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THE NEED TO EXPLORE THE POTENTIAL OF MARINE CDR WITH A ONE-EARTH STRATEGY: A GUIDE FOR POLICY-MAKERS

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EXECUTIVE SUMMARY

Rapid, deep and sustained reductions in carbon dioxide (CO_2) emissions are essential to achieve the goals of the Paris Climate Agreement of keeping the long-term global average surface temperature increase well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C[1]. In addition, the 2021 IPCC Report explains that carbon dioxide removal (CDR) will be needed to offset residual CO_2 emissions from activities and sectors that are difficult to decarbonize by 2050. The objective of CDR is removal of atmospheric CO_2 from residual emissions and its durable storage in reservoirs, which is an additional critical element towards achieving carbon neutrality by 2050 and thereby ensure less than 2°C global warming.

The annual estimates of CDR required in 2030 and by 2050 are 3.6 Gt and 9.4 Gt, respectively, leaving a CDR gap of 1 Gt by 2030 and 6.8 Gt by 2050 relative to the expected CDR from conventional land-based methods of 2.6 Gt per year by 2030. How much of this gap can be filled sustainably by land-based CDR is unknown. Novel CDR methods include direct air carbon capture and storage (DACCS), biochar, and various marine approaches. Although these novel methods currently account for <0.1% of CDR worldwide, many are being tested through model simulations and small-scale pilot projects. The ocean plays a critical role in regulating Earth's climate, and marine CDR (mCDR) offers substantial untapped opportunities that have so far been overlooked. Modeling indicates that several mCDR methods could scale to a billion tonnes annually, but their potential ecological side-effects are poorly known. Exploration of the potential of safe, durable and verifiable mCDR and its scalability within sustainability limits is urgently required, even though the process of testing, refining, verifying, and scaling mCDR will take at least a decade.

Time is short, and policymakers must therefore prioritize an ambitious timeline to deliver safe, sustainable, durable, and verifiable mCDR solutions that can potentially scale in parallel with land-based efforts, together with a regulatory framework for deployment.

KEY MESSAGES

- Carbon dioxide removal (CDR) is essential for addressing hard-to-abate, residual emissions and reducing atmospheric CO_2. Achieving the billion-tonne CDR target demands a holistic approach that considers both land and ocean.
- CDR that utilizes land and ocean (One-Earth CDR) is critical as all CDR methods face a reduced efficiency – termed "CDR tax" – due to negative feedbacks from the Earth System.

[1] Paris Agreement to the United Nations Framework Convention on Climate Change, T.I.A.S. No. 16-1104, 12 Dec. 2015, https://unfccc.int/sites/default/files/english_paris_agreement.pdf

- The potential magnitude of One-Earth CDR also serves as a buffer against side-effects related to all methods. It can counter the present over-reliance on land-based CDR, which faces challenges such as mega-fires and sustainability limits (e.g., land and water use).
- Given the size, depth and diverse carbon cycle of the ocean, innovative marine CDR (mCDR) has a large potential for carbon storage.
- Proving the effectiveness and safety of mCDR will likely take at least a decade. Ensuring its integrity is crucial for verifiable CDR. Before large-scale deployment, knowledge gaps must be addressed, including risks, sustainability, scalability, cost, permanence, side effects, monitoring, social acceptance, and governance.

1. THE NEED FOR ONE-EARTH CDR ACROSS ALL RESERVOIRS

Between 2013 and 2022, human activities released an average of 40 Gt of carbon dioxide (CO_2) annually (Friedlingstein et al., 2023). During this time, natural land and ocean sinks absorbed 12.1 Gt and 10.3 Gt of CO_2 per year, respectively. To achieve the Paris Agreement goal of limiting global warming to well below 2.0°C, emissions must be rapidly, deeply, and sustainably reduced. However, certain sectors that are difficult to fully decarbonize will continue to emit CO_2, requiring offsetting through carbon dioxide removal (CDR) (Arias et al., 2021). Without CDR, residual emissions would drive continued warming, with catastrophic consequences. Therefore, CDR is an essential element in all pathways compatible with the Paris Agreement. Importantly, CDR cannot substitute for insufficient emissions reductions; failure to cut emissions adequately would risk surpassing the 1.5°C threshold, exacerbating the climate crisis (Schleussner et al., 2024).

