Charting the technical landscape of marine carbon dioxide removal

Dr Nils Thonemann and Mona Delval from the University of Leiden consider the scientific and technical requirements for effective evaluation of emerging marine carbon dioxide removal (mCDR) approaches

As the world strives to meet ambitious net-zero targets, the ocean is emerging as a potential key territory in the fight against climate change. Marine environments already absorb over a quarter of anthropogenic CO2 emissions each year [(1)]; thus, scientists and innovators are currently exploring ways to actively enhance this natural sink through so-called marine carbon dioxide removal (mCDR) approaches. [(2,3)]

However, turning promise into practice requires rigorous science, reliable data, and transparent frameworks that effectively evaluate what truly works. This is the mission of the SEAO2-CDR project: a major European initiative bringing together world-leading research institutes, industry actors, and governance experts.

Within SEAO2-CDR, Core Theme 1 (CT1) serves as the scientific backbone, providing the tools to understand the technical performance, environmental impacts, and economic feasibility of mCDR approaches. By creating common assessment frameworks and next-generation monitoring tools, SEAO2-CDR's CT1 is helping evaluate the responsible paths and feasibility of deploying mCDR technologies safely, sustainably, and transparently at scale.

Technical evaluation of mCDR

Proposed mCDR approaches encompass a diverse set of techniques, ranging from enhancing ocean alkalinity and cultivating large-scale seaweed forests to stimulating plankton growth and capturing and storing carbon in marine sediments. [(2,3)] These methods vary widely in their mechanisms, scalability, and potential risks [(4)], making direct comparison challenging. SEAO2-CDR is tackling this challenge head-on by creating consistent, science-based frameworks and tools to assess the environmental and economic implications of different mCDR pathways.

The innovative Life Cycle Assessment (LCA), Techno-Economic Assessment (TEA), and Monitoring, Reporting and Verification (MRV) approaches developed through CT1 can provide holistic insights into how each performs across resource use, costs, carbon durability, and ecosystem interactions. The work is deeply collaborative and includes partnerships with active research and industry-led field experiments, ensuring that the latest real-world data from pilot trials can inform assessment frameworks while remaining independent. This approach grounds the evaluation of proposed mCDR approaches in reality, rather than in idealised projections.

Quantifying potential and reducing uncertainty

Current estimates of how much atmospheric CO_2 can be removed via ocean-based methods differ by orders of magnitude. Costs and environmental side effects are also uncertain, partly because most technologies are still in early development stages. To address this, SEAO2-CDR is conducting prospective LCA and TEA analyses, which assess potential impacts and costs before full-scale deployment. [4,5]

By integrating experimental and industry data with realistic deployment scenarios, the team is defining the "operational space" of each mCDR approach, the conditions under which it could be technically, environmentally, and economically viable. This involves:

- Mapping material and energy flows to understand resource demands and potential bottlenecks. [4]
- Quantifying carbon sequestration efficiency and durability, including the risks of re-emission.
- Identifying environmental trade-offs, such as potential impacts on nutrient cycling, ocean acidification, or biodiversity. [6]
- Estimating deployment costs and evaluating uncertainty for various technologies, from pilot to commercial scale. [7]

These analyses are providing an essential evidence base for comparing different mCDR methods on a level playing field. They are improving our understanding of where further innovation or policy support could make the greatest difference.

Building tools for transparency

Accurate MRV is vital to any credible carbon removal approach. Unlike land-based methods, however, ocean systems are complex, dynamic, and challenging to monitor. Quantifying how much carbon has been captured and how long it will stay sequestered consequently poses a significant challenge.

SEAO2-CDR is advancing our ability to conduct reliable MRV by testing innovative sensor systems capable of measuring dissolved carbon, alkalinity, and nutrient concentrations in seawater. These autonomous 'lab-on-chip' systems operate with high precision (8) and have the potential to provide real-time in-situ observations from a variety of mCDR sites over extended periods, thereby supporting more trusted carbon accounting. Numerical modelling systems are also being developed that allow a comprehensive investigation of efficient observing strategies for reliable MRV.

These improved capabilities and understanding of how to provide accurate, transparent data from sites of mCDR implementation are essential for facilitating regulatory assessments, supporting public confidence, and, where appropriate, enabling the future participation of mCDR activities in carbon markets.

From data to decision-making

The scientific and technical evaluations and advancements being delivered through CT1 do not stand alone. They are designed to feed into the project's other two Core Themes, creating a seamless flow of knowledge from lab to law to policy. Core Theme 2 builds upon CT1's findings to design governance and ethical frameworks that ensure the responsible implementation of ocean- based carbon removal. Core Theme 3 uses the technical and economic data from CT1 to parameterise Integrated Assessment Models (IAMs), which explore system-level trade-offs and inform policy and investment decisions.

As SEAO2-CDR progresses, these interconnected themes will continue to be integrated, providing the frameworks tools, and mechanisms needed to ensure effective evaluation and assessment of environmentally safe, socially acceptable, and economically viable marine carbon dioxide removal.

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