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POLICY BRIDGE

Implementation of marine CO_2 removal for climate mitigation: The challenges of additionality, predictability, and governability

Lennart T. Bach[1],*, Naomi E. Vaughan[2], Cliff S. Law[3,4], and Phillip Williamson[5]

Achieving net zero CO_2 emissions requires gigatonne-scale atmospheric CO_2 removal (CDR) to balance residual emissions that are extremely difficult to eliminate. Marine CDR (mCDR) methods are seen increasingly as potentially important additions to a global portfolio of climate policy actions. The most widely considered mCDR methods are coastal blue carbon and seaweed farming that primarily depend on biological manipulations; ocean iron fertilisation, ocean alkalinity enhancement, and direct ocean capture that depend on chemical manipulations; and artificial upwelling that depends on physical manipulation of the ocean system. It is currently highly uncertain which, if any, of these approaches might be implemented at sufficient scale to make a meaningful contribution to net zero. Here, we derive a framework based on additionality, predictability, and governability to assess implementation challenges for these mCDR methods. We argue that additionality, the net increase of CO_2 sequestration due to mCDR relative to the baseline state, will be harder to determine for those mCDR methods with relatively large inherent complexity, and therefore higher potential for unpredictable impacts, both climatic and non-climatic. Predictability is inherently lower for mCDR methods that depend on biology than for methods relying on chemical or physical manipulations. Furthermore, predictability is lower for methods that require manipulation of multiple components of the ocean system. The predictability of an mCDR method also affects its governability, as highly complex mCDR methods with uncertain outcomes and greater likelihood of unintended consequences will require more monitoring and regulation, both for risk management and verified carbon accounting. We argue that systematic assessment of additionality, predictability, and governability of mCDR approaches increases their chances of leading to a net climatic benefit and informs political decision-making around their potential implementation.

Keywords: Geoengineering, Climate engineering, Ocean ecosystems, Net zero, Marine biogeochemistry, Ocean solutions

1. Introduction

To avoid dangerous climate change, parties to the Paris Agreement (United Nations Framework Convention on Climate Change [UNFCCC], 2015) have committed to hold the increase in global average temperature to well below 2°C and pursue efforts to limit warming to 1.5°C above pre-industrial levels (Article 2). Achieving these goals is envisaged through an imminent plateauing in anthropogenic greenhouse gas emissions, followed by their rapid reduction, together with the strengthening of carbon sinks, that is, using carbon dioxide removal (CDR), to achieve global net zero emissions in the second half of the century (Article 4). Around 124 countries currently have national net zero emissions policies (Fankhauser et al., 2022; Hale et al., 2022), with many organisations and industries having similar, or more ambitious, targets (Joppa et al., 2021).

The Intergovernmental Panel on Climate Change (IPCC) defined CDR as 'anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products', with the specific exclusion of natural CO_2 uptake not directly caused by human activities (IPCC, 2022). CDR can be carried out using terrestrial processes (e.g., afforestation/reforestation, enhanced soil carbon) or marine processes (see Section 2). It includes 'nature-based' methods

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[1] Institute for Marine and Antarctic Studies, University of Tasmania, Tasmania, Australia

[2] Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK

[3] National Institute of Water and Atmosphere, Wellington, New Zealand

[4] Department of Marine Science, University of Otago, Dunedin, New Zealand

[5] School of Environmental Sciences, University of East Anglia, Norwich, UK

* Corresponding author:
Email: lennart.bach@utas.edu.au

(e.g., ecosystem restoration) and methods that are partly or fully engineered or industrial (e.g., biomass energy with carbon capture and storage [BECCS], direct air carbon capture and storage [DACCS], electrochemical CO_2 removal from seawater).

CDR, also known more broadly as greenhouse gas removal and negative emission technologies (NETs), serves two key functions in climate policy and associated future emission scenarios. First, it enables offsetting of residual emissions from difficult-to-decarbonise sectors (such as aviation and non-CO_2 emissions from agriculture) to reach net zero around 2050. Second, additional CDR is necessary in scenarios with a temporary overshoot in global mean temperatures, requiring net negative emissions throughout the latter half of the century (Tokarska et al., 2019; Johansson, 2021).

In IPCC assessment reports and their associated emission scenarios, CDR implementation is expected to take place on land (Riahi et al., 2022), using methods (e.g., BECCS, afforestation/reforestation and DACCS) that are represented relatively easily in integrated assessment models (Vaughan et al., 2018; Butnar et al., 2020). Nevertheless, several marine CDR (mCDR) approaches were assessed in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Bindoff et al., 2019) and in the WGIII Sixth Assessment Report (Babiker et al., 2022). Other recent reviews of mCDR include those by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2019), the US National Academies for Sciences, Engineering and Medicine (NASEM, 2019, 2022), the World Resources Institute (Lebling et al., 2022) and academics (Gattuso et al., 2018; Hoegh-Guldberg et al., 2019; Williamson et al., 2022).

Here we consider ocean NETs, ocean-based CDR and mCDR to be synonymous: all are subsequently referred to as mCDR. Consistent with the IPCC definition of CDR, this term includes coastal management interventions using ‘blue carbon’ ecosystems that are carried out primarily to increase CO_2 removal, that is, habitat restoration for CDR purposes, but excludes natural carbon sinks and their protection.

The many technical, environmental, and socio-economic issues relating to the wide range of different mCDR approaches make providing a comprehensive review in this paper impractical. Instead, we summarise key issues for five mCDR approaches (Section 2), outlining generic research gaps and operational challenges (Section 3) in the context of the contribution each mCDR approach might make to reaching net zero by 2050.

