ADDITIONAL VENTURES

Ocean Alkalinity Enhancement R&D Program

A philanthropic consortium, led by Additional Ventures, is proud to launch the Ocean Alkalinity Enhancement (OAE) R&D Program, an ambitious effort to accelerate understanding of OAE as a potential method for large-scale carbon dioxide removal (CDR).

Why ocean alkalinity enhancement?

The Intergovernmental Panel on Climate Change (IPCC) suggests that even aggressive mitigation measures to reduce CO_2 emissions will have to be complemented with carbon dioxide removal (CDR) on the order of 100–1000 billion tons of CO_2 before the end of the 21st century to avert the worst consequences of climate change.[1]

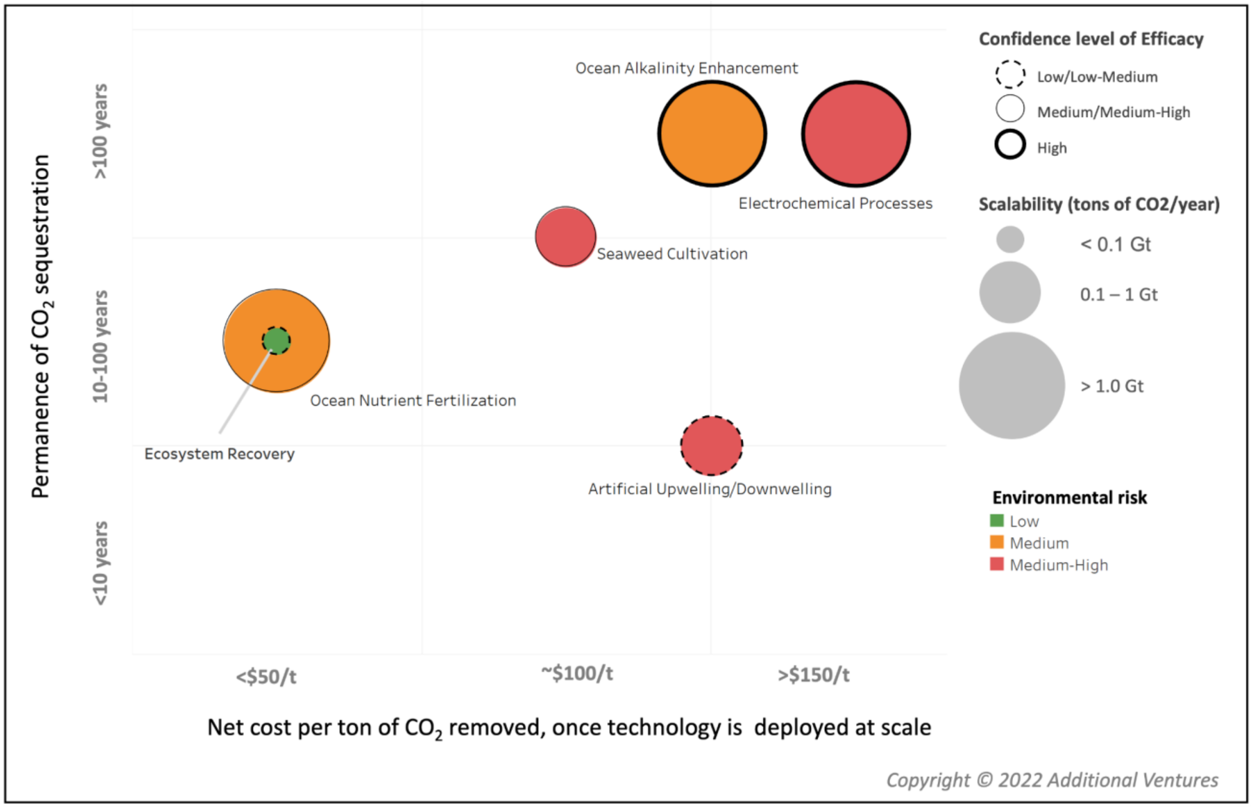
The ocean already contains 50 times more CO_2 than the atmosphere and has an enormous capacity to permanently sequester more. As ocean-based CDR has attracted more interest OAE has emerged as a particularly intriguing approach. When alkalinity increases in seawater, dissolved CO_2 is chemically transformed to bicarbonate and carbonate ions. This transformation can help de-acidify seawater, turning the chemical clock of the ocean back to pre-industrial times. OAE can, at least on paper, sequester billions tons of CO_2 annually for tens or even hundreds of thousands of years, imitating geologic weathering processes that have sequestered trillions of tons of atmospheric CO_2 in the ocean over millennia.[2]

