Future changes in the carbon cycle from deliberate ocean-based climate interventions

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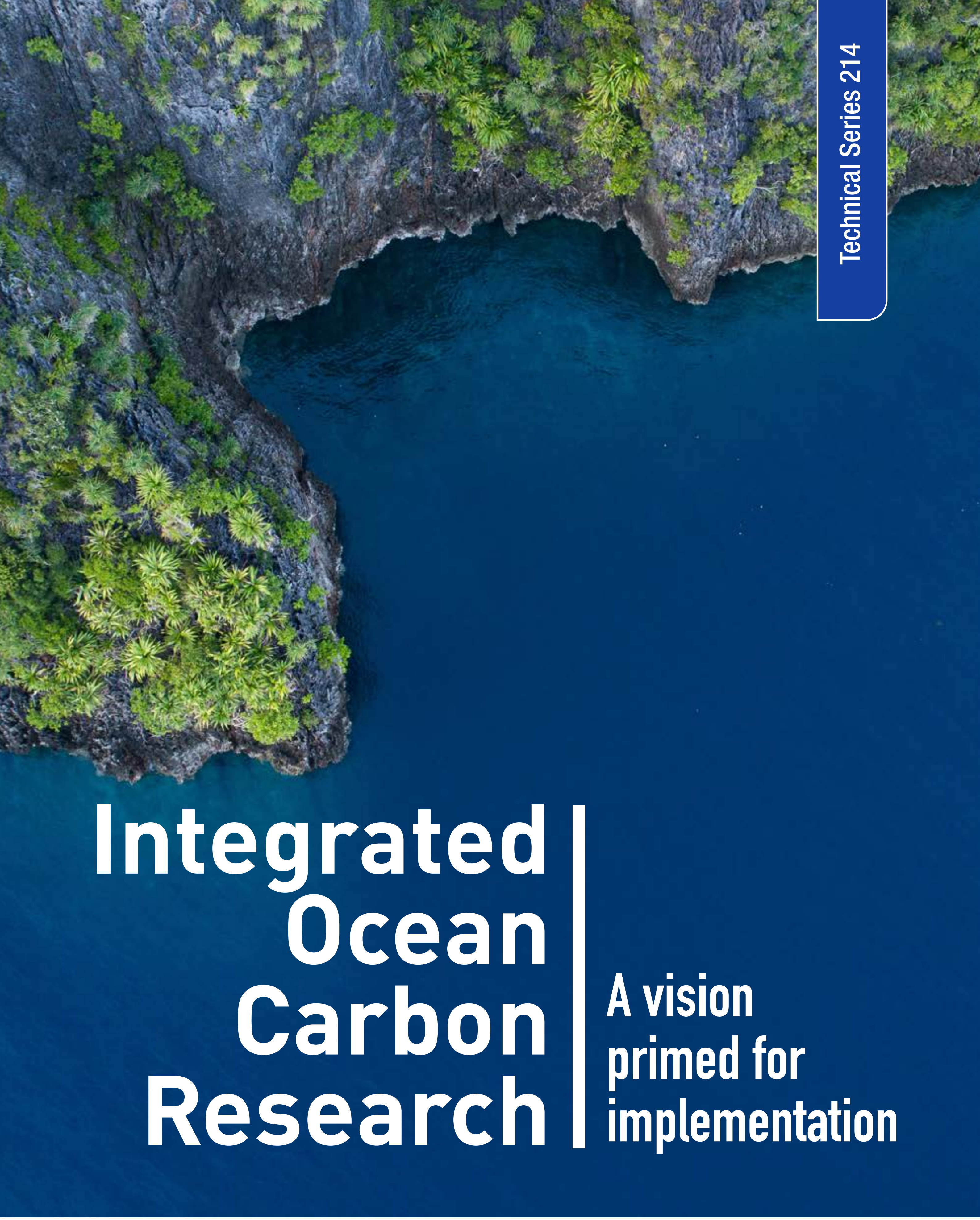

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Integrated Ocean Carbon Research

A vision primed for implementation

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7. **Future trajectories of plastics production**, waste generation and the proportion that accumulates in the surface ocean, throughout the water column, and at the seafloor.
8. **The current and future impacts of plastics** upon critical ocean functions including carbon cycling, particle sinking rates, microbial ecology and fisheries productivity.