A complementary perspective in this special feature on the Surface Ocean–Lower Atmosphere Study (SOLAS) is expected to consider the research and development priorities and enabling mechanisms needed for a wider range of ocean-based climate actions and to cover additional mCDR approaches (Johnson et al., n.d.). Relevant governance constraints for ocean interventions are addressed by van Doorn et al. (2024), and recent advances in directly relevant science (air-sea fluxes of greenhouse gases) are reviewed by Bange et al. (2024).

2. Overview of mCDR approaches

Regarding the ocean as a solution, rather than a victim, in climate change (Lubchenko and Hoegh-Guldberg, 2020) is a powerful framing to increase effort on marine climate mitigation. More objectively, NASEM (2022) identified three reasons why mCDR provides major opportunities in this regard: first, the natural capacity of the ocean and its sediments for carbon storage is large; second, the fraction of CO_2 emitted to the atmosphere by human activities already removed by the ocean is substantial (approximately 25%); and third, the processes of ocean CO_2 uptake and storage are relatively well-established. Governmental organisations (e.g., National Oceanic and Atmospheric Administration, 2023) have also recognised the potential for greater CO_2 sequestration in the ocean.

Marine CDR has been defined as ‘approaches [that] aim to enhance or accelerate natural biological or chemical processes that sequester carbon in the ocean. In a few cases, the approaches extract carbon dioxide dissolved in seawater for storage on land’ (Lebling et al., 2022). A comparative strength of mCDR relative to terrestrial CDR is the reduced competition with other land uses (food, fodder, fibre, non-CCS bioenergy crops and biodiversity; Smith et al., 2016), which has implications for social equity and human rights (Günther and Eckardt, 2022; Patrizio and Mac Dowell, 2022). Nevertheless, if mCDR is carried out at climatically significant scales, it may also affect and/or displace existing marine ecosystems and their services, of potentially high economic value, with adverse societal impacts (Williamson, 2016). A comparative weakness is that mCDR (with the exception of some coastal blue carbon approaches) does not directly remove CO_2 from the atmosphere but from seawater, necessitating subsequent re-equilibration with the atmosphere, and also sophisticated procedures to verify that atmospheric CO_2 removal is occurring (Bach et al., 2023).

Growing recognition of the potential role of the ocean in climate action is reflected in nationally determined contributions, submitted to the UNFCCC setting out climate policy to 2030, of which over 70% now mention marine and coastal ecosystems (Gallo et al., 2017; Seddon et al., 2019). However, the main focus of these contributions is on impacts and adaptation, with only a minority including plans for mCDR. The restoration of coastal blue carbon ecosystems is the only mCDR approach included in the long-term low emission and development strategies (LT-LEDS) recently submitted to the UNFCCC setting out national climate policies to 2050 (Smith et al., 2022). A much wider range of interventions is covered in the total of approximately 90 substantive research and development projects on marine climate mitigation that are currently underway (GESAMP WG 41, 2022).

Various mCDR methods have been proposed and, as noted above, reviewed extensively in the scientific literature. We are not replicating these efforts but provide a summary grouping (**Figure 1**). In the following, we briefly introduce six widely considered mCDR methods. They are coastal blue carbon, seaweed farming, ocean iron fertilisation, artificial upwelling, ocean alkalinity enhancement, and direct ocean capture. These six approaches

