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POLICY BRIDGE

Can coastal and marine carbon dioxide removal help to close the emissions gap? Scientific, legal, economic, and governance considerations

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In this Policy Bridge, we present the key issues regarding the safety, efficacy, funding, and governance of coastal and marine systems in support of climate change mitigation. Novel insights into the likely potential of these systems for use in mitigating excess carbon dioxide emissions are presented. There may be potential for coastal blue carbon and marine carbon dioxide removal (mCDR) actions to impact climate change mitigation significantly over the rest of the 21st century, particularly post 2050. However, governance frameworks are needed urgently to ensure that the potential contribution from coastal and ocean systems to climate change mitigation can be evaluated properly and implemented safely. Ongoing research and monitoring efforts are essential to ensure that unforeseen side effects are identified and corrective action is taken. The co-creation of governance frameworks between academia, the private sector, and policymakers will be fundamental to the safe implementation of mCDR in the future. Furthermore, a radical acceleration in the pace of development of mCDR governance is needed immediately if it is to contribute significantly to the removal of excess carbon dioxide emissions by the latter half of this century. To what extent large-scale climate interventions should be pursued is a decision for policymakers and wider society, but adaptive legal, economic, policy, research, and monitoring frameworks are needed urgently to facilitate informed decision-making around any implementation of mCDR in the coming decades. Coastal and ocean systems cannot be relied upon to deliver significant carbon dioxide removal until further knowledge of specific management options is acquired and evaluated.

Keywords: Marine carbon dioxide removal, Negative emissions, Climate mitigation, Governance, Blue carbon

Introduction

In order to limit warming to between 1.5°C and 2°C, human-managed carbon dioxide removal (CDR) mechanisms are unavoidable in nearly all climate scenarios (Anderson and Peters, 2016; Fuss et al., 2016; Fleurke, 2017; Obersteiner et al., 2018), due to a significant "emissions gap" (**Figure 1**) between the remaining budget of carbon dioxide (CO_2) that can be released without exceeding these targets and current likely emissions trajectories (e.g., Lawrence et al., 2018). Best estimates put the overshoot on greenhouse gas emissions to 2100 at thousands of gigatonnes of CO_2 equivalents (Gt CO_2e; Anderson and Peters, 2016; Lawrence et al., 2018; Bellamy and Geden, 2019; National Academies of Sciences, Engineering, and Medicine [NASEM], 2019), although this overshoot is highly dependent on emissions trajectories and in the best case would be zero. Coastal and ocean systems are potentially attractive locations for storing excess carbon because of their large extent and potential for relatively long-timescale storage (e.g., Siegel et al., 2021; Mengis et al., 2023). Furthermore, the ocean is under much lower usage pressure than the land surface; although recent data show significant industrialization of the coastal ocean, the percentage of total ocean

