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Commentary

Antacids for the Sea? Artificial Ocean Alkalinization and Climate Change

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There is increasing urgency for large-scale deployment of carbon-removal approaches to help avoid passing critical climatic thresholds. Given the severe risks of many terrestrial methods at extremely large scales, there is a compelling need to also assess the potential of marine negative-emissions technologies, such as artificial ocean alkalinization.

Introduction

The world community greeted the signing of the Paris Agreement in 2015 with a sense of exhilaration. However, it is increasingly evident that the regime's parties might lack the fundamental resolve to take the requisite measures to meet the Paris Agreement's objectives of holding temperatures to "well below 2°C above pre-industrial levels" and at least aspire to hold temperatures to 1.5°C. As a consequence, the remaining "carbon budget" to hold temperatures to 1.5°C might be exhausted by 2030 given that temperatures are projected to increase by 2.6°C–3.7°C by the end of the century. Moreover, because many parties to the Paris Agreement are not even on track to meet their lackluster pledges, temperatures could soar to more than 4.4°C above pre-industrial levels by 2100.

Of the scenarios in the Intergovernmental Panel on Climate Change's Fifth Assessment Report that effectuate the Paris Agreement's temperature targets, 87% contemplate the need for extensive deployment of technologies and processes to remove carbon dioxide (CO_2) from the atmosphere in addition to aggressive decarbonization strategies. In many of these scenarios, the scale of CO_2 removal (CDR) is as much as 10–20 Gt CO_2/year, or cumulative volumes of up to 1,000 Gt by 2100.[1] This would be equivalent to approximately 25 years of current annual fossil fuel emissions worldwide.

Research, development, and funding for CDR options have thus far focused on a select handful of terrestrial-based technologies, including bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, and direct air capture. However, many of these suffer from shortcomings or pose serious risks at large-scale deployment. BECCS could require enormous areas of land and water, which could imperil food systems and biodiversity conservation, especially in areas such as prairie grasslands.[2] Direct air capture could prove to be far too expensive to be deployed at large scales, and afforestation and reforestation programs might not prove permanent, especially under conditions of risings temperatures. That is why prudent observers call for "an all-of-the-above approach" in researching and developing a portfolio of CDR strategies to minimize trade-offs and detrimental side effects and maximize co-benefits.[3]

Other CDR strategies exist but remain underfunded, underdeveloped, and undertested. This is particularly true for ocean-based CDR. In contrast to the relative scarcity of valuable land, the ocean covers 71% of the planet's surface and already passively absorbs about 10 Gt of CO_2 per year, and it could probably store much more. Given the urgency of climate change, researching the potential to enhance this carbon sink is an opportunity we cannot afford to ignore. To date, most of the focus has been on ocean iron fertilization (OIF)—the seeding of the ocean with iron to stimulate phytoplankton blooms and trigger uptake of CO_2 from the atmosphere, after which carbon is transferred to the seafloor upon the organisms' death. However, OIF research has been largely abandoned because its sequestration rates have proved disappointing, and the approach could pose severe risks to ocean ecosystems. The pioneering research into OIF has, however, provided some impetus for scrutinizing a more diverse portfolio of other marine CDR approaches. "Blue-carbon" approaches seek to enhance carbon uptake in mangroves, salt marshes, and sea grasses; ocean-based bioenergy with carbon capture and sequestration; and the deployment of equipment to increase upwelling or downwelling of ocean nutrients to enhance carbon storage. Here, we focus on artificial ocean alkalinization (AOA), an approach we believe presents some of the greatest potential in terms of CO_2 sequestration and co-benefits.

Overview of Ocean Alkalinization

We argue that AOA is a CDR method with some of the greatest potential in terms of carbon removal and co-benefits. Adding alkalinity to ocean ecosystems increases ocean pH, which spurs greater carbon uptake by oceans while also reducing the pace of ocean acidification. Several options for enhancing ocean alkalinity have been proposed, including the addition of powdered olivine, highly reactive lime (CaO), or calcium hydroxide ($Ca(OH)_2$) produced by the calcination of limestone to ocean surfaces or injection into deep seawater currents that ultimately end in upwelling regions. Another proposal is to manufacture alkalinity at sea by using local marine energy sources. Reacting waste CO_2 with minerals on shore and then pumping the resulting dissolved alkaline material into the ocean is still another option. These approaches could massively accelerate natural processes that otherwise remove CO_2 from the atmosphere on much slower scales.