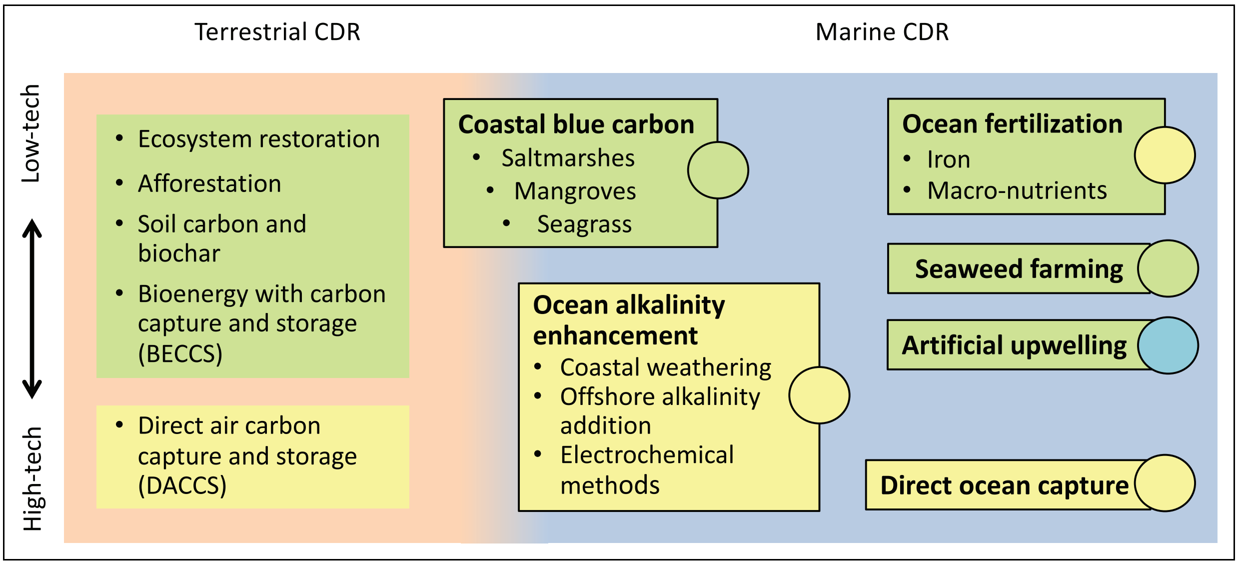

Figure 1. Summary typology of carbon dioxide removal methods. The six marine CDR (mCDR) approaches (in bold) and their main sub-groups considered in this paper are shown. The colour-shading of the boxes indicates whether chemical (yellow) or biological processes (green) ultimately drive CO_2 removal. The colour-shading of the circles next to the mCDR boxes indicates which ocean processes need to be manipulated to induce CO_2 removal, including blue for physically manipulated artificial upwelling. Note that: (i) this typology is not exhaustive (for other mCDR approaches, see GESAMP, 2019, and NASEM, 2022); (ii) the vertical axis broadly indicates the spectrum from low-tech to high-tech approaches; (iii) coastal blue carbon methods straddle the terrestrial-marine interface; and (iv) seaweed farming may also have a terrestrial component, if providing feedstock for bioenergy and/or bioenergy with carbon capture and storage (BECCS).

dominate the scientific literature on mCDR (e.g., as reviewed by GESAMP, 2019; NASEM, 2019, 2022).

Coastal blue carbon is here considered as the restoration (including new habitat creation) of three ecosystems—salt marshes, mangroves, and seagrass meadows—to increase or initiate the relatively high carbon burial rates in their anoxic sediments (Nelleman et al., 2009; McLeod et al., 2011). These ecosystems are usually considered together in the marine context (e.g., Gattuso et al., 2018; Bindoff et al., 2019; Hoegh-Guldberg et al., 2019; NASEM, 2019; Lebling et al., 2022). However, salt marshes and mangroves are also sometimes grouped with soil or terrestrial CDR (Bossio et al., 2020; Roe et al., 2021). All three can also contribute to net zero through emission reductions (conservation, preventing further habitat loss), but this is not a CDR process and therefore not considered further here.

This restoration approach has high public and political acceptability (Hilmi et al., 2021; United Nations Environment Programme and International Union for the Conservation of Nature, 2021) with associated conceptual development of coastal blue carbon farming and markets (Claes et al., 2022; de Paula Costa et al., 2022). Coastal blue carbon has been prioritised for US CDR research (NASEM, 2019) and has been considered a 'low regret' or 'no regret' climate mitigation option on the basis of the many co-benefits (primarily for coastal protection and biodiversity) that it provides (Gattuso et al., 2021). However, the scale of climate benefits that might be achieved by coastal blue carbon restoration is contested: not only are there biophysical limits on the area available for such action, but there are also many carbon-accounting problems, including high variability and potential error in measuring carbon burial rates, complex carbon fluxes into and out of the ecosystem, changes in the release of other greenhouse gases, and vulnerability to human impacts and future climate change (Williamson and Gattuso, 2022). The need for relatively demanding site-specific monitoring and protection is likely to reduce the cost-effectiveness of this approach.

Seaweed farming for CDR aims to grow seaweed (macroalgae, such as kelp) on either free-drifting or tethered platforms in shelf seas or the open ocean in order to fix carbon in biomass. Harvesting would be needed to ensure long-term carbon removal, either through deliberate sinking of the seaweed to the deep seafloor or land-based processing (e.g., biofuel production, with subsequent CCS). This mCDR approach has been investigated since the late 1980s with several field trials (Ritschard, 1992) and has recently seen increased levels of attention (Krause-Jensen and Duarte, 2016; Duarte et al., 2017; Froehlich et al., 2019; Capron et al., 2020). Some studies suggest that seaweed farming could deliver CDR on the gigatonne-scale, although biotic feedbacks have the capacity to reduce its efficiency (Orr and Sarmiento, 1992; Bach et al., 2021; Gallagher et al., 2022; Wu et al., 2023) and carbon accounting for this approach would be difficult (Hurd et al., 2022). Environmental impacts from seaweed farming are likely to be mixed, with the potential for economically valuable co-benefits (DeAngelo et al., 2023) but potentially negative ecological effects (Boyd et al., 2022; Wu et al., 2023).

Ocean iron fertilisation aims to stimulate marine primary production and associated CO_2 sequestration by adding soluble iron to surface waters where it is the limiting nutrient (mostly in the Southern Ocean). Ocean iron fertilisation is relatively well-investigated in 13 open ocean experiments (Boyd et al., 2007; Yoon et al., 2018); nevertheless, many issues relating to long-term carbon storage and large-scale feedback effects remain unresolved (Williamson et al., 2012). Modelling studies estimate a CDR potential of 1–4 gigatonnes CO_2 year^{-1} if iron was added to the global surface ocean or over entire ocean basins, with values declining with time (Aumont and Bopp, 2006; Zahariev et al., 2008; Keller et al., 2014). Concern regarding environmental side-effects, such as trace gas production, oxygen loss or the risk of harmful algal blooms (Law and Ling, 2001; Strong et al., 2009; Williamson et al., 2012; Cox et al., 2021) has resulted in regulation of further field-based research and international prohibition of operational deployment under the London Convention/London Protocol. Ocean fertilisation by other nutrients (nitrogen and phosphorus) has also been proposed as a mCDR technique but is not considered here.

