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The Science We Need to Assess Marine Carbon Dioxide Removal

As companies begin selling credits for marine carbon dioxide removal in largely unregulated marketplaces, scientists must develop standards for assessing the effectiveness of removal methods.

By **Jaime B. Palter**, **Jessica Cross**, **Matthew C. Long**, **Patrick A. Rafter,** and **Clare E. Reimers**
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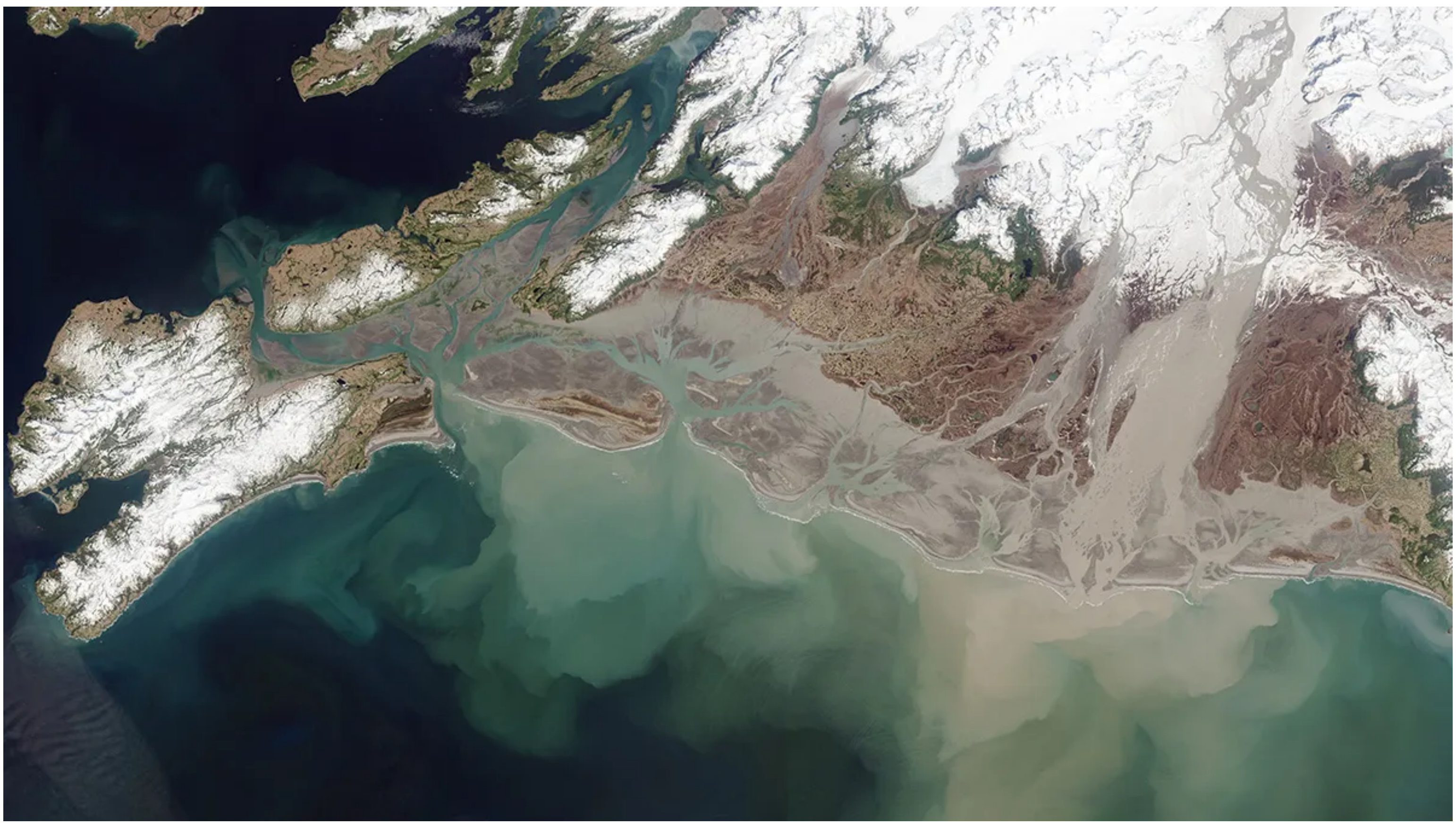