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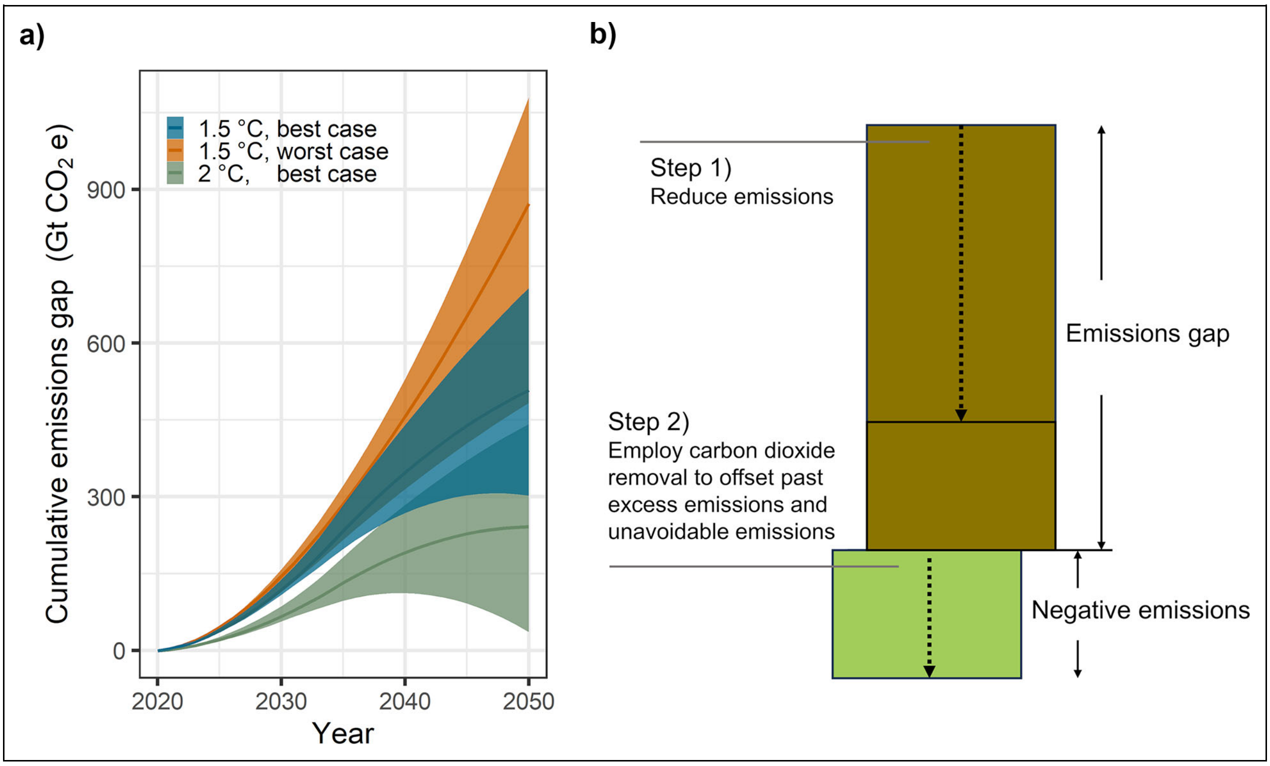

Figure 1. Closing the emissions gap. Left panel: We calculated the cumulative emissions gap using data and scenarios from the latest Emissions Gap Report by the United Nations Environment Programme (UNEP, 2023). These calculations demonstrate that, under best case policy action (current conditional nationally determined contributions and all net zero commitments), there likely will be hundreds of gigatonnes of excess CO_2 equivalents (Gt CO_2e) in the atmosphere in 2050 compared with least cost 1.5°C or 2°C pathways; in the worst case (current commitments only), there will be as much as 1000 Gt CO_2e for the 1.5°C pathway. Thus, there is no current realistic pathway to limit warming to 1.5°C or even 2°C without significant additional policy action in terms of emissions cuts or substantial application of carbon dioxide removal (CDR; UNEP, 2023). We can expect the cumulative emissions gap to be on the order of 1000–3000 Gt CO_2e by the end of the century under current policy commitments (Anderson and Peters, 2016; Lawrence et al., 2018; Bellamy and Geden, 2019; NASEM, 2019). Note that an emissions gap of zero is not the same as net zero—the emissions gap is the excess emissions relative to a least-cost pathway of emissions reductions to keep warming within certain bounds; that is, zero emissions gap equals *on track* to limit warming to within target following least-cost pathways (UNEP, 2023). Right panel: There are two components to closing the emissions gap: (1) primarily we must enact further cuts in emissions (dotted arrow in brown bar), with (2) CDR being used as a last resort (dotted arrow in green bar) to counter any remaining excess carbon (brown bar with no arrow).

area used is still vanishingly small (Paolo et al., 2024). The protection and restoration of coastal ecosystems are targeted explicitly in the nationally determined contributions (NDCs) of some countries (e.g., Herr and Landis, 2016), and marine carbon dioxide removal (mCDR) is relied upon implicitly, given the projected overshoot of the Paris Agreement temperature goals under current policy (United Nations Environment Programme [UNEP], 2023).