Actions to be taken

I. **Generate information on the key processes within the biological pump** (such as grazing, particle sinking, remineralization and plankton mortality), that are likely to be impacted by industrial extraction and the addition and degradation of plastics. Multiple approaches to address this can be envisaged ranging from in vitro incubations (Geisen et al., 2022), mesocosm studies (e.g. Lagaria et al., 2017) and *in situ* studies potentially around mine tailing discharge (e.g. Ramirez-Llodra et al., 2022) as an analogue for deep sea mining discharges.

II. **Quantify the lability and bioavailability of material released from the seabed during industrial activities and that produced through photodegradation of plastics.** Studies to address this should take place at a range of scales, from bottle incubations, through to *in situ* studies along trophic gradients (e.g. Pusceddu et al., 2005) and large scale meta analyses / modelling (e.g. Zhang et al., 2024).

III. **Improve knowledge on the resilience of carbon sequestration** to distortions / reorganisations of food webs by fisheries.

IV. **Undertake coherent and targeted research on the effects of fishing, industrial processes (including wind farms) and plastic pollution** on plankton ecology and biogeochemistry in a range of settings, including the continental shelves.

V. **Improve numerical models to receive, use and generate new information**: many of the models that we currently use to predict the future evolution of climate contain simplified representations of the ecosystem that do not consider or parameterise explicitly the key processes (such as photochemistry and competition between bacteria and phytoplankton for nutrients), taxa and functional groups that will be impacted by human activity in the ocean.

VI. **Adapt fishery ecosystem models to provide explicit knowledge about the consequences of removing large numbers of fish**, e.g. reduced deadfall and defecation flux. This problem is much more difficult for the shelf than for the off-shelf seas, and effort should be focussed there.

VII. **Develop regionally focussed ocean system pathways to drive numerical models**, informed by representative stakeholder consultations encompassing both the groups that regulate human activities in the ocean and those that seek to undertake these actions for profit.

3.e Future changes in the carbon cycle from deliberate ocean-based climate interventions

Phillip Williamson, Nina Bednaršek, Jean-Pierre Gattuso, Nianzhi Jiao, Robert C. Steenkamp, Erik van Doorn, Philip W. Boyd

There are two main groups of ocean-based climate interventions: those aiming to reduce atmospheric CO_2 (mCDR; **Figure 8**); and those intended to reflect sunlight (solar radiation management, SRM). Whilst ocean-based SRM methods (e.g. marine cloud brightening and sea-surface foams) are likely to impact ocean ecosystems, and therefore the carbon cycle, such effects would be indirect, through changes in light availability, temperature, and ocean mixing. SRM approaches are therefore not considered further here.

Climatically-meaningful mCDR (i.e. at Gt scale) would necessarily change the carbon cycle: that is its purpose. However, many marine processes can be used for initially capturing carbon, with many different pathways for the subsequent fate of captured carbon. As a result, there is high method-specificity for carbon-related consequences, and for other environmental impacts, scalability, and storage durability. These factors affect acceptability and cost, hence the likelihood of implementation.

Biologically-based mCDR approaches include:

- *Coastal blue carbon*: the restoration of mangrove, saltmarsh and seagrass ecosystems that accumulate organic carbon in their sediments.
- *Large-scale seaweed cultivation* (also known as ocean afforestation), with either deep-sea sinking of macro-

algal biomass (with impacts on benthic ecosystems and seafloor pH and O_2) or its removal to land for processing into biofuel (with carbon capture and storage) or biochar.