Over the 21st century, the projected CDR requirement ranges from 100-1,000 Gt CO_2 (Lamb et al., 2024). The annual requirement will be 3.6 and 9.4 Gt in 2030 and by 2050, respectively, leaving gaps of 1 and 6.8 Gt relative to the expected CDR from conventional land-based methods of 2.6 Gt per year by 2030 (Smith et al., 2024). However, priority must be given to reducing greenhouse gas (GHG) emission, and one scenario calls for a 40% reduction in gross GHG emissions from 2020 levels by 2030 and a 77% reduction by 2050 (Lamb et al., 2024).

The Earth's carbon cycle intricately links the land, ocean, and atmosphere, creating feedback mechanisms that balance carbon fluxes across these reservoirs. Human-induced CO_2 emissions have driven natural land and ocean sinks to absorb about a quarter and a third of anthropogenic CO_2 since 1750, respectively, accounting for 50% of total emissions (Friedlingstein et al., 2023). As CDR lowers atmospheric CO_2 levels, it would trigger compensatory CO_2 releases from land and ocean systems (Figure 1), potentially offsetting more than a quarter of the amount removed by CDR (Jeltsch-Thömmes et al., 2024). This compensatory, negative Earth-System feedback effect is called here "CDR tax".

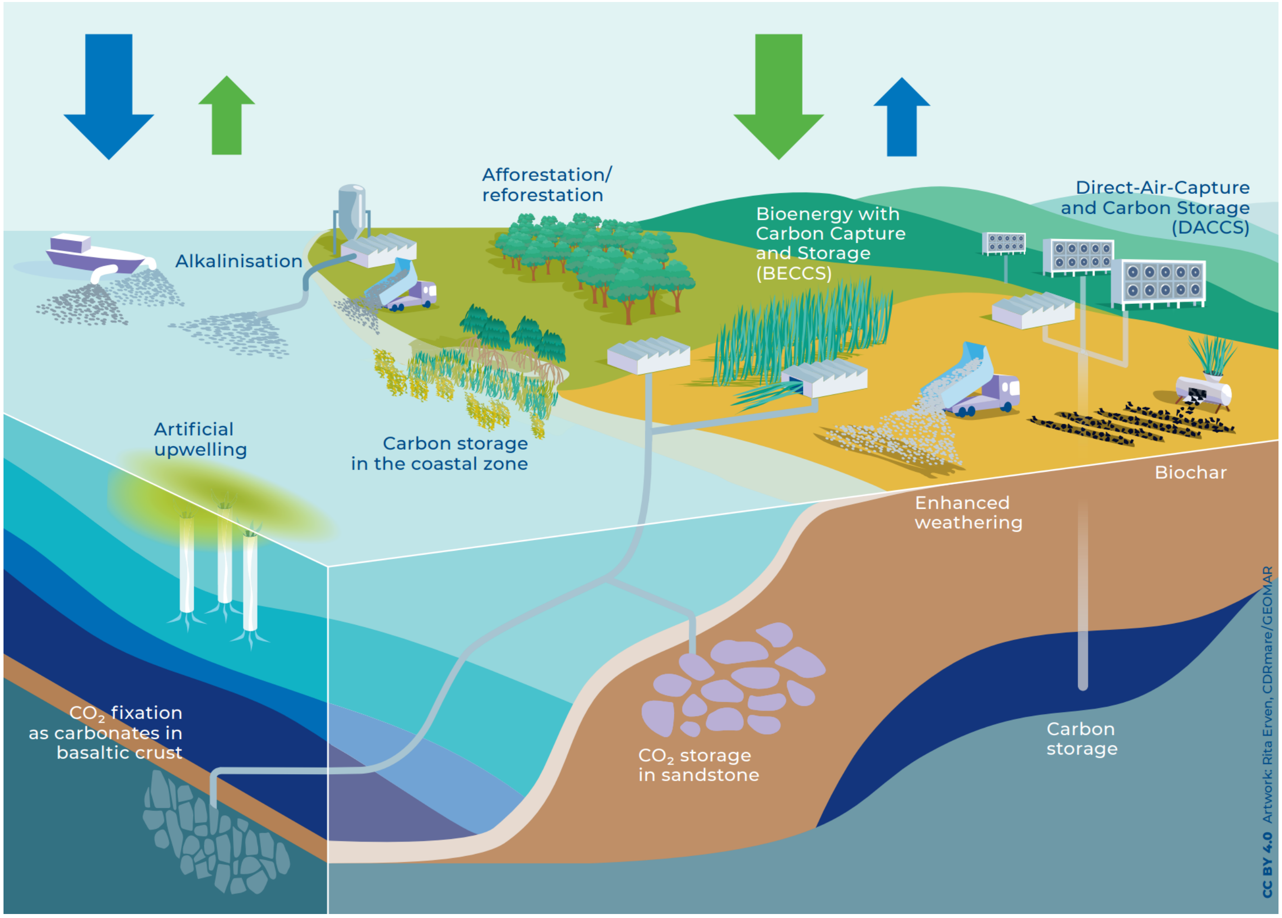

Figure 1: Examples of methods for land-based CDR and mCDR. These methods include techniques that are both conventional (e.g. afforestation) and novel (e.g. DACCS, or ocean chemically-based CDR such as alkalinisation, i.e., accelerated chemical weathering of natural minerals). The blue and green arrows indicate the effect of an individual CDR method on moving stored anthropogenic carbon between reservoirs. The green arrows denote land-based CDR removing CO_2 (downward arrow) but causing the ocean to release some of the anthropogenic CO_2 it stores (upwards arrow). The blue arrows represent mCDR removing CO_2 (downward arrow) but resulting in the land reservoir releasing some of its stored anthropogenic CO_2 (upwards arrow). When both land-based and mCDR (termed One-Earth CDR, Boyd et al., submitted) are deployed, it also results in compensatory CO_2 release from ocean and land reservoirs. The compensatory negative Earth-System feedback is called here "CDR tax". Artwork: Rita Erven, CDRmare/GEOMAR.