Commercial and government-funded mCDR initiatives are increasing in number, scale, and ambition. However, successfully demonstrated offshore CDR is limited in scale (Smith et al., 2023). There are substantial uncertainties and risks associated with large-scale marine climate interventions, highlighting the need for delayed or restricted implementation until extensive further research is conducted and policy frameworks put in place (e.g., Anderson and Peters, 2016; Carton et al., 2020; Williamson et al., 2022; Bach et al., 2024). While action and ambition ramp up, the economic, legal, and governance structures around mCDR are outdated, inadequate, irrelevant, or nonexistent (Boyd and Vivian, 2019; Gagern et al., 2022; Lebling et al., 2022b; Boettcher et al., 2023; Smith et al., 2023).

This Policy Bridge aims to provide a high-level synthesis of the background science and an analysis of the potential for coastal and marine carbon storage to contribute to mitigating excess CO_2 emissions and of the many barriers and uncertainties that might prevent this potential being reached, highlighting the need for effective and adaptive governance frameworks to support positive, beneficial, and timely action. We also consider responses of the marine system to climate change and human interventions that currently are not accounted for in climate models and thus could have a further positive or negative effect on achieving climate neutrality.

We take the approach of considering cumulative emissions and the *cumulative emissions gap* (**Figure 1**), which puts the potential scales of marine and coastal carbon storage in the context of the total amount of carbon that can be released while remaining within Paris Agreement temperature goals (1.5°C or 2°C). Full details, background and justification of this approach are provided in the Supplemental Materials (Text S1).

Carbon dioxide removal versus avoided emissions

Actions such as the preservation and conservation of natural carbon stocks (e.g., forests, coastal blue carbon [CBC] ecosystems) *avoid emissions* of carbon that is locked up in the biomass or sediment of the ecosystem (e.g., Mengis et al., 2023). Human actions that result in an uptake of carbon from the atmosphere that would have remained there were the actions not taken (*additionality*) and that store it securely for a sufficiently long timescale (*durability*) can be considered CDR (e.g., Mengis et al., 2023; Bach et al., 2024).

Protection of existing carbon stocks or storage services generally would not be considered CDR (e.g., Mengis et al., 2023) because the release of CO_2 from naturally formed carbon stocks sits on the opposite side of the CO_2 balance sheet (emissions reductions) to CDR actions (**Figure 1**, right panel). Protection of offshore natural carbon stocks or storage services (e.g., carbon stored in shelf sediments or phytoplankton-driven carbon uptake and export to the deep ocean) from anthropogenic impacts might also be considered as emission reduction (e.g., Hilmi et al., 2023b), although currently such processes are not incorporated into international frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC; Luisetti et al., 2019; Luisetti et al., 2020).

Restored or newly created ecosystems that enhance carbon storage into durable stocks, however, would be considered CDR, at least by some (Mengis et al., 2023). This article focuses on the potential for human action on coastal and marine systems to impact the emissions gap, whether as emissions reductions through preservation of CBC stocks and services or CDR actions.

Coastal blue carbon

CBC systems are recognized as important carbon sinks with substantial co-benefits for biodiversity and provision of ecosystem services such as storm protection, fish nurseries, biological filtering, and nutrient processing, as well as having climate adaptation benefits (e.g., Nellemann et al., 2009; Barbier et al., 2011; Gedan et al., 2011; Luisetti et al., 2014; Wylie et al., 2016; Luisetti et al., 2019; Hilmi et al., 2021; Hilmi et al., 2023a). CBC systems have been heavily encouraged on an international level for more than a decade and have emerged as key features of many NDCs under the Paris Agreement (e.g., Herr and Landis, 2016; Lecerf et al., 2021). Unfortunately, blue carbon habitats continue to be degraded and lost around the globe at alarming rates, with drivers including habitat destruction, nutrient loading, overexploitation, sea level rise, and climate-driven regime changes (Valiela et al., 2001; Gedan and Silliman, 2009; Polidoro et al., 2010; Pendleton et al., 2012; Macreadie et al., 2019). Further progress in NDC commitments to CBC preservation and restoration could result in significant additional climate benefits (Arkema et al., 2023). Recognition of the many benefits brought by these ecosystems, including carbon storage, along with innovations in funding mechanisms has led to an increase in protection and conservation projects (e.g., Wylie et al., 2016; Paulo et al., 2019; Layton et al., 2020). However, there is only limited, regional evidence that a slowing of the global net rate of loss of CBC ecosystems has been achieved (e.g., Friess et al., 2020; Saunders et al., 2020; Kuwae et al., 2022; Macreadie et al., 2022).