- *Ocean fertilization* to increase phytoplankton productivity and subsequent deep-water carbon sequestration through the biological pump. Fertilization can be achieved by directly adding limiting micronutrients (ocean iron fertilization) or macronutrients (nitrogen or phosphorus), or by physical manipulation, increasing nutrient supply through enhanced upwelling. The latter has the counterproductive effect of bringing CO_2-rich water to the surface.

Chemically-based mCDR involves the manipulation of carbonate chemistry, for example:

- *Adding alkaline minerals*, to convert dissolved CO_2 to carbonate and bicarbonate ions, thereby increasing the ocean capacity to take up anthropogenic CO_2 from the atmosphere, and potentially mitigating ocean acidification at the local level. This is referred to as ocean alkalinity enhancement (OAE).
- *Electrochemical CO_2 removal* from seawater, with its subsequent collection and geological storage (direct ocean removal, DOR). After further processing, climate benefits are obtained when CO_2-depleted seawater is released and re-equilibrates with the atmosphere.

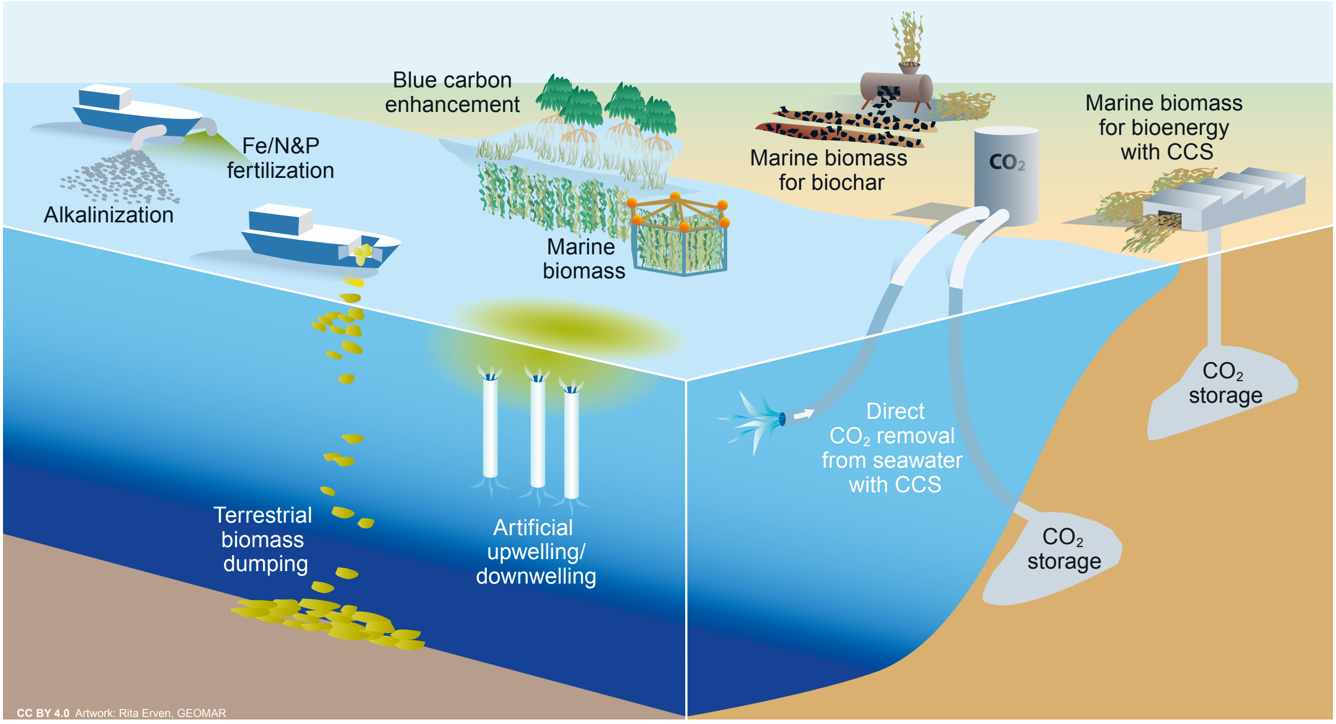

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Figure 8. Overview of carbon dioxide removal approaches using ocean processes and ocean-land linkages.
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In addition, a range of land-ocean hybrid methods would involve ocean storage for carbon initially captured on land (e.g. Raven et al., 2024; Zhu et al., 2024).

