Earth’s carbon cycle. Given the immense scale of atmospheric carbon dioxide removal (CDR) necessary to achieve international climate goals, ocean-based CDR approaches (or “ocean CDR”) warrant serious consideration. Ocean CDR is a still nascent, but cautiously promising, area of scientific research with several approaches under evaluation. Here, we examine one of the most promising approaches, ocean alkalinity enhancement, to highlight and exemplify challenges and opportunities of an emerging ocean CDR industry in the blue economy.

Keywords: carbon dioxide removal, ocean carbon cycle, ocean alkalinity enhancement, blue economy

Challenge of the Century

Since the 1850s, humans have emitted 1,670 billion tons (Gt) of planet-warming carbon dioxide (CO₂) into the atmosphere and collectively are on track to increase average global temperatures by 3°C–4°C compared to preindustrial levels within the next 80 years (Friedlingstein et al., 2021). As an optimistic and challenging climate target, international consensus aims to cap warming to 1.5°C. To reach this goal with 50% probability, emissions must not exceed more than 420 Gt of CO₂ between 2022 and 2100 (Friedlingstein et al., 2021). This is our remaining carbon budget. At current emission trends, this budget will be spent in approximately 11 years (Friedlingstein et al., 2021). The carbon math is clear: Even the most aggressive projections of emission reductions do not get anywhere close to staying within the 1.5°C carbon budget, and emission reductions will have to be complemented with intentional atmospheric carbon dioxide removal (CDR) on the order of 100–1,000 billion tons in the next 70–80 years. We have to prevent further pollution (emission reductions as well as carbon capture and storage [CCS]), and we have to clean up historic pollution (CDR) (IPCC, 2018).

The Ocean Is the Ultimate CO₂ Sink

The ocean plays an important role in Earth’s carbon cycle. The ocean has absorbed approximately a quarter of all anthropogenic CO₂ emitted into the atmosphere since the beginning of the industrial revolution—another quarter has been sequestered in soils; the remaining half is still in the atmosphere (Friedlingstein et al., 2021). Atmospheric CO₂ moves into seawater whenever CO₂ concentrations in the atmosphere exceed those in the ocean’s surface layer. When CO₂ dissolves into the ocean, carbonic acid is formed, which creates a decline in pH, a process that is called ocean acidification. Ocean acidification is harmful to marine life and presents an additional complexity to the need for atmospheric carbon management (Doney et al., 2009). Over millennia, slow geologic processes, such as rock weathering, will buffer seawater acidity. This means that, over thousands of years, the ocean would ultimately be the final destination for much of the excess CO₂ in the atmosphere caused by our emissions (National Academies of Sciences, Engineering, and Medicine [NASEM], 2021). Furthermore, stated by the authors of the recent NASEM study on ocean-based CDR:

“This raises the question of whether society could (and should) attempt to accelerate ocean processes that remove and store CO₂ away from the atmosphere” (NASEM, 2021).

Emergence of Ocean-Based CDR

Several approaches have been proposed to enhance and accelerate the ocean’s natural biological and abiotic carbon pumps (Table 1), and early
modeling suggests that these approaches could remove tens of billions of tons (“gigatons”) of CO₂ from the atmosphere every year (Energy Futures Initiative [EFI], 2020; NASEM, 2021). These approaches are often referred to as “ocean-based CDR” or “marine CDR.” They target the removal of dissolved CO₂ in surface waters and rely on influx of atmospheric CO₂ into the, then CO₂-undersaturated, surface waters to achieve CDR. Biological approaches boost photosynthesis of marine plants or algae to convert dissolved CO₂ into organic carbon, which is then, either naturally or artificially, exported to the deep ocean where it remains isolated from the atmosphere for potentially hundreds to thousands of years. Carbon export efficiency, and

