THE URGENT NEED FOR BILLION-TON-PER-YEAR CARBON DIOXIDE REMOVAL

Even under the most optimistic decarbonization scenarios, the world will need to remove tens of billions of tons of carbon dioxide from Earth's atmosphere in the coming decades to stay under 2 degrees Celsius of warming – a key threshold beyond which climate impacts become more severe and irreversible. While there are many proposed strategies to remove carbon dioxide from the atmosphere, one of the most promising approaches seeks to leverage the natural attributes of the ocean.

THE OCEAN: A NATURAL ALLY IN REMOVING CARBON DIOXIDE

The ocean is a natural ally in carbon dioxide removal, playing a key role in the Earth's primary mechanism for controlling carbon dioxide concentrations in the atmosphere. Since the Industrial Revolution alone, the ocean has absorbed around 30 percent of all carbon dioxide emitted on Earth. Covering over 70 percent of Earth's surface, the ocean represents the largest reservoir available for capturing carbon dioxide from the atmosphere. This natural ability to draw down carbon dioxide, combined with its vast surface area, makes the ocean a potential game-changer in the climate crisis.

STUDYING OCEAN ALKALINITY ENHANCEMENT AS A METHOD FOR CARBON DIOXIDE REMOVAL

The Yale Center for Natural Carbon Capture (YCNCC) is bringing together scientists from multiple departments on campus to study mCDR approaches that focus on the process of ocean alkalinity enhancement (OAE). Increasing alkalinity in seawater enables the ocean to pull additional carbon dioxide from the air and store it as bicarbonate ions – a natural form of carbon storage that is stable for around 10,000 years. While more research is needed into its efficacy, verification strategies, and safety, OAE holds the promise to draw down massive amounts of carbon dioxide with minimal impact on the ocean. For example, relying on OAE alone to remove all of the carbon dioxide needed by 2050 to meet climate targets would increase the concentration of carbon stored in the ocean (mostly as bicarbonate ions) by just 0.1 percent. Put another way, the ocean can play an enormous role in mitigating climate change with only negligible perturbations to the ocean itself.

REMOVING ACID FROM SEAWATER

One method of OAE being studied by YCNCC scientists involves removing acid from seawater using electrochemistry. The process works by filtering seawater through ion-selective membranes to create alkaline and acidic solutions. The alkaline solution is mixed with the seawater and returned to the ocean where it pulls carbon dioxide from the air, storing it as bicarbonate ions in the ocean.

OTHER METHODS OF OAE

Another method of OAE being studied at YCNCC is the addition of alkaline minerals – such as brucite (magnesium hydroxide) – directly to the surface of the ocean. For this approach to be effective, minerals must remain in contact with the atmosphere in the surface layer of the ocean, so understanding how particles are distributed in an energetic marine environment is key to ensuring efficacy. YCNCC scientists are also leading research on how "blue carbon" ecosystems – such as seagrass, marshes, and mangroves – can naturally release alkalinity into the ocean, which advances carbon dioxide storage and rings additional benefits such as the reduction of ocean acidity locally. For more information into natural carbon sequestration via protecting, restoring and enhancing blue carbon see YCNCC's blue carbon research brief.

ADVANCING THE FIELD OF OCEAN ALKALINITY ENHANCEMENT

YCNCC is working to address many of the critical questions around the safety, efficacy, and reliability of OAE approaches, including:

- **The behavior of alkaline particles.** How do particles behave in dynamic marine environments? What are the relevant fluid dynamics? How do ocean currents, stratification, and particle size impact carbon dioxide drawdown?
- **The dispersion of alkaline solutions.** How do alkaline solutions disperse in the ocean under various conditions and settings?
- **Biological impacts.** What is the impact of mCDR on specific marine species? How can we define safe operational bounds with regards to health and survival and assess the potential benefits to species like shellfish?
- **Advancing monitoring, reporting, and verification (MRV) tools.** What are the fit-for-purpose ocean models, sensors, and unique methodologies that will increase certainty and confidence in these technologies' ability to make a meaningful impact on climate change?

WHAT COMES NEXT?

The research being done by YCNCC scientists is fundamental to advancing the understanding of mCDR. By addressing key questions, YCNCC is informing which of these methods can be safely and effectively scaled to make a meaningful impact on the climate crisis.

ADDITIONAL READING

- National Academies of Sciences, Engineering, and Medicine, 2022: A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (https://nap.nationalacademies.org/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration).
- Yang, J.K. and M.-L. Timmermans, 2024. Assessing the effective settling of mineral particles in the ocean with application to ocean-based carbon-dioxide removal. Environmental Research Letters (https://doi.org/10.1088/1748-9326/ad2236).
- Eisaman, M. D. et al., 2023. Assessing the technical aspects of ocean-alkalinity-enhancement approaches, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, edited by: A. Oschlies, et al., Copernicus Publications, State Planet, 2-oae2023, 3 (https://doi.org/10.5194/sp-2-oae2023-3-2023).
- Eisaman Lab Publications (https://www.eisamanlab.com/publications).
- Nature: Ocean alkalinity enhancement through restoration of blue carbon ecosystems (https://www.nature.com/articles/s41893-023-01128-2).