The natural addition of glacial silt colors coastal waters, as seen here in the Gulf of Alaska near the mouth of the Copper River. This process is a potential analogue for ocean alkalinity enhancement, one proposed method for marine carbon dioxide removal. Alpine glacier melt streams react with carbonate bedrock, increasing the alkalinity delivered to the marine environment. Credit: Robert Simmon and Jesse Allen/NASA Earth Observatory

The window to limit global warming to **Paris Agreement** targets by reducing greenhouse gas emissions alone is rapidly closing. According to the Intergovernmental Panel on Climate Change [***Pörtner et al.***, 2022], to have a 50% chance of keeping warming below 1.5°C, the whole of society will need to limit all future carbon dioxide (CO_2) emissions to less than a few hundred billion tons. With global emissions of CO_2 in 2021 totaling 36 billion tons [***Friedlingstein et al.***, 2022], this limit implies a need to halve emissions within a decade, on our way to eliminating nearly all emissions by midcentury.

This is a formidable challenge that becomes harder to overcome with each passing month. Therefore, many scientists, policymakers, entrepreneurs, and others have begun grappling with the reality that staving off intergenerational harms of climate change—from increasingly intense heat waves to more severe droughts and floods to rising risks from wildfire and tropical cyclones—will also require removing legacy CO_2 from the atmosphere.

Several carbon removal methods are now being deployed on land, such as producing energy with biological material and **capturing and storing the CO_2 produced** (i.e., bioenergy with carbon capture and storage), planting more forests, or **drawing massive amounts of air** through absorbent filters. Because the ocean covers 71% of Earth's surface and, apart from the atmosphere, already serves as the largest net sink for anthropogenic CO_2 emissions [***Friedlingstein et al.***, 2022], various ocean-based, or marine, CO_2 removal (mCDR) strategies are being proposed (Figure 1).

