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Marine carbon dioxide removal: scientific foundations and implementation priorities

Antaeres Antoniuk-Pablant and Erica Belmont

Hybrid Decarbonization, Carbon Direct, 17 State Street, New York, NY, US

Editorial

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Corresponding author:
Antaeres Antoniuk-Pablant;
Email: apablant@carbon-direct.com

Marine carbon dioxide removal (mCDR) pathways are emerging as a promising approach for achieving large-scale, durable carbon sequestration. As carbon dioxide removal (CDR) becomes increasingly central to achieving net-zero targets by 2050, growing attention is being directed toward leveraging the ocean's natural capacity as a vast and ancient carbon sink. Natural ocean processes have absorbed about 25% of anthropogenic CO_2 emissions and currently sequester around 2.9 $GtCO_2$ per year (DeViers et al., 2023; Doney et al., 2025). This capacity highlights the ocean's current and future potential to support climate mitigation. One mCDR method alone, ocean alkalinity enhancement (OAE), could theoretically remove 10–30 $GtCO_2$ annually (Cross et al., 2023; Oschlies et al., 2023). The permanence of mCDR storage ranges from centuries to millennia, depending on the approach (Oschlies et al., 2025). Some mCDR pathways have already reached meaningful technical readiness levels of approximately 5–6, demonstrating early promise and technical feasibility. To maintain momentum in the mCDR field, it is essential to pursue multiple priorities in a coordinated and sustained manner.

The mCDR field encompasses a broad spectrum of approaches and technologies, spanning nature-based (biotic) solutions and engineered (abiotic) pathways. Biotic approaches enhance photosynthetic carbon fixation and result in additional carbon storage either as oceanic biomass or as increased organic carbon sequestration in ocean sediments. These nature-based approaches include methods, such as macroalgae and microalgae cultivation, ocean iron fertilization and blue carbon restoration. Biotic approaches offer varying levels of carbon storage permanence ranging from 10 to >1,000 years (Cross et al., 2023). Abiotic methods manipulate seawater chemistry to ultimately increase its capacity to absorb and remove atmospheric CO_2 (Lebling, 2022). These engineered approaches encompass pathways such as ocean alkalinity enhancement (OAE) and direct ocean removal (DOR). Abiotic techniques offer the ability to store carbon for >10,000 years and have the potential to mitigate ocean acidification locally (Cross et al., 2023).

Current state of mCDR and actions needed to advance the field within a systemic paradox. Advancing mCDR pathways toward deployment at scales that can mitigate climate change requires demonstrating that these technologies can operate in ways that are verifiably environmentally safe and can remove carbon in rigorously quantifiable ways. For successful demonstration, data from in-ocean testing are required to further develop and validate MRV and eMRV methods; however, to conduct in ocean testing, it is necessary for projects to have secured a social license to operate and sufficient funding. This situation creates a foundational paradox: evidence from early-stage deployments is necessary to build the methodologies and tools, financial confidence, social license and regulatory certainty needed to unlock those same deployments. Currently, multiple projects are progressing to the pilot stage, several have achieved pilot scale, and some commercial-scale deployments are anticipated by 2030; however, many mCDR projects struggle to achieve field trials or pilot scale due to this paradox. Despite these challenges, standardized protocols for mCDR and connected fields are being considered and are currently in development by certain registries. Regulatory pathways for permitting select projects are already available through the (US Environmental Protection Agency, 2025). Advancing mCDR technologies will require a strong emphasis on developing MRV and eMRV methods, tools and standardized protocols, along with robust demonstrations of environmental integrity.

Mesocosm and in-ocean studies conducted at appropriate spatial and temporal scales are essential for validating individual mCDR pathways. The data generated from these tests are crucial for accurately quantifying carbon sequestration and deepening our understanding of ecosystem responses. To ensure the integrity of these studies, rigorous pre-deployment assessments and adaptive monitoring frameworks will be required, with the capacity to detect and respond to any unintended consequences. The data generated must be supported by transparent, accessible and openly shared frameworks to ensure credibility, collective progress and social acceptance. These efforts should be driven not only by the mCDR research community but also developed in close collaboration with industry, stakeholders and coastal communities, whose active engagement is essential for long-term success.

Continued development and validation of carbon MRV systems and standardized protocols is critical for scaling mCDR technologies. The ocean encompasses dynamic chemical, physical and biological processes, which have inherent uncertainties. The intrinsic nature of mCDR, which uses these open and vast systems, adds significant complexity to carbon MRV. To achieve precise attribution and quantification of net CO_2 removal from mCDR activities requires high-resolution modeling combined with in-ocean monitoring (Cross et al., 2023; Ho et al., 2023). Data from in-ocean monitoring are essential for developing, refining and validating models and for strengthening confidence in accurate carbon accounting. In addition, the data will be crucial for understanding and addressing key uncertainties.

Robust and standardized eMRV methodologies are critical priorities. In addition to the unique ecosystems it contains, the ocean plays a foundational role in marine industries and the livelihoods of coastal communities. Close scrutiny of the environmental safety and ecological compatibility of mCDR interventions is essential for the development of a sustainable CDR pathway. A thorough understanding of ecological outcomes is essential to advancing regulatory approval and earning a social license to operate. The methodologies and tools for monitoring oceanic ecosystem health are currently in development, aiming to establish consistent and reliable indicators of environmental performance across mCDR projects. Once more, due to the complex and dynamic nature of the ocean, data from mesocosm and in-ocean testing are essential to understand and evaluate the potential impacts of mCDR activities.

Advancing mCDR technologies requires robust scientific data, clear frameworks, and interdisciplinary collaboration to understand and unlock their potential and ensure environmental integrity. The ocean offers vast carbon removal potential and provides vital ecological, social and economic functions. As mCDR technologies mature and our understanding deepens, supporting early-stage mCDR efforts is essential to unlocking their full promise. Continued investment and responsible deployment will ensure that mCDR pathways develop with the integrity and momentum needed to make a lasting, positive impact.

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