In late 2021, the National Academies of Sciences, Engineering, and Mathematics (NASEM) released a study on ocean-based CDR approaches. In this consensus report, OAE stands out as a potentially efficient and highly scalable CDR pathway.[3]

Figure 1: Current knowledge on ocean-based CDR approaches. Visual representation of key quantitative and qualitative results summarized by NASEM (2021, Table S.1 therein). Note that some of the most cost-effective and scalable "electrochemical processes" described in NASEM (2021) increase

[1] IPCC (2018). Special Report: Global Warming of 1.5 ºC.
[2] Burt et al. (2021). https://doi.org/10.3389/fclim.2021.624075
[3] NASEM (2021) https://www.nap.edu/catalog/26278

the alkalinity of seawater, and/or force the precipitation of solid alkaline materials that can be used for OAE. Our definition of OAE encompasses these electrochemical approaches.



What are the open questions?

While OAE is potentially efficient, permanent, and scalable on paper, determining whether it can live up to its promise in practice requires a focused R&D effort. Three questions merit special attention:

1. 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 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.

- Dissolution: The surface ocean is oversaturated for CaCO3, blocking dissolution of lime and making it slow for other carbonate-based minerals unless added as extremely fine powder, modified in some way before deployment (calcination, hydration), or added to seawater that accelerates dissolution (e.g., artificially enriched with CO_2 or with naturally low saturation state, such as upwelling regions or high latitude waters).

- Secondary precipitation: High seawater saturation states can lead to inorganic CaCO3 precipitation, thereby decreasing the efficiency of CDR. This effect might, in some cases, even lead to the net release of CO_2 from seawater.
- Slow equilibration: When the partial pressure of CO_2 (pCO_2) in seawater is lower than in the atmosphere (e.g. as a result of alkalinization), atmospheric CO_2 is taken up into the ocean surface layer to equilibrate this pCO_2 gradient. However, full equilibration of perturbed seawater will take weeks to months, enough time to move alkalized seawater into the deep ocean in certain locations and/or times of year, thereby delaying equilibration (and as such CDR) for at least part of the added alkalinity.

2. Can OAE be cost-effectively deployed at scale? Irrespective of the mode of alkalinity enhancement, estimated costs remain above (or close to) $100 per net ton removed, largely as a result of high energy costs. Over the past 10-15 years, researchers have explored different solutions to reduce costs and speed up dissolution rates.

- **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). This approach is tested in labs but no commercial application is currently considering the approach.
- **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.
- **Coastal enhanced weathering**: Proposes to use olivine as alkaline rock (apply alkaline material on coasts, hoping that wave/beach interaction accelerates dissolution). The approach is being tested in lab and mesocosm settings, but olivine dissolves very slowly, and wave action would have to accelerate the process by 10-100x in order to be effective over short time periods.
- **Accelerated weathering reactors**: Combine concentrated CO_2 from flue gas with seawater and limestone in a “reactor” to accelerate the reaction. This is not strictly speaking CDR (more akin to CCS), but “excess” alkalinity can be added to the reactor, thereby enhancing ocean alkalinity as well. This technology is slowly moving into the prototype phase.
- **Ocean liming**: Quicklime can be produced by heating up limestone in a kiln at >900 degrees Celsius. It’s 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 + CO_2. Thermal energy can be directly or indirectly generated through solar. Quicklime dissolves immediately in the ocean.
- **Modification of minerals**: The reason for low reactivity is that the ocean is already saturated with the molecular components of widely available minerals (e.g., CaCO3), but there are ways to modify those minerals to make them more reactive.