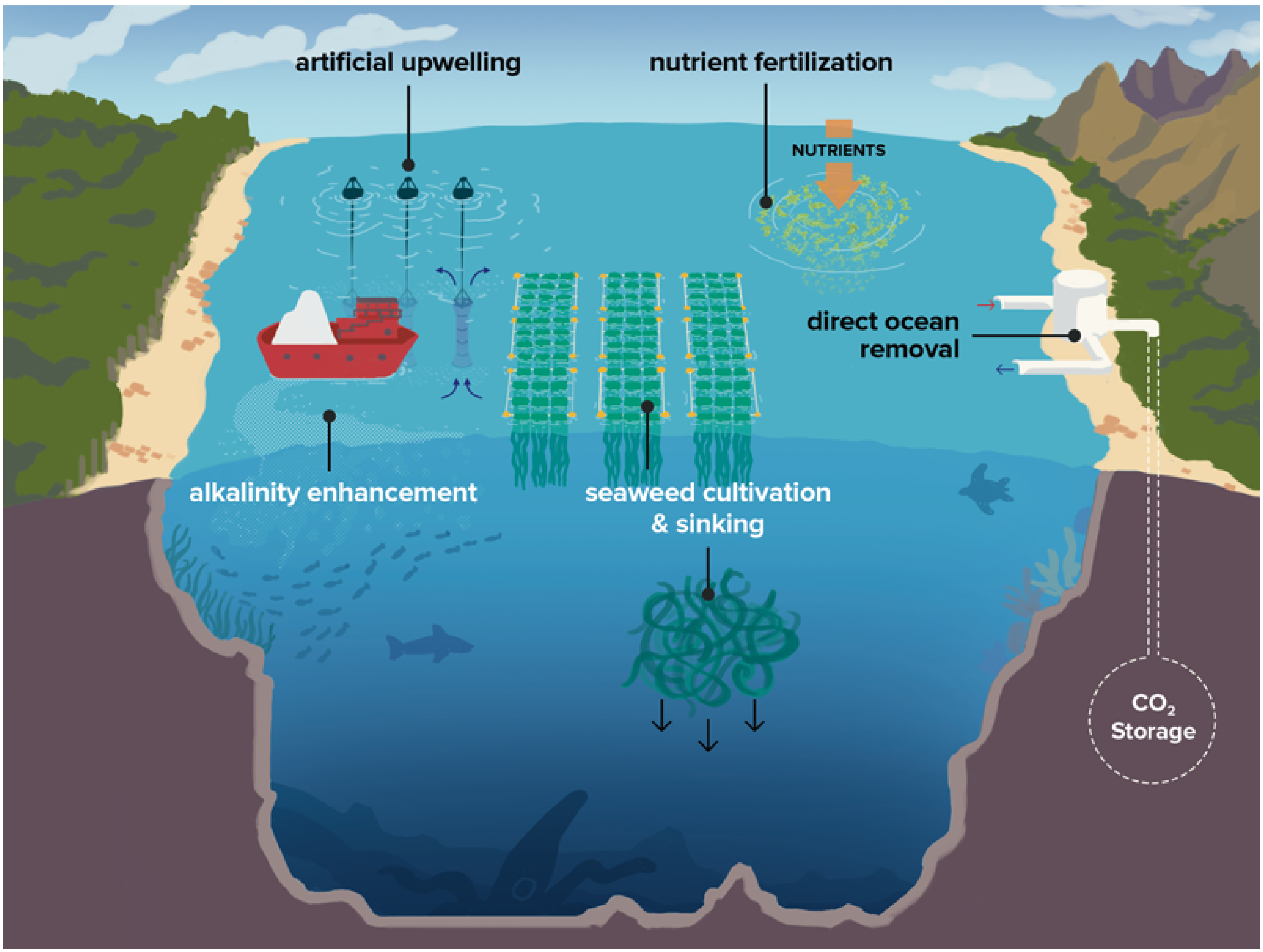

Fig. 1. Various strategies for removing carbon dioxide from seawater and sequestering it for long periods of time have been proposed, each with its own considerations, complications, and potential durabilities. Credit: Mary Heinrichs/AGU

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> *Quantifying the effectiveness and durability of marine carbon dioxide removal (mCDR) processes requires robust science for monitoring, reporting, and verification (MRV).*

Three categories of mCDR approaches—**ocean iron fertilization**, **artificial upwelling**, and **seaweed cultivation**—aim to stimulate **primary productivity** at the ocean’s surface with the expectation that some of the additional biomass produced will sink into and remain in the deep ocean. In contrast, **ocean alkalinity enhancement** (OAE) involves intentionally dispersing alkaline materials such as lime on the ocean’s surface to shift the chemical equilibrium of the seawater carbon system and thereby increase uptake of atmospheric CO_2. Still another approach proposes to remove CO_2 **directly from seawater** through electrochemical reactions and then store it underground.

Commercial, philanthropic, and government resources are increasingly being directed toward the development of these mCDR strategies, with several pilot deployments planned. But how effective might these pathways be at increasing ocean carbon uptake? Key to any carbon dioxide removal (CDR) method is that it must durably store billions of tons of CO_2 in places where it cannot easily return to the atmosphere. Quantifying the effectiveness and durability of these processes in the ocean requires robust science for monitoring, reporting, and verification.

Need for Standards and Transparency

Monitoring, reporting, and verification (MRV) refers to the multistep process of monitoring the amount of greenhouse gas removed by a CDR activity over a period of time and reporting the results of the monitoring to a third party. The third party then verifies the reporting so the results can be certified. MRV is often pursued so that a commercial entity can seek payment for removal activities in rapidly growing voluntary carbon credit markets or in smaller, regulated compliance markets established under specific governance structures.

At least half a dozen companies involved in mCDR, and more that are rapidly entering the space, are starting to market CO_2 removal services to **potential buyers interested in purchasing credits** to offset carbon emissions. To support verification of these services, there is an urgent need for methods that rigorously quantify net carbon removal rates and storage durability of different mCDR approaches.