### TABLE 1
Ocean-based CDR approaches under evaluation.

<table>
<thead>
<tr>
<th>Category: Approach</th>
<th>Intended Effect</th>
<th>Leading Benefits</th>
<th>Leading Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotic approaches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean nutrient fertilization</td>
<td>Increase net transport of organic carbon below mixed layer by increasing biomass production of primary producers</td>
<td>Potentially cheap and easy to achieve</td>
<td>Efficacy of carbon export remains unknown; verification of CDR is a challenge</td>
</tr>
<tr>
<td>Seaweed cultivation</td>
<td>Sequester carbon in seaweed biomass and then sink to depth of ocean or otherwise permanently remove it</td>
<td>No additional inputs are needed to grow seaweed; some biomass could be sold into profitable markets</td>
<td>Infrastructure needs for cultivation in the open ocean; environmental considerations of nutrient removal from surface ocean</td>
</tr>
<tr>
<td>Ecosystem recovery</td>
<td>Increase primary production and restore food webs, thereby increasing organic carbon pool and net transport below mixed layer</td>
<td>Conservation of marine ecosystem services (food, biodiversity); societal support</td>
<td>CDR potential is very low; quantification of CDR impacts is complex</td>
</tr>
<tr>
<td>Artificial upwelling</td>
<td>Fertilize surface waters with nutrient-rich deep waters, with a similar intended effect as ocean nutrient fertilization</td>
<td>Natural source of nutrients; could benefit fisheries and aquaculture irrespective of CDR impact</td>
<td>Deep waters are CO₂ rich and so will reduce the CDR impact; verification of CDR is a challenge</td>
</tr>
<tr>
<td>Abiotic approaches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrochemical processes</td>
<td>Splitting of seawater into acid and base streams, for subsequent manipulation of carbonate chemistry (produce alkalinity, remove CO₂ from seawater, precipitate calcium carbonate, weather alkaline rock, or increase carbonate/bicarbonate pool in seawater)</td>
<td>Local mitigation of ocean acidification; valuable by-products (H₂, Cl₂, silica)</td>
<td>Energy requirements are high; may require expansion of industrial mining</td>
</tr>
<tr>
<td>Ocean alkalinity enhancement (OAE)</td>
<td>Increase the ocean’s absorptive capacity for CO₂ by increasing seawater pH</td>
<td>Local mitigation of ocean acidification; long sequestration expectancy</td>
<td>Expansion of industrial mining on land; marine environmental impact of trace metals; quantification of CDR inefficiencies</td>
</tr>
<tr>
<td>Artificial downwelling</td>
<td>Physically move CO₂-rich surface waters to deep ocean layers to accelerate storage of CO₂ into the deep ocean</td>
<td>Theoretically could boost the biological pump by enhancing physical transport of organic carbon</td>
<td>Challenging and energetically costly</td>
</tr>
</tbody>
</table>

This table shows summarized findings from NASEM (2021).
thus CDR, is primarily constrained by how much of the organic carbon can escape degradation, and remineralization from organic carbon back to CO₂, by the food web. Abiotic approaches, on the other hand, imitate natural geologic processes of weathering that convert dissolved CO₂ into the more stable and less reactive forms of dissolved carbon (bicarbonate and carbonate), thereby increasing the ocean’s absorptive capacity for CO₂ while at the same time countering ocean acidification. There is growing consensus that biotic and abiotic ocean CDR may ultimately be able to contribute to several gigatons of CO₂ removal per year, but technological readiness is low and knowledge gaps remain large (GESAMP, 2019; EFI, 2020; Gattuso et al., 2021; Ocean Visions, 2021; NASEM, 2021).

As with land-based CDR, there is no silver bullet approach in ocean-based CDR. Each approach has advantages and disadvantages, and they all vary in terms of CDR potential, technological readiness, social license, and environmental impacts (GESAMP, 2019; EFI, 2020; NASEM, 2021; Ocean Visions, 2021). Early estimates of durability, efficacy, and costs of the different approaches point to a few priority pathways, including ocean alkalinity enhancement (OAE) and some electrochemical approaches (Figure 1). Significant financial investments are needed to better understand if these approaches can actually achieve their theoretical potential, meet the yet-to-be-defined criteria for acceptable environmental impacts, and gain social acceptance for implementation (NASEM, 2021). A careful analysis of benefits, costs, and risks must precede consideration of deployment at any scale, no matter how urgently CO₂ has to be removed from the atmosphere.

OAE Is a Research Priority

Based on its high efficacy, scalability, and permanence (Figure 1), OAE (see Box 1) stands out as a particularly interesting ocean-based approach.

OAE Is Effective Based on Seawater Chemistry and Gas Exchange Alone

Alkalinity is a measure of the buffer capacity of seawater. When reactive alkalinity is added, dissolved CO₂ is converted into bicarbonate and carbonate, and pH is elevated. This creates seawater with less dissolved CO₂, which, when in contact with an atmosphere of a respectively higher CO₂ concentration, results in seawater uptake of atmospheric CO₂. The net effect is thus a transfer of atmospheric CO₂ into the ocean, which decreases seawater pH until the CO₂ content of the now CO₂-poor surface water has equilibrated with the atmosphere.