- **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, then discharge water into the ocean.
- **Electrochemical processes**: Various electrochemical approaches are being explored to increase the alkalinity of seawater, and/or to force the precipitation of solid alkaline materials (i.e hydroxide minerals such as brucite and portlandite).

3. How can desired and undesired effects be identified, measured, monitored, and mitigated? 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 field trials, it is difficult to predict these changes and to develop meaningful frameworks for monitoring, reporting and verification (MRV). Any MRV framework will have to focus on two major questions, however. First, how much CO_2 is permanently moved from the atmosphere to the ocean and how quickly does this happen (carbon accounting)? Second, what are the undesired effects of OAE on marine organisms and ecosystems (monitoring of environmental impacts) and how can they be mitigated?

- **Carbon accounting.** OAE in the real world will be less efficient than on paper. That's because stoichiometric efficiencies (i.e. the simplified chemical formula of OAE on paper) do not take into consideration dissolution kinetics, equilibration timelines, and biogeochemical feedback systems. We therefore will have to get much better at either directly measuring or predicting the real effect of OAE on CDR under different conditions (e.g. alkaline material, grain size, water temperature, saturation state, biological activity, and so on). Since OAE will not necessarily occur at the same site or the same time of alkalinity addition, the dilution of the alkalinity-enhanced body of seawater will likely make it near impossible to detect CDR above background variability in carbon chemistry.

  Field research and innovation is therefore needed to build a strong and affordable MRV framework. Field work to better understand what happens when alkalinity is added to surface waters (dilution, secondary precipitation, equilibration); innovation to build the hardware and software necessary to measure and CDR.

- **Environmental monitoring.** Environmental impacts of OAE are poorly understood. Broadly speaking, both pH swings and trace metals (from mineral impurities) can impact metabolic activities of marine organisms and conceivably affect entire food webs. Field research is absolutely imperative to identify and rank environmental impacts and to design MRV frameworks that address the most prevalent and consequential side-effects.

Data collection for carbon accounting and environmental monitoring is difficult and expensive and entails the use of tracers, sensors, robotics, platforms, and communication networks, at a minimum. To drive down costs of MRV as OAE scales, empirical relationships will have to be established in controlled settings that can enable reliance on modeling and proxies, such as remote sensing and input-output modeling.

Where does the field stand today?

In 2018, the ocean CDR conversation was entirely focused on blue carbon ecosystems and their ability to sequester and store organic carbon. Since then, the conversation has grown significantly with the following milestones:

- The UN advisory body GESAMP published a review of two dozen proposed marine geoengineering techniques, including solar radiation management and CDR approaches.
- The Energy Futures Initiative published an influential report on CDR technologies, including ocean pathways and their high-level R&D needs.
- The ClimateWorks Foundation launched its ocean CDR fund, focused on field building, science, and policy. ClimateWorks helped launch Ocean Visions' CDR task force and funded the NASEM ocean CDR report.
- The Grantham Foundation heavily invested into the ocean CDR science and startup landscape.
- ARPA-E funded $50 million of macroalgae R&D through its MARINER program.
- The European Union granted €7 million to the Geomar-led OceanNETs program.
- Germany's Federal Ministry of Education and Research granted €5 million to CDRmare to assess marine carbon sinks in the context of national decarbonization pathway analyses.
- UK's £30 million GGR program includes a small ocean component.
- Private companies such as Stripe and Shopify have started to purchase negative emission credits from ocean CDR companies to artificially create demand in the absence of an existing CDR market.
- Numerous climate tech venture funds are emerging, with dedicated budgets and/or interests in ocean CDR (Builders Initiative, Thistledown Foundation, Voyager, Prime Coalition, Quadrature Climate Foundation, CREO, etc.).

As a result of this work, other ocean CDR approaches have bubbled to the top of the ocean CDR conversation, including OAE, macroalgae cultivation, artificial upwelling, and electrochemical approaches of "direct ocean capture" (for more information, see www.oceancdr.net and www.oceanvisions.org/roadmaps/).