2. BENEFITS AND LIMITATIONS OF CDR APPROACHES

The only way to meet the billion-tonne CDR target is to extend the deployment at scale of CDR beyond land to the ocean, i.e. to use the One-Earth CDR approach (Boyd et al., submitted). Because of the Earth System feedbacks and the resulting CDR tax (Figure 1) along with limitations examined below, terrestrial CDR alone cannot remove billions of tonnes of CO2 annually. In addition, a diverse portfolio that includes mCDR provides an 'insurance policy' against potential feedbacks that can decrease land-based CDR sinks. Feedbacks such as megafires (Byrne et al., 2024) can rapidly wipe out decades of CDR efforts.

2.1. Land-based CDR

Land constitutes 29% of the Earth's surface, of which 76% is habitable (excluding glaciers, deserts, dunes, and mountains). Within this habitable land, 45% is used for agriculture (mainly livestock-related activities), with less allocated to crops. The rest is primarily forested (38%) or covered by grasses and shrublands (13%). Thus, land availability for CDR is limited, which could lead to geopolitical or other conflicts if CDR demands increase (Kato and Yamagata, 2014). Additionally, CDR expansion could strain other resources like water and potentially breach sustainability thresholds, such as food security. Sustainability limits are not considered by current estimates of land-based CDR (Deprez et al., 2024). These challenges are exacerbated by growing exposure to climate extremes (e.g., droughts). Side-effects of large-scale land-based CDR, including changes in surface albedo (i.e., reflectance of solar energy), are often underestimated (Dooley et al., 2024). The limitations around this finite resource make it clear that land-based approaches cannot solely deliver all of the CDR needed.