Ocean alkalinity enhancement aims to increase seawater pH and alkalinity through the acceleration of mineral weathering or the application of electrochemical methods, and thereby increase CO_2 uptake and long-term storage in the ocean (Hartmann et al., 2013; Renforth and Henderson, 2017). The chemical processes leading to increased CO_2 storage in the marine carbonate system are well understood, although the cost-efficiency of ocean alkalinity enhancement on large scales is not yet clear (Gagern et al., 2022). Modelling studies have shown that this method could provide CDR of several gigatonnes CO_2 year^{-1} (Ilyina et al., 2013; Keller et al., 2014; Lenton et al., 2018), but may result in environmental side-effects and biotically mediated positive and/or negative feedbacks on oceanic CO_2 uptake (Hauck et al., 2016; Bach et al., 2019).

Artificial upwelling aims to transport nutrient-rich deep water to the surface ocean to increase carbon fixation by phytoplankton and enhance carbon export to depth. The stimulation of CO_2 uptake by phytoplankton production is expected to exceed emissions arising from the upwelling of CO_2-enriched deep water, thereby enabling net removal of atmospheric CO_2 (Lovelock and Rapley, 2007). The ability of artificial upwelling to increase primary production is well known from experimental studies (Pan et al., 2016; Pan et al., 2019; Ortiz et al., 2022) and observations in nature (Bach and Boyd, 2021), but its capacity to sequester additional CO_2 is far less certain (Karl and Letelier, 2008; Baumann et al., 2021). Modelling studies indicate that artificial upwelling has limited CDR potential (Yool et al., 2009; Oschlies et al., 2010; Koweek, 2022) and, if deployed widely, could actually cause net warming (Kwiatkowski et al., 2015). A recent modelling study suggested that artificial upwelling has more potential to induce CDR through abiotic processes and that its efficiency is highly dependent on future CO_2 emission trajectories (Jurchott et al., 2023).

Direct ocean capture is conceptually similar to DACCS in that it aims to chemically extract CO_2 from the ambient environment (here seawater) for subsequent long-term storage, usually in a geological reservoir. The extraction of seawater CO_2 via direct ocean capture is a fully engineered process, achieved for example through pH swings (de Lannoy et al., 2018) or specific solvents (Lieber et al., 2023). The extracted CO_2 is then transported to a terminal storage location. This storage could be geological storage below the seabed but also storage in carbonates, for example, where strong acids generated during the process are neutralised via rock weathering (La Plantae et al., 2023), with the carbonates then stored in the ocean.

3. Challenges for marine CDR

As already noted, the wide-ranging scientific unknowns and uncertainties around mCDR have been identified by several recent international reviews (Gattuso et al., 2018; GESAMP, 2019; NASEM, 2019, 2022; Williamson et al., 2022). All these reports concluded that improved understanding of mCDR methods is needed before they can be used at scale for significant climate mitigation. Although some uncertainties are method-specific, many are generic, relating to: efficiency and costs; environmental impacts; monitoring, reporting, and verification; societal acceptability; and environmental justice.

Here we consider the potential for real-world implementation of the main mCDR methods at gigatonne-scale in the context of three cross-cutting challenges: the requirement to demonstrate additionality, the relative predictability of different mCDR approaches, and the crucial requirement of their governability. We recognise that there are other critical constraints on the operational application of mCDR methods, including scalability, technological readiness, duration of benefits, undesirable side-effects, cost effectiveness and financing issues. Such criteria (and others) have been used in assessments by Gattuso et al. (2018), Bindoff et al. (2019), and NASEM (2022). However, we consider the above three challenges are more fundamental and hierarchically important; for example, problems associated with scalability are basically those of additionality (the demonstration of net climatic benefits, taking account of consequences outside deployment areas), predictability (increasing uncertainties over large space and time scales), and governability (risks of adverse trans-boundary impacts and difficulties in international standardisation of carbon accounting). Furthermore, we consider that these three challenges are potentially 'weak links', in that if any one is not adequately met or is practicably unachievable, then the mCDR approach is non-viable. They therefore warrant priority research attention.

3.1. Additionality

The concept of additionality is an important one for climate policy action. Whilst it is similar to effectiveness, additionality gives much greater attention to the wider consequences of mCDR and the need to demonstrate quantifiable net benefit. In the context of CDR, additionality requires that any mitigation intervention should result in an outcome that is quantifiably distinct from the baseline that would occur in the absence of such action (Gustavsson et al., 2000; Michaelowa et al., 2019).

Furthermore, this net benefit needs to be verified using standardised methods that are internationally recognised. This definition of additionality is fully consistent with IPCC (2022), although wider meanings are also possible.

Implementation of mCDR must therefore not only result in increased uptake of CO_2 from the atmosphere but also its long-term sequestration (i.e., >100 years; Fearnside, 2002) and preferably permanent storage at a level that is demonstrably higher than the baseline CO_2 sequestration that was occurring previously and that could be expected to continue. Although shorter storage periods may help to lower peak warming when combined with ambitious emission reductions (Ruseva et al., 2020; Matthews et al., 2022), they may also make achieving the UNFCCC goal of long-term climate stabilisation (Kirshbaum, 2006) more difficult.

The additionality of carbon sequestration (C_{add}) of an mCDR action can be defined as:

$$C_{add} = C_{CDR} - (\Delta C_{base} + C_{LCA}) \tag{1}$$

where C_{CDR} is the total amount of observed removal following deployment of the mCDR method; ΔC_{base} is the decrease in baseline, natural carbon sequestration that can occur as a result of the mCDR implementation; and C_{LCA} represents additional emissions arising from the mCDR action that are assessed in 'conventional' (attributional) life cycle analysis (LCA). The additional emissions include those from implementation and monitoring (Smith and Torn, 2013; Goglio et al., 2020; Terlouw et al., 2021), and also leakage from non-permanent storage (**Figure 2**). Units for 'C' can either be fluxes of carbon, carbon dioxide, or carbon dioxide equivalent, thus allowing for fluxes of other greenhouse gases. More generally, 'C' can be considered as representing climate benefits, as the decrease in radiative forcing (RF) (see below).