These efforts have helped start the field and lend legitimacy to this emerging set of ocean-based CDR pathways. However, knowledge generation remains slow and R&D funding is limited to few, relatively small efforts. OAE in particular has not received the attention it requires. OAE stands out as a pathway with immense CDR potential but many of the fundamental questions of efficiency, environmental impact, and costs remain unanswered and R&D efforts are scarce and poorly funded.

What is our approach?

Additional Ventures is building an R&D program consisting of three pillars:

1. **An ocean sciences team** to systematically assess the conditions under which OAE approaches are maximally effective at safely and permanently sequestering atmospheric CO_2 in the ocean.

2. **A technology innovation cohort** to build proof-of-concept prototypes for cost-effective and reliable OAE deployment, including monitoring, reporting, and verification hardware.

3. **A global support team** to help contractors and grantees plan experiments, seek permits, hire new staff, and organize events. This team will set up a handful of pre-permitted test-bed sites for field work, prototype testing, and early deployment.

What is new in our approach and why do we think it will be successful?

The OAE R&D Program is designed to be iterative, collaborative, and fast-paced, and will include the following attributes:

Generous funding: Teams will be well resourced; beyond salaries for core staff, this includes sufficient budget to set up laboratories, mesocosms, and in-situ test arrays where needed, and to bring in external expertise as helpful. We know that trial and error is part of learning and grantees will be asked to build the team and budget that allows for rapid adjustments in research questions and methodology.

Transparency and collaboration: Technical solutions must be deeply informed by the ongoing scientific research and oceanographic modeling; similarly, experimental research must be deeply informed by technical capabilities and lessons learned across hardware teams. As such, communication channels between the ocean sciences/modeling team and the hardware teams will be wide open from day one. This includes formalized relationships that allow all teams to tap into knowledge of cohort peers, as well as in-person meetings that will also be attended by the ocean sciences team.

Centralized learning: Additional Ventures will work with each team to centralize learning across teams and to identify common pain points. In addition, all teams will meet twice annually to present progress and bottlenecks in detail, to align technical roadmaps and dependencies, and to benefit from the knowledge of cohort peers as they progress.

Integrated with existing efforts: Where R&D has already commenced, we will build off of it rather than reinventing the wheel. This includes major research efforts (NASEM, OceanNETs, CDRmare), field building efforts (Ocean Visions), ongoing university research (UCSB, OSU, Dalhousie, SDU, University of Tasmania, Woods Hole, Stony Brook University), and specific solutions-driven entrepreneurial efforts (Ebb Carbon, SeaChange, Caltech, Planetary Hydrogen, Project Vesta). In almost all of these efforts, project PIs are already close collaborators. This R&D program will build connective tissue across this community through frequent in-person ideation sessions, curated webinars, and pre-permitted test-beds that will serve as a natural magnet for practitioners around the world to conduct research, test prototypes, and build a strong technical community of practitioners.

Attracting the best people from adjacent fields. As ocean CDR proposals move from concept to practice, the existing community will have to productively join forces with innovators across a variety of disciplines: mechanical engineers, material scientists, naval engineers, sensor & robotics experts, and so on. We will actively and systematically build these bridges through a combination of ideation workshops and collaborative proposal teams.

Who cares? If we are successful, what difference will it make?

In the absence of a well-funded and top-down OAE R&D effort, there will be no central and credible learning effort to serve as a reference to entrepreneurs, investors, regulators, and the public any time soon. A cohort of expert grantees and a fully open-source approach will help bootstrap an emerging field while developing scientific consensus.

We expect that this R&D effort will significantly accelerate answers to the three threshold questions for OAE described above:

1. Under what conditions does OAE most efficiently sequester atmospheric CO_2?
2. Can OAE be cost-effectively deployed at scale?
3. How can desired and undesired effects be identified, measured, monitored, and mitigated?

We expect a well-funded and well-run R&D effort to make enough headway on these key questions to:

- Focus the OAE community on approaches and deployment mechanisms that are most cost-effective, scalable, and environmentally acceptable.
- Catalyze significant public R&D funding in the US and EU.
- Quickly build the capacity of the OAE field to absorb public R&D funding.
- Equip market and regulatory actors to support OAE deployment, if proven effective, scalable, and safe.

Questions?

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Partners