Table 1. Three Functions of Governance

Enablement	provide financial support, technical resources, strategic priorities, and scientific quality control
Control	assess risk, create and enforce rules to limit those risks, and oversee progress
Legitimation	foster a sense of responsibility in research teams and build societal support, transparency, and public engagement

Assessments of AOA's potential for CDR range widely from a mere 30 parts per million (ppm) to much greater concentration reductions ranging from 166–450 ppm.[4] At the high end, AOA could substantially reduce projected temperature increases and associated sea-level rise under high-emissions scenarios.[5] But even at the lower end, AOA could represent a meaningful contribution to global efforts on carbon drawdown. This potential alone justifies additional research.

AOA is doubly compelling because it could also potentially help combat climate change's "evil twin," ocean acidification. Acidification of the ocean reduces levels of carbonate and compromises the ability of corals, bivalves, crustaceans, and echinoderms to form their calcium carbon skeletons and shells. Acidification could also harm many finfish species through negative impacts on critical habitat, food sources, behavior, and larval survival. Ocean acidity has increased by 30% since the onset of anthropogenic CO_2 emissions, and current pH levels are the lowest they have been for two million years. Although more research is needed, AOA has the potential to counteract ocean acidification by moderating potential declines in both pH and carbon ion concentrations.[6]

Although AOA advocates are right to laud its promise and potential co-benefits, as with terrestrial-based CDR, it is not without its risks. Specifically, AOA could inhibit photosynthesis in phytoplankton communities, altering their trophic structure and biogeochemical functions in unpredictable ways. AOA could also raise ocean pH levels in some regions *above* those experienced in pre-industrial times and ultimately have uncertain impacts on marine life—one study concluded that alkalinity addition could disrupt the acid-base balance of marine organisms. The addition of alkaline substances could also introduce toxic heavy metals, such as cadmium, nickel, and chromium, into ocean ecosystems and have potentially adverse impacts on ocean biogeochemical cycles and marine ecosystem services.[7] Any potential execution of these approaches, including field testing, would therefore require careful governance structures.

The Need for Good Governance

One need only recall the high-profile failure of the 2012 Haida OIF experiment to know why governance is critical for the success of CDR research. Russ George, a US businessman, worked with the Haida First Nation to develop an OIF venture that dumped about 100 tons of iron into the high seas off Canadian waters. The project marketed itself as "salmon restoration." Dumping iron would spur a large algae bloom, in turn boosting salmon levels while also hopefully sequestering CO_2, generating carbon credits for resale. The team, however, failed to notify Canadian authorities and did not obtain a required permit. It was internationally condemned as a "rogue" experiment, tarnishing the reputation of OIF activities worldwide. It also failed to produce evidence of lasting carbon removal or a financial return for the Haida Nation.

The poorly realized 2012 Haida OIF experiment was designed to evade requirements under Canadian and international law and damaged the legitimacy of marine carbon removal. The experiment's failure highlights three functions that good governance provides to all CDR research: enablement, control, and legitimation.[8] It enables research by providing financial and technical resources, strategic priorities, and quality control. The Haida experiment team, in contrast, lacked traditional scientific credentials and unjustly drew (and probably wasted) millions of dollars from the Haida for funding. Good governance also controls research by identifying potential risks and creating and enforcing rules to limit those risks. Finally, it legitimizes research by conveying responsibility and building societal support.

Good governance is needed for all research, design, and development on CDR technologies to produce useful data, to manage environmental and social risks, to develop robust emissions accounting, and to legitimize activities. AOA governance in particular must closely consider risks for marine ecosystems. It must also develop reliable, sensitive methods of carbon monitoring over vast areas of ocean (Table 1).

International Law and AOA Research

Initial studies suggest that AOA could be most effective in shallow coastal waters. This has legal significance because international law divides national authority over oceans into zones. Under the UN Convention on the Law of the Sea (UNCLOS), coastal countries possess sovereignty over the water, air, seabeds, and marine resources within their territorial sea, the part of the ocean within roughly 12 nautical miles of the coast. AOA research within the territorial sea would be subject to the exclusive jurisdiction of the coastal country and would need to comply with national permitting processes. A supervising government agency might also wish to conduct a more expansive review on the unique risks associated with AOA, ideally in coordination with international guidelines on the subject.