The timescale considered within the concept of additionality needs to be specified. Whilst additionality can be expressed as an annual flux, it is important to recognise that different fluxes operate on different timescales. For example, when an mCDR deployment removes a certain amount of carbon within 1 year, additionality will still be zero if the baseline change releases the same amount of carbon over 10 years. The question then concerns the timescale over which additionality is integrated. Cumulative additionality (e.g., with reference to 2100) is therefore preferable for comparative purposes, although processes occurring after arbitrary dates can still be important for the climate.

In the simplest case, C_{add} can be determined by measuring C_{CDR} and with knowledge of C_{LCA} (e.g., CO_2 emissions arising from use of non-renewable energy sources). This approach is valid for some land-based CDR methods that do not significantly affect existing CO_2 sink processes. An example of such a method is DACCS, where CO_2 is extracted from air and stored in secure geological reservoirs. Here, any impact on natural carbon sinks is likely to be climatically negligible, limited to the land footprint needed for DACCS facilities and associated renewable energy infrastructure and supply chain emissions.

For the mCDR methods considered here, such assumptions do not apply, because the deployment C_{CDR} is likely to substantially affect C_{base}. For example, models show that any iron fertilisation-driven increase of C_{CDR} due to increased phytoplankton productivity (enhancing the biological carbon pump) at one location may lead to a decrease in productivity elsewhere, due to 'nutrient robbing' (Gnanadesikan et al., 2003; Aumont and Bopp, 2006). Reliable quantification of this effect through direct measurement and attribution to mCDR is, however, extremely difficult—if not impossible—because the

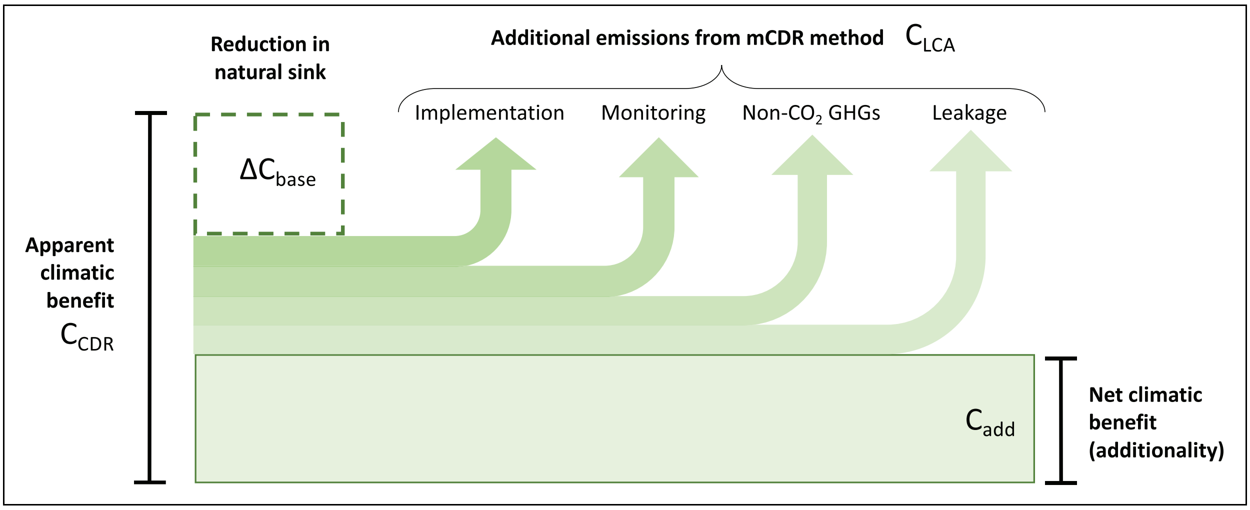

Figure 2. Conceptual representation of additionality issues for marine CDR. The dashed rectangle represents the loss of natural sinks (ΔC_{base}) arising from the mCDR action, for example, productivity replacement. Additional emissions (C_{LCA}) are those assessed by life cycle analysis, comprising emissions arising from implementation of the mCDR approach; emissions from its monitoring, reporting, and verification; fluxes of non-CO_2 greenhouse gases (primarily N_2O and CH_4); and non-permanence of storage (leakage). The relative importance of the different losses and pathways are shown diagrammatically; proportions will vary according to the mCDR approach. Albedo and other indirect effects may also affect additionality but are not represented here. See text for additional details.

reduction in C_{base} is temporally and spatially separated from the mCDR deployment location, potentially by decades and several thousand kilometres. Similar issues arise for mCDR with artificial upwelling or seaweed farming, particularly if the latter is implemented in the open ocean. Unless additional nutrients are supplied, the increase in seaweed biomass may be at the expense of other primary producers, which in the baseline scenario would fuel natural CO_2 removal (Orr and Sarmiento, 1992; Bach et al., 2021; Berger et al., 2023; Wu et al., 2023).