Terrestrial CDR has given rise to many certifications, along with more than 2 dozen standards-developing organizations, yet this abundance has not consistently translated to high-quality CDR [***Arcusa and Sprenkle-Hyppolite***, 2022]. Here, “high-quality” refers to carbon removal that is both *additional*, meaning it would not have occurred without the intervention, and *durable*, meaning it is removed from the atmosphere for centuries to millennia.

Perhaps the most attention-grabbing example of attempted terrestrial CDR has been the use of **afforestation**, especially since the World Economic Forum began promoting its **1-trillion-tree project** in 2020. Despite the attention, MRV protocols for afforestation efforts lack standardization and can fail when compared with independent verification methods [*Marino et al.*, 2019].

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> ***There are presently almost no MRV standards for mCDR. This vacuum opens an opportunity for oceanographic researchers to build needed frameworks.***

Forest MRV protocols often rely on satellite monitoring supplemented by field-based tree inventory assessments to estimate changes in forest biomass. Simple models are then used to convert biomass changes into carbon storage inventories. To evaluate additionality, this carbon storage is compared to a hypothetical baseline representing the assumed trajectory of the system in the absence of intervention. But uptake of CO_2 by an afforested region is not typically measured. In the few instances where uptake has been measured directly, these analyses have revealed quantitative inconsistencies [*Marino et al.*, 2019]. Assessing durability is complicated by the difficulty of predicting wildfires and plant diseases, which can rapidly release sequestered carbon to the atmosphere [*Joppa et al.*, 2021].

With all the different approaches and organizations involved, the terrestrial CDR landscape has grown into a tangled web of **competing protocols** that lack standardization and transparency. In contrast, there are presently almost no MRV standards for mCDR. We argue that this vacuum opens an opportunity for oceanographic researchers to build needed frameworks for MRV practices with high integrity, applying lessons from both successful and problematic protocols developed in the terrestrial CDR environment [*Bach et al.*, 2023].

Inventing Applied Ocean Biogeochemistry

Many oceanographers have been reluctant to do mCDR research. They cite various fears, including that doing so will shift public and private investment away from urgently needed emissions reductions and push ocean scientists away from basic research. However, staying on the sidelines as mCDR companies begin to sell carbon credits in largely unregulated marketplaces means that the industry will move forward in the absence of much-needed expertise.

For mCDR strategies to either grow into viable and quantifiable climate mitigation tools or be dispensed with because research reveals they are ineffective, ocean scientists must step up to collaborate and codevelop MRV frameworks. In so doing, there is still room to pursue new, fundamental science and train the next generation of scientists in the emerging field of applied ocean biogeochemistry.

Evidence that some scientists are starting to take on more active roles was abundant at a **September 2022 workshop** on mCDR that was sponsored by the **Ocean Carbon & Biogeochemistry** Project Office with support from the U.S. National Science Foundation (NSF) and NASA and held at the University of Rhode Island. More than 150 ocean scientists gathered—in person and virtually—with industry, nonprofit, and government agency stakeholders to explore key requirements and challenges of establishing MRV frameworks for several widely considered mCDR methods [*National Academies of Sciences, Engineering, and Medicine*, 2022].

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One point of agreement was that the details of any MRV framework depend on which mCDR strategy is being tested. MRV for any of the methods intended to increase primary productivity would require assessments of the additional biomass created by the intervention, the fraction of that biomass exported to the deep ocean, and the timescale that its carbon would stay in the ocean interior without being mixed back to the surface where it could be released to the atmosphere.

Moreover, it would be imperative to assess whether the consumption of nutrients (e.g., nitrate, phosphate) to stimulate additional productivity would cause decreased productivity elsewhere, and whether additional oxygen consumed in the ocean interior through the respiration of the added carbon ultimately would lead to additional production of other greenhouse gases, such as nitrous oxide or methane, due to enhanced anaerobic respiration. Both decreased productivity in other locations and increased production of other greenhouse gases could partially or fully negate the benefits of these mCDR approaches.