Jurisdiction over marine research becomes somewhat more complex within a country's exclusive economic zone (EEZ), the area beyond the territorial sea and up to roughly 200 nautical miles from the coast. Research activities are presumptively allowed, but the coastal country retains authority to regulate conduct to limit harms to ecosystems and marine resources. The governance structure for AOA research in the EEZ would therefore be similar to that in the territorial sea.

Environmental protection and marine conservation have long proven challenging in the high seas—the areas of the ocean beyond the EEZ and thus national jurisdiction. However, a draft agreement under UNCLOS, focused on "marine biological diversity of areas beyond national jurisdiction" (BBNJ), would formalize marine biodiversity protections for these regions.[9] Among other measures, it would require countries to establish conservation areas and to conduct environmental assessments for activities potentially affecting BBNJ, including marine research. International governance on AOA could incorporate these standards, and national governments could apply them to ships and research teams under their control.

Models for International Governance

Some researchers might be tempted to "shop" between maritime jurisdictions for waters with less regulation. It would therefore be prudent to develop international governance tools to ensure that AOA research, wherever it is done, complies with acceptable environmental and scientific standards. Instruments implemented for OIF provide a useful starting point for such a framework given that the risks and promises of AOA and OIF are similar.

In 2013, parties to the London Protocol, the international instrument prohibiting ocean dumping without a national permit, passed an amendment regulating OIF research. The amendment states that countries cannot permit OIF activities without first completing an environmental assessment concluding that the research will cause no or minimal marine pollution. The 2013 amendment has not yet been ratified, but AOA researchers would do well to follow its common-sense requirements: minimize pollution, obtain a permit, and scientifically justify proposed activities.

AOA governance should also consider two important differences from OIF. First, AOA could reduce ocean acidification, promising value as a potential adaptation measure. Second, AOA's mechanisms for CDR and anti-acidification are inorganic; unlike OIF, AOA does not rely directly on ecological disruption to work. (*Indirect* ecological disruption, however, would remain a significant risk.)

A Moderate Path toward AOA Development

Governance questions become more challenging when one considers AOA deployment on a climatically significant scale, namely questions of transboundary harm, deployment control, and liability.

- Uncertainty: What are the risks of environmental harm? Of transboundary harm? Which risks are tolerable? How quickly could deployment be reversed?
- Control: Who decides whether to deploy? How would decisions be reached? Who resolves disputes?
- Liability: Which injuries would be compensable? Who pays? Could AOA itself be used to compensate for other climate-based harms?

Scientific ignorance limits our ability to begin answering these questions. There is also widespread skepticism and fear of proposals to manipulate the environment on a planetary scale, preventing research from being considered at all. Furthermore, although research might reduce technical ignorance, it could fail to resolve or even increase uncertainties about deployment risks.

Given widespread aversion to proposals for deliberate, planetary-scale climate intervention, researchers should proceed cautiously with AOA. Researchers could investigate AOA primarily as an adaptation method to combat ocean acidification. Activities would be regulated largely by the domestic law of coastal countries with an overlay of international governance. If AOA's carbon sequestration proves measurable, long lasting, and net negative, carbon removal could become a co-benefit of AOA adaptation programs or a primary objective in its own right.

Experience with local AOA treatments might encourage greater depositions to capture more carbon. It might not. But this moderate path—gradual, incremental exploration of AOA as an adaptation measure with CDR as a potential co-benefit—would allow governance structures to mature alongside advances in technical understanding. Future policymakers would then be well positioned to decide whether to scale up AOA for CDR. The risks, rewards, and uncertainties of deployment would be better understood.

Conclusion

AOA could play a role as one of many approaches to annually remove billions of tons of atmospheric CO_2. But, as is true with many other CDR strategies, it remains poorly understood and underdeveloped. Governments and research institutions should dedicate more resources to assess AOA's potential benefits, risks, and governance. Given the implications of unchecked climate change, they should act quickly to do so, and advocates should keep the pressure on until they do.

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