In the above examples, the change in baseline CO_2 removal (ΔC_{base}) results from productivity replacement; however, other pathways may be involved. For coastal blue carbon, a key additionality issue is whether the organic carbon accumulating in mangroves, saltmarsh, or seagrass sediment results from in situ CO_2 fixation (i.e., autochthonous) or originates elsewhere (allochthonous), for example, is land-derived. Because the latter might have been preserved anyway, at a different location, it should be excluded when estimating the additionality of blue carbon ecosystem restoration (Williamson and Gattuso, 2022). Another uncertainty in assessing additionality for all mCDR techniques, not further discussed here, is how the baseline would alter with climate change (Lovelock and Reef, 2020).

Additionality is discussed above primarily from a CO_2 perspective. However, for climate mitigation what actually matters is the net change in the energy balance of the Earth system, that is, radiative forcing (RF) (Myrhe et al., 2013). Thus, the more comprehensive formulation of Equation 1 is:

$$\mathrm{RF}_{\mathrm{add}} = \mathrm{RF}_{\mathrm{CDR}} - (\Delta \mathrm{RF}_{\mathrm{base}} + \mathrm{RF}_{\mathrm{LCA}}) \qquad (2)$$

where RF_{add} is the net change of RF by the system following the mCDR manipulation, after allowing for baseline replacement (RF_{base}) and LCA effects (RF_{LCA}). Considering additionality in terms of RF allows for mCDR-induced changes in the fluxes of a wider range of non-CO_2 biogenic gases that are climatically active. These not only include the potential for increased emissions of the greenhouse gases nitrous oxide (N_2O) and methane (CH_4; Law and Ling, 2001; Williamson et al., 2012; Rosentreter et al., 2021), but also of dimethyl sulphide (affecting albedo) as a result of changes in phytoplankton productivity and/or community composition (Wang et al., 2018), and halomethanes such as bromoform ($CHBr_3$, affecting ozone dynamics) as a consequence of large-scale seaweed farming (Carpenter and Liss, 2000). Significant albedo changes may also arise directly from increases in seaweed coverage of the surface ocean (Bach et al., 2021) or indirectly via changes in sea ice coverage as a consequence of artificial upwelling and ocean alkalinity enhancement (Keller et al., 2014).

3.2. Predictability

Marine CDR methods generally aim to transfer carbon from the atmosphere into the ocean or its sediments; however, different methods use different physical, chemical, or biological processes to achieve this, operating through different control systems and drivers. The predictability of CO_2 removal is lower when an mCDR method involves greater system complexity (Boyd, 2008). Assessing the complexity of the component processes that collectively drive CO_2 removal (and also their unintended consequences) for any given mCDR approach is therefore necessary.

A first aspect affecting the predictability of mCDR arises from the inherent differences in the predictability of physical, chemical, and biological processes. Physical and chemical oceanographic systems are generally more predictable than biological systems (Coveney and Fowler, 2005). For example, physical and chemical changes due to ocean acidification are predictable in observations and experiments, while the biological changes remain variable and enigmatic in many cases (Hester et al., 2008; Kroeker et al., 2013; Doney et al., 2020; Taucher et al., 2020). More generally, marine biogeochemical models are able to simulate chemical properties (e.g., nutrient fields or carbonate chemistry) much better than species distributions, biomass, and productivity, primarily due to our poor understanding of ecological complexity, involving physiological and behavioural adaptation as well as complex food-web interactions (Anderson, 2005; Flynn, 2006; Shimoda and Arhonditsis, 2016).

The inherently higher complexity of biological systems can therefore be expected to reduce the predictability of biologically based mCDR compared with chemical manipulation, even when both manipulations are applied directly (**Figure 3A**). For example, when modelling biotic mCDR such as seaweed farming, more assumptions are required and more processes are incorporated than when modelling chemical mCDR, such as simpler versions of ocean alkalinity enhancement. Consequently, the climatic and ecological outcomes of the latter are arguably more predictable than the former (Bach et al., 2021).

A second aspect determining the predictability of an mCDR method involves the biogeochemical complexity of the method itself. Ocean alkalinity enhancement, for example, can be achieved through a range of methods which differ in the degree to which they perturb ocean chemistry. Using electrodialysis via sodium hydroxide can be considered the biogeochemically simplest approach to enhance alkalinity, as it is based exclusively on direct manipulation of marine carbonate chemistry to achieve the desired effect on CO_2 fluxes (de Lannoy et al., 2018), with limited observations suggesting only minor impacts on plankton communities (Ferderer et al., 2022; Subhas et al., 2022). However, the implementation of ocean alkalinity enhancement through the addition of finely ground minerals (such as olivine) would not only alter carbonate chemistry but also involve additional changes in nutrients, trace metals and turbidity, all potentially affecting phytoplankton community structure and productivity (Bach et al., 2019). Such a 'multiple driver' perturbation will likely induce additional feedbacks on other biogeochemical processes, unintentionally invoked by dissolution products from the weathering process (Hauck et al., 2016). Such feedbacks would reduce the predictability of CO_2 removal and also likely cause other ecological impacts. These feedbacks would be hard to simulate in models,