2.2. Marine CDR

The ocean is a promising venue for CDR to complement land-based approaches (Ho and Bopp ,2024). Covering ~70% of the Earth's surface and accounting for 97% of the planet's water, the ocean has a massive potential for CDR through physical, chemical, and/or biological pathways. Already sequestering ∼25% of anthropogenic emissions, the ocean's carbonate chemistry provides a natural "lockbox" for permanent CO_2 removal through CDR approaches such as alkalinisation (Figure 1). Indeed, as CO_2 dissolves in the ocean, it reacts with water molecules to form bicarbonate and carbonate ions, which cannot degas to the atmosphere and thus lock carbon in the ocean. Models project that several marine CDR (mCDR) methods, including alkalinisation (Keller et al., 2014) and ocean iron fertilization (OIF) (Tagliabue et al., 2023) might be capable of scaling to billions of tonnes of CO_2. The ocean's characteristics make it a critical, yet underexplored, component of the global climate solution, although no mCDR approach is ready for deployment at scale (Doney et al., 2024).

3. MANAGING mCDR ACROSS MULTI-USE OCEANS - A ROLE FOR BASIN-SCALE ZONED MANAGEMENT

The ocean, while less occupied than land, is also a multi-use space. It is a globally shared resource, with ~61% of the ocean comprising the so-called “high seas,” which do not fall under the authority of any nation but are open to use by all in accordance with international law. Coastal countries have authority over the remaining ~39% of the ocean (Englander, 2019). These waters have diverse uses, including marine protected areas, fisheries, aquaculture, offshore wind farms, mineral extraction, transportation, and recreation. Implementing mCDR must therefore consider potential conflicts with existing or planned uses, which differ in coastal, shelf and offshore environments. For instance, large-scale macroalgal cultivation in nearshore waters followed by deliberate sinking of biomass in deep waters could compete for space with aquaculture for food production, and require additional shipping for harvesting and transportation that could disrupt local maritime activities. Offshore, mCDR approaches like OIF may deplete macronutrients causing a "nutrient robbing" effect that could reduce fisheries productivity elsewhere (Tagliabue et al., 2023).

To integrate mCDR into such heavily utilized environments, and mitigate the potential for adverse ecological, economic and social impacts, spatial planning at the ocean-basin scale in the framework of ecosystem-based integrated management will be essential. This could include zoning coastal areas for mariculture, designating offshore zones for mCDR methods with co-benefits (e.g., alkalinisation to counteract acidification), and avoiding overlap zones. Such strategic resource management provides a further criterion for selecting mCDR approaches that align with sustainable ocean use. The dynamic nature of ocean circulation spreads the water ‘parcels’ in which CDR has taken place, making it difficult to track the efficacy of mCDR, monitor ecological side-effects, or to prevent dispersal into multi-use areas especially nearshore (Boyd et al., 2023b).

3.1. Governance

The shared nature of the ocean makes governance challenging. A large body of international law governs ocean-based activities, and those activities may (depending on location) also be subject to regional, national, and/or subnational laws. International law on mCDR is under-developed, with no binding international agreements specifically or comprehensively addressing the practice. The Paris Agreement[1] implicitly supports the use of mCDR as one means of (partially) mitigating climate change (Honegger et al., 2021). It directs parties to reduce GHG emissions and conserve and enhance GHG “sinks” (i.e., defined broadly to include any process or activity that removes atmospheric GHG). The parties have recently emphasised the importance of “marine ecosystems” as GHG sinks and called for “accelerating removals” (UNFCCC 2023), but have not adopted a comprehensive governance framework for mCDR activities.

Other international regimes – most notably the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter (London Convention, LC) and 1996 Protocol to that Convention (London Protocol, LP) – have considered the issue. In a series of non-binding resolutions and statements, the parties to the LC and LP have indicated that some mCDR activities involving "legitimate scientific research" may be allowed, but deployments should be deferred[2]. This approach was codified in a 2013 amendment to the LP, but that amendment only applies to OIF and has yet to enter into force. There have been proposals to regulate additional mCDR activities, including ocean alkalinity enhancement, under the 2013 amendment, but the Parties are still discussing those proposals.