OAE Is Immensely Scalable Due to the Sheer Size of the Ocean

The most recent global modeling effort by the Max Planck Institute for Meteorology suggests that mean dissolved inorganic carbon in the ocean could increase by 82–175 Gt of C over the course of 75 years, and this is equivalent to 300–642 billion tons of CO₂ (Burt et al., 2021). This amounts to 4.0–8.4 Gt of CO₂.
per year and is in line with previous modeling efforts (e.g., Keller et al., 2014; Lenton et al., 2018).

**Box 1. OAE includes all methods that lead to a net increase in surface water alkalinity. This entails the addition of natural or synthetic sources of alkalinity (definition of OAE by NASEM, 2021) as well as the creation of alkalinity by electrochemical splitting of seawater into acid and basic streams (listed as one of the “electrochemical processes” by NASEM, 2021).**

As is the case for several ocean CDR approaches under consideration, much of the current knowledge on OAE is based on modeling exercises and laboratory research. Mesocosm experiments have only begun in 2021, and one pioneering OAE field experiment has demonstrated that short-term OAE can mitigate negative impacts of ocean acidification on a coral reef (Albright et al., 2016). Increased mesocosm and field research is therefore needed to quantify real-world impacts on marine ecosystems and seawater chemistry and to develop an approach for carbon accounting (i.e., monitoring, reporting, and verification [MRV]), for which there is currently no framework or criteria (Ocean Visions, 2021). OAE is at a critical crossroad: The knowledge is incomplete, but technology needs to be developed now in order to deploy this technology in a climate-relevant timeframe and scale. Many open questions remain, and those must be thoroughly assessed before society and regulators give the green light to commercially deploy this technology. This is not an unsurmountable effort but will require cross-sectoral collaborations and efforts well beyond the walls of academic science.

To realize the potential to safely and equitably remove billions of tons of CO$_2$ via OAE in the coming decades, significant work is required: (a) research is needed to determine if OAE is safe, effective, affordable, and environmentally and societally desirable; (b) policies and governance frameworks need to be developed to foster and oversee field research over progressively larger spatial scales; (c) investments into OAE hardware and software are needed to support research and drive down the costs of carbon verification and environmental monitoring; and (d) civil society must be heavily engaged at all steps and scales to avoid single-variable optimization (e.g., CDR removal at any cost of negative environmental and social externalities).

**Research and Development Priorities for OAE**

As public and philanthropic funding in this field increases, three questions seem of highest priority for the swift and responsible assessment whether there are environmentally and socially responsible ways to deploy OAE at scale.

Under What Conditions Does OAE Most Efficiently Sequester Atmospheric CO$_2$?

Developing the most efficient deployment strategy requires identifying and understanding the main factors that will impact CDR efficacy. These factors include location (e.g., physical and biogeochemical environment where the alkalinity is added) and the type, mode, frequency, and rate of alkalinity addition. CDR inefficiencies and challenges around carbon accounting stem from processes that occur once the alkalinity source is added to the seawater. This includes particle dissolution rate (when adding minerals), secondary precipitation, and CO$_2$ gas exchange dynamics, all of which still require research, evaluation, and quantification.

- **Slow dissolution**: The surface ocean is oversaturated for calcium carbonate (CaCO$_3$), and this blocks passive dissolution of limestone and other carbonate-based minerals. Dissolution efficiencies could be increased by grinding and adding minerals as extremely fine powder or chemically modifying minerals in some way before deployment (calcination, hydration). Alternatively, minerals could be added to surface waters with naturally lower CaCO$_3$ saturation state, such as upwelling regions and high-latitude waters. The use of silicate-based minerals such as olivine and brucite might significantly increase dissolution rates since surface oceans are not oversaturated for silica, and ongoing research will provide much-needed guidance in the selection of reactive alkaline materials to use for OAE.

- **Secondary precipitation**: When seawater alkalinity is increased, so is the saturation state of CaCO$_3$. 

---

*January/February 2022 Volume 56 Number 1*
Higher saturation states make it easier for calcifying organisms to precipitate CaCO₃ shells and skeletons, and they can also trigger spontaneous, inorganic, precipitation of CaCO₃. Both biological and inorganic precipitation of CaCO₃ removes alkalinity from seawater and releases CO₂. Secondary precipitation could thus reduce and, under some environmental conditions, potentially reverse the intended CDR effect. However, these risks could be mitigated by dosing and diluting alkalinity addition and keeping pH below levels at which spontaneous precipitation is triggered.