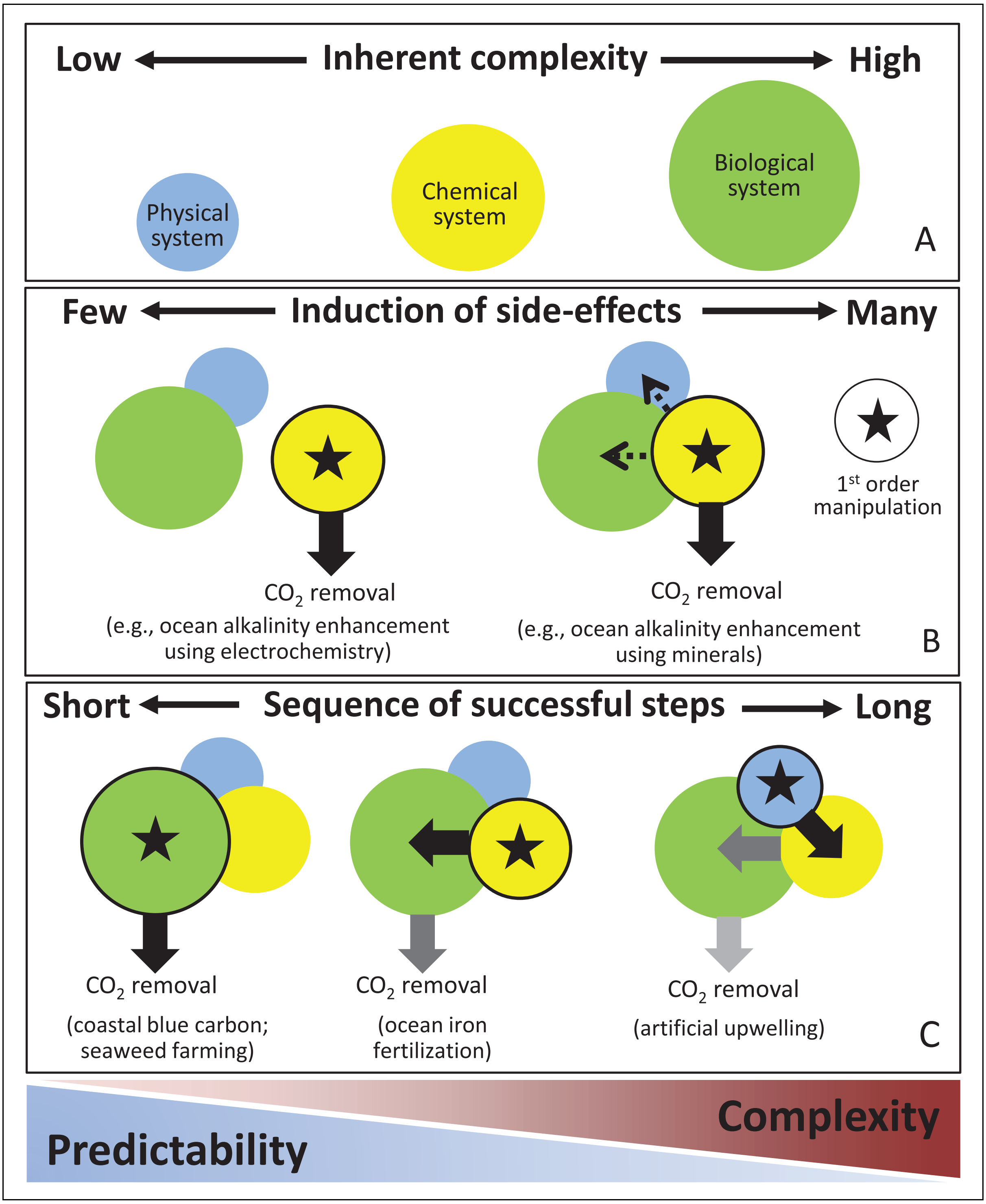

Figure 3. Predictability for marine CO_2 removal, based on complexity of the processes involved and their interactions. (A) The inherent complexity of physical, chemical, and biological systems for marine CO_2 removal (mCDR) indicated by the different circle sizes. (B) Increasing complexity of mCDR potential to induce environmental side-effects. Exemplified here is electrochemical ocean alkalinity enhancement where only carbonate chemistry is altered, in contrast to ocean alkalinity enhancement with a mineral alkalinity source where a range of bioactive dissolution products are added that can induce additional biogeochemical processes. (C) Increasing complexity as a consequence of the change from direct to increasingly indirect stimulation of biologically driven mCDR. Note that the effects of temporal and spatial scales on complexity and predictability are not represented in this schematic.

which simulate much lower complexity than the real world, and their importance might only become apparent in experiments and test deployments (**Figure 3B**).

A third component of mCDR predictability relates to whether CO_2 removal is achieved directly or indirectly. For biologically driven CDR, ecosystem productivity can be manipulated directly, as with coastal blue carbon and seaweed farming where the biomass of primary producers is directly increased, resulting in an increase in photosynthetically fixed CO_2. However, for ocean iron fertilisation the manipulation is indirect, as changes in chemistry (soluble iron addition) are used to increase biomass. Thus, even though ocean iron fertilisation is based on chemical manipulation, CDR is driven by the subsequent actions of inherently more complex biological systems. For artificial upwelling, a further step is involved: the physical process of deep-water upwelling is enhanced artificially in order to alter ocean chemistry (increase surface nutrient concentrations), which is then expected to increase biological productivity and hence CDR. The longer the sequence of necessarily successful steps involved (each with its associated uncertainties) means the greater the number of possibilities for unforeseen consequences, both climatic and non-climatic (**Figure 3C**).

3.3. Governability

The governability of mCDR is arguably more important than its technological potential in determining whether or not any approaches will undergo 'real world' implementation at operational scale. In this context, governability is the application of governance, with the latter not only including law and regulation but also all the issues affecting social licence to operate and financial viability: 'the structures, processes, and actions through which private and public actors interact to address societal goals' (IPCC, 2022).