Moving forward, the recently adopted Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) could provide a framework for governing mCDR activities in areas beyond national jurisdiction or affecting them. Among other things, the BBNJ Agreement provides for the establishment of area-based management tools, which could be used to control where and how mCDR activities take place, and manage conflicts with other ocean uses (Scott, 2022; Webb, 2024). The BBNJ Agreement is, however, yet to enter into force.

3.2. Social Acceptance

A key element of social acceptance for CDR depends upon recognition of the diverse uses of coastal areas, along with the livelihoods and rights of local communities, including Indigenous rights when considering the need for nearshore space. Research and decision protocols will need to be widely shared across countries given varying stages of interest and development. It is important to be transparent about the full life cycle of mCDR methods, such as alkalinisation, which may involve preparatory 'upstream' activities such as mining. These activities may be perceived by different social groups as either beneficial or harmful. Trust must be maintained or built into the monitoring and fate of mCDR approaches from surface waters to depth where ecosystems are fragile and poorly known. It is essential to provide evidence that mCDR efforts do not hinder broader decarbonization goals (termed mitigation deterrence) or enable continued reliance on fossil fuels. Tailored research is needed to address environmental risks associated with mCDR, including impacts on chemistry, ecosystems, fisheries, and underwater noise. Additionally, the development of programmes that assess community impacts, risks, and benefits is necessary.

There is also a need for capacity building and sharing of expertise. Indeed, current mCDR activities are led by nations that have invested in research, and it is difficult for others to participate in the rapidly developing activities. Summer schools and other knowledge dissemination and training activities should be organized.

[2] International Maritime Organization, 45th Consultative Meeting of Contracting Parties to the London Convention and the 18th Meeting of Contracting Parties to the London Protocol (LC 45 / LP 18, Marine Geoengineering – Statement, https ://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/LC-45-LP-18.aspx (last visited 19 Jan. 2025).

4. NEXT STEPS FOR mCDR

4.1. Integrity

The integrity of mCDR in producing verifiable carbon removal is influenced by scientific understanding, technological maturity, scalability, cost effectiveness, permanence, side effects, monitoring, reporting and verification (MRV), social acceptance as well as quality of governance and policy. Each factor has knowledge gaps that should be filled promptly. Permanence is essential: for CDR to have a long-term effect on the climate, the CO_2 storage period should be long, e.g. at least 1,000 years (Brunner et al., 2024).

4.2. Sustainability

Land- and ocean-based CDR must consider socio-ecological limits and the need to identify viable pathways to the 1.5°C warming threshold that do not overstep sustainability thresholds associated with CDR such as land or water use in the terrestrial biosphere. CDR governance should consider the need for sustainable characteristics of deployments – such as the areal extent of the CDR method.

4.3. Governance

Past efforts to establish governance frameworks, such as the 2013 Amendment to the London Protocol, have focused exclusively on mCDR research. The frameworks established for research projects are incomplete and have proved difficult to apply. There has been no consideration of the process and requirements for moving beyond research to deployments. It follows that new decision-making frameworks are needed. They should ensure an inclusive approach that appropriately balances both the potential benefits and harms of different mCDR activities, and establish clear rules for MRV and decommissioning of projects.

4.4. Social Acceptability

Socially suitable sites of deployment and impact require early engagement with rights holders and stakeholders, awareness of competing or nearby uses (e.g., marine protected areas) downstream of mCDR deployments, and an understanding of perceived risks and benefits for local communities. Robust decision-making and engagement should clearly outline objectives, potential impacts, and alternatives for deployment, along with responsibilities for funding, emergency preparedness, and fail-safe conditions. Impact and benefit agreements can facilitate community consent, while independent advisory bodies may help build trust.

4.5. Transparency

The location, approach and results of mCDR research activities must be shared transparently, irrespective of outcome. We advocate a public registry for field experiments, and recommend that project be designed to answer scientific questions, be peer reviewed and be transparent. Research projects must not be influenced by economic interests and should be designed to avoid, minimize, or mitigate adverse environmental impacts. The same should be true for future mCDR deployments.