- **Slow atmospheric CO₂ equilibration**: CO₂ equilibration of alkalinized seawater could take weeks to months and would be enough time for that seawater to be transported to the deep ocean, depending on the location and season. Export of unequilibrated seawater to the deep ocean would delay equilibration (and, as such, CDR) for at least part of the added alkalinity.

**Which OAE Methods Could Be Cost-Effectively Deployed at Scale and How?**

Preliminary estimates of OAE approaches range from $10 to $200 per ton CO₂ removed and are largely driven by the cost of material inputs and the energy costs associated with grinding, calcining, or electrochemical splitting of seawater (Renforth & Henderson, 2017; NASEM, 2021). Over the past 10–15 years, researchers have explored different ways to make OAE more cost-effective, each of which has different resource requirements and requires careful cost analyses.

- **Grinding up alkaline rock**: Dissolution of alkaline rock accelerates with increased surface area of rock. Also, rock sinks more slowly when added as fine powder; however, grinding up rock is costly (electricity increases exponentially with decreasing grain size).

- **Use of mine tailings**: Industrial waste products with alkaline properties could theoretically be used as cheap sources for OAE. In some cases, these mine tailings are simply too fine to be used in construction. In some cases, they contain substances that are unsuitable for the built environment as they add to corrosion or rustiness. DeBeers and the University of British Columbia are collaborating to explore this role of mine tailings, and experts at Aachen University are exploring similar approaches (Service, 2020).

- **Coastal enhanced weathering**: This approach takes advantage of natural processes that weather rock. For example, alkaline minerals could potentially be spread over beaches where breaking waves accelerate the physical breakdown and chemical dissolution of the minerals, without the need for an external energy source. The approach is under evaluation (e.g., by Project Vesta), and a key question is whether coastal weathering sufficiently increases dissolution rates to increase surface water alkalinity in a relevant timeframe.

- **Ocean liming**: Quicklime can be produced by heating up limestone in a kiln at >900°C. It has been applied on agricultural lands for millennia to decrease soil acidity. A challenge is thermal energy, as well as the need for CCS since CaCO₃ + heat = CaO + CO₂. Thermal energy can be directly or indirectly generated through solar. Quicklime dissolves immediately in the ocean. DESARC-MARESANUS is an Italian academic collaboration that is exploring the use of biomass CCS and calcination for OAE.

- **Modification of minerals**: As an alternative to physical modification via grinding, CaCO₃ minerals could potentially be chemically modified prior to dispersal in the ocean. Experts at Heriot-Watt University are currently exploring pathways to cost-effectively hydrate minerals to use them as more reactive alkaline feedstocks (personal communication, Dr. Phil Renforth).

- **Dissolution before water is added**: If there are cost-effective ways to keep a body of seawater in motion, dissolution of alkaline rock could be facilitated before the alkalized water is added back into ocean water. An example would be aquaculture ponds or wastewater treatment plants that pump seawater into ponds, keep water in suspension, and then discharge water into the ocean.

- **Electrochemical weathering of alkaline minerals**: This approach has received attention from startups (Planetary Hydrogen, Sea-Change, and others) because of marketable side products.

- **Electrochemical OAE**: In contrast to adding alkalinity, electrodialysis can remove acid from seawater (in the form of CO₂ or hydrochloric acid [HCl]), thus allowing the remaining alkalinity to draw in atmospheric CO₂ upon return to the ocean. To effect safe CDR, the CO₂ and/or HCl must be sequestered from the atmosphere or
Accelerated weathering reactors: In this approach, concentrated CO₂ can be reacted with seawater and CaCO₃ to store CO₂ as seawater alkalinity—bicarbonate and carbonate ions (Rau & Caldeira, 1999). For this approach to contribute to CDR, the CO₂ used for this reaction must come from the atmosphere (e.g., via direct air capture) rather than from point sources where CO₂ is captured to avoid emissions. For the latter, the addition of “excess” alkalinity to the reactor would result in CDR from alkalinity enhancement and may even be cost-effective. Experts at Caltech are currently building a prototype; experts at Hamburg University are testing this approach with a prototype that was built for the de-acidification of post-coal lakes in Germany.

How Can Desired and Undesired Effects Be Identified, Measured, Monitored, and Minimized?