Successful governance of mCDR as an internationally recognised climate mitigation strategy must therefore satisfy a wide range of socio-economic criteria as well as be regarded as scientifically feasible and effective. In particular, mCDR will compete with other CDR options for policy adoption, including those options given much greater prominence to date in IPCC modelling and climate change scenarios (i.e., afforestation and BECCS; Riahi et al., 2022). There are also broader societal objectives relevant to decisions about mCDR, such as food production (fisheries), biodiversity conservation, livelihoods, equity, and environmental justice.

The inherent complexity and (un)predictability of an mCDR approach are directly relevant to its governability. More complex mCDR methods (e.g., those with many pathways and interactions) will lead to less predictable CO_2 sequestration, with more potential to induce environmental side-effects. As a result, they will require more complex governance and regulatory control, if they are allowed at all. The latter is because the occurrence of uncertain outcomes, risk of adverse impacts, and poor controllability are factors that strongly influence public and political acceptability (Bellamy et al., 2017; Shrum et al., 2020; Dooley et al., 2021; Cooley et al., 2023) and are closely related to ethical considerations (Baatz et al., 2016; Hale and Dilling, 2020).

For example, the perceived risk of transboundary environmental harm resulted in a 'moratorium' on ocean iron fertilisation by the Convention on Biological Diversity (Decision X/33 in 2010) and the subsequent development of detailed regulation for this approach by the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention and London Protocol, LC/LP). Resolution LC/LP.1(1) prohibits ocean fertilisation except for 'legitimate scientific research', and Resolution LP.4(8) requires ocean fertilisation experiments to seek permission under a two-step approval process (GESAMP, 2019). However, these constraints are not yet legally binding due to the timescales for international decision-making being extremely slow. Indeed, the current timescale for developing and implementing international regulations represents a major impediment to using mCDR to help achieve net zero.

The political and public acceptability of ocean alkalinity enhancement and seaweed farming for CDR have received far less attention than ocean iron fertilisation. However, there may be less international concern regarding such activities if they can be carried out within territorial waters, particularly within controlled settings, as any environmental impacts may be more localised and monitoring would be easier.

Such monitoring is not limited to the detection of unintended side-effects but is a core component of national reporting for climate mitigation—as measurement, reporting, and verification (MRV) of carbon accounting under UNFCCC auspices. The MRV framework, based on transparency and additionality, was strengthened at UNFCCC COP26 by the new Article 6 of the Paris Agreement (International Institute for Sustainable Development, 2021). Relatively detailed MRV guidelines for direct emission reductions have been developed at the international level (UNFCCC, 2014; European Commission, 2021).

Equivalent international standards are generally lacking for CDR. However, the European Union has recently published proposals for establishing a regulatory framework for terrestrial approaches (European Commission, 2022), and Australia is planning to recognise coastal blue carbon as a carbon offset mechanism (Australian Government, 2022). Non-governmental accreditation frameworks (e.g., Verra, 2021) have also been developed for coastal blue carbon, with strong interest from the voluntary carbon market (Arcusa and Sprenkle-Hyppolite, 2022; Claes et al., 2022), despite the uncertainties affecting carbon accounting for this approach (Williamson and Gattuso, 2022).

The feasibility of operational MRV-based carbon accounting for seaweed farming, iron fertilisation, alkalinity enhancement, and artificial upwelling has not yet been critically investigated. There are major challenges in establishing reliable MRV methods for approaches that depend on deep-water storage of biologically derived carbon, in relation to the large space and time scales involved in potential 'leakage'. In addition, there is inherent deep uncertainty (Adler et al., 2019) regarding future ocean hydrodynamics on decadal and basin scales, as these hydrodynamics will alter with future climate change. Resolving this uncertainty will require major investment and expansion in autonomous monitoring capacity and deployment, and significant improvement in measurement capability for dissolved inorganic and organic carbon species (Hurd et al., 2022), linked to very high-resolution modelling for potential deployment sites.

4. Conclusions

The wider relevance of our analysis is to highlight the need for transdisciplinary research (Lang et al., 2012; Yates et al., 2015) in considering marine systems for CDR. Such research must include not only field experiments at a range of scales, but also the full spectrum of social sciences and, crucially, engagement with society and policymakers. In particular, our focus on additionality shows that carbon accounting (through MRV) should not be seen as an afterthought, but as an integral part of CDR feasibility. This issue of predictability and related complexity highlights the need for a wide range of research and development, from technology innovation and high-resolution modelling to understanding carbon market business practices, policy design, and social justice.

Furthermore, our focus on governability emphasises the importance of co-production of knowledge, through the participation, from research design to completion, of relevant stakeholders—involving industry, policy (at relevant scales from local to national and international), NGOs, and communities, including those from the global south. Such engagement is not an optional 'add on' but is essential to ensure that mCDR development achieves social licence to operate, through responsible research and innovation. There are already examples of how this goal might be achieved (e.g., the EU-funded OceanNETs project); such initiatives need to be built upon and scaled-up to meet societal needs.

In this paper we have not attempted a ranking of different mCDR approaches in terms of their relative merits or feasibility. Nevertheless, the forms of mCDR that deliver additional CO_2 removal with climatic benefits that are verifiable and predictable would seem more likely to be internationally adopted and funded—and thus to make the largest contribution to CDR.

Data accessibility statement

There were no datasets generated in the preparation of this paper.

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Competing interests

The authors have no competing interest to declare.

Author contributions

All authors discussed and developed the intellectual content of the manuscript. LTB led the drafting and NEV, CSL, and PW contributed to the writing of the manuscript. All authors revised the manuscript and approved its submission.

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