For further details of specific methods, and discussion of their effectiveness, risks, costs and governance, see Gattuso et al. (2018, 2021), GESAMP (2019), Hoegh-Guldberg et al. (2023), Cai and Jiao (2022), NASEM (2022), Williamson et al. (2022), Zhang et al. (2022), Cross et al. (2023), Jiao et al. (2023), Doney et al. (2024), Roberts et al. (2024), and Oschlies et al. (2025).

Unlike land-based CDR, mCDR has yet to be included in IPCC mitigation scenarios. That is due to scientific uncertainties regarding effectiveness and potential environmental risks, in addition to legal constraints. In particular, open-ocean mCDR methods are currently strongly discouraged as geoengineering under the UN Convention on Biological Diversity (CBD), and the deployment of ocean fertilisation is restricted under the London Protocol (IMO, 2023). Furthermore, the International Tribunal for the Law of the Sea (ITLOS) has recently designated anthropogenic CO_2 as a marine pollutant, with hazards that should not be transferred from one area to another (ITLOS, 2024; Klerk, 2025).

In contrast, coastal blue carbon has relatively high public and political acceptability. This 'nature-based' mCDR approach was identified as a climate mitigation policy in 23 initial Nationally Determined Contributions to the Paris Agreement (Gallo et al., 2017) and was considered a no-regrets action by Gattuso et al. (2021) on account of its important co-benefits. However, IPCC assessed the mitigation potential of coastal blue carbon as 'very modest' or 'small', at 0.05 – 0.3 Gt CO_2 per year (Bindoff et al., 2019; Canadell et al., 2021), and there are concerns that such removal rates may be over-estimated (Williamson and Gattuso, 2022).

Major knowledge gaps

1. **Demonstrating safety and long-term effectiveness**.

   The potential climatic benefits of other mCDR methods (with much greater theoretical CO_2 removals) could arguably be achieved if their main knowledge gaps could be resolved, demonstrating their safety and long-term effectiveness. NASEM (2022) recommended a ~$1.5 billion mCDR research program to address such issues, in the context of increasing need for CDR to meet the internationally-agreed goal of net zero (IPCC, 2023), together with realisation of the limitations of land-based CDR approaches (Boysen et al., 2017; Deprez et al. 2024). There are also market opportunities for UNFCCC-approved carbon trading under Article 6.4 of the Paris Agreement.

2. **Demonstrating additionality.**
   To qualify for emission credits, mCDR methods need to demonstrate additionality: i.e. that their climate benefits are unequivocal and can be reliably measured relative to a well-established baseline (Michaelowa et al., 2019). Uncertainties relating to additionality are crucial for mCDR research and development (Boyd and Bressac, 2016; Bach 2024; Bach et al., 2024), requiring information on the energy used (as CO_{2e}) to carry out the mCDR action as well as an assessment of all its climate-related biogeochemical consequences; i.e. a fully comprehensive life cycle analysis (Terlouw et al., 2021; Delval et al., 2025), relative to a counterfactual baseline.

Many of those consequences (shown conceptually in **Figure 9**) will likely occur over large spatial and temporal scales, influenced by ocean conditions over thousands of km^2 and decadal-to-century time periods. Their robust quantification is extremely challenging, with future conditions depending on emission scenarios.