4.6. Urgency

The science and governance of mCDR needs to be propelled ahead of the industry. Time is short and a shortfall of CDR of 1 Gt CO_2 is projected within six years (see above). CDR spin-up times at the million-tonne scale (and beyond) must factor in exploratory studies, their appraisal for the above desired characteristics and checks/balances, third party MRV, upscaling, and assessment of associated changes to the characteristics of the mCDR approach being assessed (such as scale-dependencies for side-effects, MRV, governance). Based on the spin-up time of other technologies operated at the basin-scale, such as those for offshore renewable energy, that for mCDR will be decadal (Boyd et al., 2023a). Even with international support and action now, this will mean that no proven scalable (i.e., billion tonne) mCDR would be available until at least 2035.

References

Arias *et al.* (2021). Technical Summary in *Climate Change 2021 – The Physical Science Basis.* https://doi.org/10.1017/9781009157896.002

Boyd *et al.* (2023a). *Nature.* https://doi.org/10.1038/d41586-023-02649-8

Boyd *et al.* (2023b). *Oceanography.* https://doi.org/10.5670/oceanog.2023.s1.2

Boyd et al. (submitted). Effective Carbon Dioxide Removal requires a One-Earth approach.

Brunner *et al.* (2024). *Communications Earth & Environment*. http://doi.org/10.1038/s43247-024-01808-7

Byrne *et al.* (2024). *Nature*. http://doi.org/10.1038/s41586-024-07878-z

Deprez *et al.* (2024). *Science*. https://doi.org/10.1126/science.adj6171

Doney *et al.* (2024). *Annual Reviews of Marine Science*. https://doi.org/10.1146/annurev-marine-040523014702

Dooley *et al.* (2024). *One Earth*. https://doi.org/10.1016/j.oneear.2024.08.009

Englander (2019). *Nature Sustainability*. http://doi.org/10.1038/s41893-019-0389-9

Friedlingstein *et al.* (2023). *Earth System Science Data*. http://doi.org/10.5194/essd-15-5301-2023

Ho and Bopp (2024). *Dialogues on Climate Change*. https://doi.org/10.1177/29768659241293223

Honegger *et al.* (2021). *Review of European, Comparative and International Law.* https://doi.org/10.1111/reel.12401

Jeltsch-Thömmes *et al.* (2024). *Environmental Research Letters*. http://dx.doi.org/10.1088/1748-9326/ad4401

Kato. & Yamagata (2014). *Earth's Future*. http://doi.org/10.1002/2014ef000249

Keller *et al.* (2014). *Nature Communications*. https://doi.org/10.1038/ncomms4304

Lamb *et al.* (2024). *Nature Climate Change*. http://doi.org/10.1038/s41558-024-01984-6

Oschlies et al. (2025). *Frontiers in Climate*. https://doi.org/10.3389/fclim.2024.1506181

Pongratz *et al.* (2024). Chapter 7 in *The State of Carbon Dioxide Removal 2024* – 2nd Edition. https://doi.org/10.17605/OSF.IO/ ZXSKB

Scott (2022). *The BBNJ Agreement: Strengthening the Oceans-Climate Nexus?* https://doi.org/10.1163/9789004518629_026

Schleussner *et al.* (2024). *Nature*. https://doi.org/10.1038/s41586-024-08020-9

UNFCCC (2023). *Draft Decision -/CMA.5: Outcome of the First Global Stocktake*, FCCC/PA/CMA/2023/L.17.

Smith, *et al.* (2024). *The State of Carbon Dioxide Removal 2024* - 2nd Edition. https://doi.org/10.17605/OSF.IO/F85QJ

Tagliabue *et al.* (2023). *Global Change Biology*, https://doi.org/10.1111/gcb.16854

Webb (2024). *International Governance of Ocean-based Carbon Dioxide Removal: Recent Developments and Future Directions*. https://scholarship.law.columbia.edu/sabin_climate_change/216/