MRV for OAE, meanwhile, would need to ensure that an intervention does in fact elevate seawater alkalinity and that the alkalinity-enhanced waters remain at the surface long enough to absorb additional atmospheric CO_2. Unlike the biologically mediated mCDR methods that rely on organic carbon remaining for centuries in the deep ocean, OAE increases the ocean’s **buffering capacity**, similar to the natural process of rock weathering, and the associated CO_2 uptake is likely to be durable on millennial timescales [***Hartmann et al.***, 2023].

It’s Time to Engage

The most emphatic point of agreement among workshop participants is that we now are within a fleeting window of opportunity to fill the MRV void for mCDR. Acting now could prevent inadequate or opaque protocols from becoming accepted defaults. Equally important, the nascent mCDR industry needs guidelines and baselines to verify whether their methods can work and therefore have value in the marketplace. Lacking such groundwork, the industry could fail to launch, eliminating or delaying promising carbon removal pathways. Or resources could be wasted through prolonged investments in techniques with little likelihood of working at scale.

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Oceanography blends knowledge from physics, biology, geology, and chemistry, and oceanographers use observations, laboratory analyses, and numerical models to create holistic understanding. Now is the time for these scientists to apply their expertise to establish best practices for the quickly growing mCDR community.

Academic research into mCDR must accelerate and be transdisciplinary, while maintaining rigor and fulfilling commitments to equity and transparency. A positive sign for the needed acceleration is that funding agencies, such as the **National Oceanographic Partnership Program** and the **U.S. Department of Energy**, are developing programs for mCDR and MRV, and new sources of funding from philanthropy, venture capital firms, and private industry are also growing swiftly.

Participants at the recent workshop rallied around several recommendations. One is that field trials following detailed protocols are needed to prove the efficacy and safety of mCDR methods. These protocols should be codesigned by expert teams, including private-company engineers along with impartial scientists, with regulatory bodies taking responsibility as knowledge matures. It's possible that coastal and island communities could be affected by mCDR—for example, via the build-out of macroalgal farms and associated ship traffic. So as part of the codesign effort, scientists should also partner with these communities to develop tools of MRV to prevent environmental degradation and fraud, and to ensure that the communities share in the benefits of mCDR actions.

Another recommendation, to further promote equity and transparency, is that data associated with MRV should be publicly available, accessible, and quality-assured. Ideally, a centralized registry of MRV protocols and outcomes from field trials should be created and indexed for easy reference, which may require surmounting issues related to intellectual property.

Ocean models will be critical tools in MRV, because many mCDR approaches will create changes that are hard, if not impossible, to observe directly in the vast, variable, and turbulent ocean. However, ocean models historically have not been built for this purpose. Adapting model simulations and related analysis tools to provide probabilistic quantifications of carbon removal with robust uncertainty budgets requires focused development aligned with that goal.

There is clearly a lot of work to be done to evaluate mCDR approaches and bring needed, internationally recognized MRV protocols to fruition. Considering the stakes, there is also a palpable urgency to do so. We urge the ocean sciences community to engage deeply in this work, whether by collecting and sharing relevant experimental or modeling data; teaching about mCDR approaches; providing expert reviews to journals, funding agencies, or private enterprises; contributing to best practices documents; or other means. With a sustained community effort, we can ensure that robust frameworks for verifying the effectiveness and safety of mCDR are developed in ways that advance the fundamental goal of helping mitigate the harms of a warming climate.

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Roger Clifton

a month ago edited

Even if it were possible to capture the excess CO2, there is no place to put that much corrosive stuff without polluting it even more than the atmosphere. As well-read scientists we have a responsibility to warn our respective communities that we are being distracted by quackery from the main game – the complete eradication of fossil fuels.

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Keith Alverson

a month ago

Sure, look into CDR scientifically, but please don't pretend that the science is, or will any time be, clear enough to sell credits. Or even that selling such credits is a good idea for combatting global warming. Terrestrial credits mostly don't work and are mostly a sham. So why would marine credits be any different. Don't fall in the trap of serving the interests of companies and governments that wish to avoid reducing emissions by buying 'credits'.

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