Although models can greatly assist in determining mCDR additionality for open-ocean mCDR (Zhou et al., 2024), direct measurements will still be needed, not only of carbon-related parameters (Doney et al., 2024) at much greater accuracy than currently possible (McKinley et al., 2024) but also of other environmental impacts (that may be adverse or beneficial) within a regulatory framework of Monitoring, Reporting and Verification (MRV; Smith et al., 2024). Such monitoring is itself likely to involve significant CO_{2e} emissions, affecting the cost-effectiveness of the intervention.

The relative importance of factors determining mCDR additionality is technique-specific. However, for most mCDR actions, the following are relevant (in addition to CO_{2e} costs for implementation and MRV):

2.1 Reduction in natural carbon sinks, shown as a dashed rectangle in **Figure 9**. Increasing local productivity through ocean fertilization can decrease productivity 'downstream' through nutrient depletion (Gnanadesikan et al., 2003; Aumont and Bopp, 2006; Tagliabue et al., 2023), with similar effects occurring for large-scale seaweed cultivation (Berger et al., 2023). Abiotically-induced regional changes in the ocean carbon sink may also affect terrestrial sink efficiency (Keller et al., 2018; Boyd et al., 2025), as also likely for ocean storage of land-derived biomass. These feedback effects need to be taken into account when comparing mCDR effectiveness with any other CDR approaches (Yamamoto et al., 2024; Jeltch-Thömmes et al., 2024; Oschlies et al., 2025).

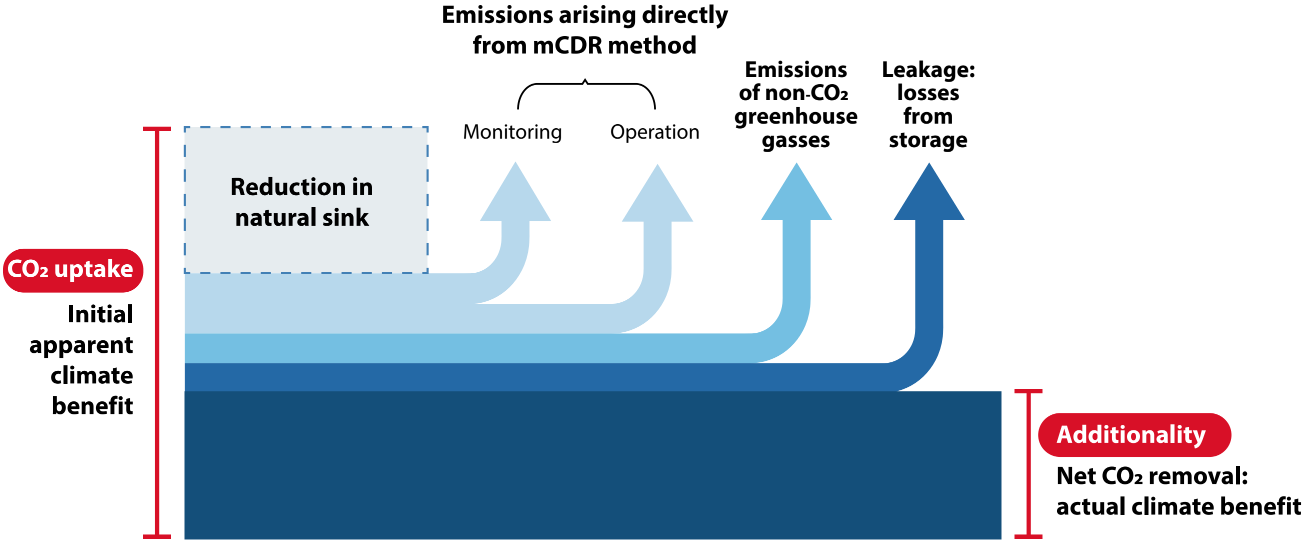

Figure 9. Conceptual representation of additionality (excluding albedo effects) for a generic mCDR action, adapted from Bach et al. (2024). See text for details.