Large-scale and permanent modification of seawater carbon chemistry will have desired and undesired environmental impacts, and these impacts are likely to differ across the various modes of alkalinity addition. In the absence of data from mesocosm and in-situ research, it is difficult to predict these changes and, as such, develop a meaningful framework for MRV. A robust, widely acceptable OAE MRV framework is required to accurately account for and credit any CDR achieved as well as to ensure that ecological and environmental integrity is maintained within a still yet-to-be-determined acceptable level:

- Carbon accounting: Unlike land-based CDR, the ocean-based CDR MRV challenges stem from the air-sea interface whereby one cannot simply assume that dissolved CO₂ removed from seawater at a project’s location is replaced with an equivalent quantity of atmospheric CO₂ (e.g., Bach et al., 2021). The CDR effect from OAE will occur over potentially vast areas and large volumes of water, and observing the diluted signature of OAE over background variability in carbon chemistry will be challenging. As such, MRV will likely have to rely on a combination of field trials, modeling, tracers, and proxies. Use of various autonomous underwater vehicles and remote sensing platforms will also be needed, and such direct observations could become simpler, faster, and more precise as observation technologies are optimized for OAE.

- Environmental monitoring: Given the lack of field trials, the extent of potential environmental impacts is restricted to informed hypotheses and early lab-based experiments (Bach et al., 2019). Both positive and negative environmental impacts can be expected, and identifying and quantifying those is a research priority (NASEM, 2021). Understanding biological impacts can also lead to revision of OAE approaches to minimize harmful impacts (e.g., adjust timing of OAE to avoid impacts on phytoplankton during the period of greatest production) and optimize secondary benefits (e.g., ocean acidification mitigation or fisheries enhancement). What constitutes a negative environmental impact may be subjective, and societal consensus on an acceptable level of (un)desired environmental change will need to be reached to identify which impacts require close monitoring. In the coming years, marine biogeochemists will therefore have to closely collaborate with engineers, regulators, the civil society, and the private sector to quickly and iteratively establish MRV frameworks that generate not only data but also trust in OAE’s ability to safely and efficiently remove CO₂ from the atmosphere.

Across all ocean CDR approaches, field trials and pilot-scale studies across different spatial and temporal scales will be key to identifying and ranking (un)desired environmental impacts and inform MRV frameworks that address the most prevalent and consequential side effects. As field trials identify important impacts, steps can be taken to revise the methods to minimize potential harmful impacts and optimize secondary benefits. For OAE, this could include, for example, the adjustment of timing of alkalinity addition to avoid impacts on phytoplankton during the period of greatest production or maximize ocean acidification mitigation effects.

Even for field trials, innovation of hardware and software is needed. Data collected at project sites will likely require deployment of sensors for ocean carbon chemistry (i.e., pH, pCO₂, dissolved inorganic carbon, and total alkalinity), trace metals, and indicators of primary production (e.g., chlorophyll a). These could be in the form of fixed autonomous sensors, profiling floats, and autonomous/ remotely operated underwater vehicles. Seawater samples, biological samples, and surveys in and around the project area may be required to monitor environmental impacts. Tools such as eDNA might become
important elements in this expanded biological monitoring regime. Remote sensing tools such as satellite imagery for high-frequency tracking of phytoplankton blooms may also be important.

Some of the above-listed MRV tools are commercially available today in the form of high-grade research equipment, while others are still under development (e.g., prototype development with few expert users). Should ocean CDR approaches be determined safe and deployable at scale, MRV tools will need to be modified to become more affordable and tailored to the specific approaches. This process requires stakeholder consensus on MRV criteria and specifications, such as sensor/model precision and accuracy (Ocean Visions, 2021) as well as monitoring duration and observation frequency.

A New Opportunity for the Blue Economy

As the world advances into 2022, interest in “the blue economy” is gaining momentum across governments and non-governmental organizations. As a few examples:

- In 2016, the Organisation for Economic Co-operation and Development (OECD) published The Ocean Economy in 2030, which focused on the economic contribution of ocean-related industries worldwide and estimated that, in 2010, they produced value-added equivalent to 3% of global gross domestic product and full-time employment for around 30 million people (OECD, 2016).
- In 2020, the National Oceanic and Atmospheric Administration (NOAA) announced the U.S. marine economy, including goods and services, contributed about $373 billion to the nation’s gross domestic product in 2018 and grew faster than the nation’s economy as a whole (NOAA, 2020).
- Also in 2020, the World Resource Institute’s Ocean Panel published a report, A Sustainable Ocean Economy for 2050: Approximating Its Benefits and Costs, in which it noted “investing $1 in key ocean actions can yield at least $5 in global benefits” and “investing $2 trillion to $3.7 trillion globally across four key areas—conserving and restoring mangrove habitats, scaling up offshore wind production, decarbonising international shipping and increasing the production of sustainably sourced ocean-based proteins—from 2020 to 2050 would generate $8.2 trillion to $22.8 trillion in net benefits, a rate of return on investment of 450–615 percent” (Ocean Panel, 2020). It is relatively clear that there exist both financial and environmental opportunities in the blue economy.
- Such analyses do not yet incorporate the potential impact and value of an ocean CDR economy, which could be on the order of half a trillion dollars per year assuming 5 Gt of CO₂ removal at a carbon price of $100 per ton removed. At scale, any of the ocean CDR approaches in discussion will have to rely on maritime infrastructure, engineering, and supply chains, including offshore platforms, wind energy, and transnational shipping.

Alongside a general economic interest in the ocean, there is an increasing need to find solutions for net zero commitments and, more importantly, reverse the course of the climate crisis entirely. These interests meet at the frontier of ocean CDR and have culminated in a growing ocean CDR investment by philanthropists, entrepreneurs, and investors. However, the near-term steps to advance in ocean CDR remain hampered by incomplete knowledge. In sectors such as offshore wind or decarbonization of shipping, the technical and economic considerations are largely known. These markets operate within relatively well-understood regulatory frameworks with established risk management processes driven by both private and public forces. Shippers have been able to turn to organizations such as Lloyds of London for insurance and risk management for over 300 years. The field of ocean CDR, however, is far behind much of the blue economy in developing tools and techniques to deliver the financial and environmental benefits it promises. Addressing these gaps is the opportunity at hand for scientists, engineers, entrepreneurs, investors, agencies, and philanthropists. There are several critical needs that require attention and investment to advance ocean CDR writ large. These include, but are not limited to, the following:

- Tools and techniques: From ocean sensors to track OAE impacts to methods for cultivating and sinking seaweed, there is significant work to be done by engineers and technologists.
- Understanding of impacts and outcomes: developing sufficient understanding for scientists and policymakers to assess overall impacts on the ocean and society.
- Creation of markets and business models: identification of opportunities for profit within appropriate bounds of social license.
truly functional ocean CDR ecosystem, should any of the approaches be deemed safe and effective at scale. Some of these topics are starting to be addressed by conventional research funding sources. This includes the following:

- **In Europe**: Horizon 2020’s Ocean NETs (NETs is an acronym for Negative Emissions Technologies) program tackles “major open questions concerning the feasibility of using ocean-based NETs for climate stabilization.” The United Kingdom’s £30 million Greenhouse Gas Removal program includes a small ocean component, and most recently, Germany’s Federal Ministry of Education and Research granted 5 million euros to the program “CDRmare” to assess marine carbon sinks in the context of national decarbonization pathway analyses.

- **In the United States**: NASEM (2021) calls for federal funding of research and development, highlighting the urgent need for large-scale field research and recent requests for proposals by the NOAA on ocean CDR research.

- **Philanthropic sources**: In the last few years, ClimateWorks Foundation has funded several ocean CDR research grants through their ocean CDR portfolio. In February 2022, Additional Ventures launched a significant philanthropic research and development program focused entirely on OAE. Beyond these traditional funding routes, new funding is coming into the field from angel investors and venture capitalists through the support of new startups. Many of these startups to date, if not all, have leveraged private funding to fund basic science that helps improve their understanding of commercially attractive pathways of ocean CDR. These entrepreneurs are important actors in a nascent field.

As the blue economy and climate community meet at the frontier of ocean CDR, the opportunities for investment and innovation are substantial. The spectrum of scientific and technical questions requires the participation of many disciplines and sectors and the engagement of governments, philanthropists, and the private sector. Progress over the next few years will see these opportunities unfold, and new technologies and business models will appear. If proven safe and desirable, ocean CDR might become an important and much-needed arrow in the CDR quiver.

**Acknowledgments**

The authors thank Brad Ack and an additional referee for reviewing the manuscript and providing valuable feedback.

**Corresponding Author:**
Antonius Gagern
Additional Ventures, Washington, DC
Email: antonius@additionalventures.org

**References**