2.2 Emission of non-CO_2 greenhouse gases. Anaerobic conditions in coastal sediments and mid-water oxygen minimum zones favour methane (CH_4) and nitrous oxide (N_2O) production, with the potential to significantly offset the CO_2 removal benefits of coastal blue carbon (Rosentreter et al., 2021, 2023) and ocean fertilization (Law and Ling, 2001). Measurement of the efflux of these gases therefore needs to be included in MRV protocols. For seaweed cultivation, the production of dimethyl sulphide (DMS) and halomethanes (e.g. bromoform, $CHBr_3$) may also have climatic impacts (Carpenter et al., 2009).

2.3 Leakage. The non-permanence of carbon storage for most biotic mCDR approaches is a cause for concern, since the durability of CO_2 removal is critical for effective climate mitigation (Brunner et al., 2024). For ocean fertilization, leakage results in declining effectiveness over time for global-scale deployment (Aumont and Bopp, 2006; Oschlies et al., 2025); similar effects are likely for seaweed cultivation with deep-sea biomass sinking. For coastal blue carbon, rising sea level, warmer temperatures, and human disturbance all threaten the long-term integrity of carbon stores (Williamson and Gattuso, 2022).

Actions to be taken

I. Model improvement

Roberts et al. (2024) reviewed the inclusion of CDR-relevant parameters in marine ecosystem models and ESMs. They identified 14 deficiencies with medium/high relevance to specific mCDR methods: most related to seaweed cultivation, including the effects of changes to surface ocean ecosystems, benthic smothering, and the attraction of seafloor biomass to deep sea fauna.

Modelling priorities identified by Buesseler et al. (2024) for ocean iron fertilization included observing system simulation experiments, storage durability, and the biological carbon pump. Despite the research attention given to the biological carbon pump, many aspects remain poorly understood (Henson et al., 2022; Baker et al., 2022; **Sections 3.a, 3.b, 3.d** and **4.a**).

II. Field experiments and operational deployment

Buesseler et al. (2024) also proposed a new generation of iron fertilization field experiments, of larger size and longer duration than previously, to improve understanding of carbon fluxes and environmental impacts. MRV protocols should also be developed and tested, using autonomous platforms and novel biogeochemical sensors (including for total alkalinity and dissolved inorganic carbon). Relatively few field experiments have been carried out on ocean alkalinity enhancement (Cyronak et al., 2023). Although controversial (Cornwall, 2024), these are needed to demonstrate safety (or otherwise) and should be closely linked to experimental studies of potential biological impacts (Bednaršek et al., 2025; Ferderer et al., 2022), as well as high-resolution modelling of physico-chemical processes and exposure risk (Laurent et al., 2025 ; Wang et al., 2025)

The only mCDR method currently in operational deployment is coastal blue carbon, regulated through the voluntary carbon market. It is unclear whether the MRV protocols developed to date (e.g. VERRA, 2023) meet UNFCCC certification requirements, since major methodological uncertainties remain (Kristensen et al., 2025; Dahl et al., 2025; Williamson et al., 2025).

III. Updated comprehensive assessment of proposed marine-based climate interventions

An updated version of the GESAMP (2019) report is needed to provide a systematic, policy-relevant review of the effectiveness and feasibility of mCDR methods. In addition to potential for climate mitigation, assessments of wider implications should include environmental effects on biodiversity, ecosystem functioning, and ecosystem services – issues not always well-covered in other reviews. The new Scientific Summary for Policymakers released in 2025 provides a first overview in this respect (GESAMP, 2025).

IV. Improving mCDR credibility

The scientific literature shows that a wide range of interventions to increase the ocean uptake of CO_2 are theoretically possible. Further research on the ocean carbon cycle and related ecological processes should help resolve key knowledge gaps; such research will also be necessary to establish a wider consensus on whether or not mCDR can contribute to a credible and scalable climate mitigation strategy, that is also both societally and politically acceptable.