CBC actions are not without risks, nor are the climate benefits of CBC universally recognized. Friess et al. (2022) identified that the moral hazard of greenwashing, through the sale of carbon credits from CBC initiatives with no credible plans for emissions reduction, is a key political risk to the success of and public support for CBC. Further, we assert that the moral hazard of failure, ineffectiveness, or disingenuous claims of carbon benefits in CBC initiatives used to offset emissions is a risk to global climate mitigation. Johannessen and Christian (2023) recognized the potential social and environmental benefit of CBC conservation and restoration but question the carbon mitigation value of these systems due to the magnitude of their carbon storage globally being small relative to the scale of the problem, the risk of future loss of protected sedimented carbon (e.g., due to climate feedbacks) and the fundamental difference in timescale (and durability) between fossil and modern sedimentary carbon storage. These are all valid points. However, we argue that even a small amount of relatively short-term but robust and quantifiable emissions reduction or additional storage into coastal sediments can play a real, if modest, role in the urgent challenge of meeting Paris Agreement temperature goals, which is indeed recognized by Johannessen and Christian (2023) who stated "Expanding the area or increasing the carbon burial efficiency of blue carbon ecosystems could draw down some additional CO_2 from the atmosphere in the short term, buying time to implement other actions. Protecting existing blue carbon ecosystems could also help to stabilize the organic carbon already stored in the underlying sediment, preventing future losses."

Marine carbon dioxide removal

An mCDR action is any mitigation action that uses technical solutions or intervenes artificially in natural processes to modify carbon uptake by the marine system, predominantly by enhancing net air–sea CO_2 flux by a range of methods, including enhancing biological productivity or altering ocean chemistry (e.g., Gagern et al., 2022; Bach et al., 2024). The recognized associated risks of mCDR are significant, including possible negative side effects, potential ineffectiveness due to second-order effects, moral hazard (delaying emissions reductions), and challenges associated with its termination following successful climate change mitigation (e.g., Anderson and Peters, 2016; Haszeldine et al., 2018). All of these challenges must be mitigated for safe and effective deployment of mCDR, and a code of conduct for mCDR research and development has recently been proposed to address these issues (Loomis et al., 2022; Boettcher et al., 2023).

Timescales and natural system responses

There is a substantial lag time until mCDR is likely to be able to contribute significantly to mitigation (McGlashan et al., 2012; Nemet et al., 2018), and the urgent need to develop mCDR now for it to contribute successfully to climate change mitigation is "largely underappreciated" (Nemet et al., 2018). Overall, there is a serious disconnect between the perceived or implicit role of mCDR in future climate change mitigation and the readiness of technologies and knowledge of their potential impacts, as well as the policy, governance, legal, and economic frameworks, and the public discourse needed for the delivery of safe, effective, and socially acceptable mCDR to meet CO_2 removal requirements post 2050 (Larkin et al., 2018; Nemet et al., 2018; Fajardy et al., 2019; Carton et al., 2023).

The risks and potential benefits associated with climate change mitigation actions cannot be considered in isolation. The natural system will respond to climate change and its associated effects. The potential responses of the natural system are important to consider because (i) any negative response in the natural carbon cycle not captured in current projections will increase the size of the emissions gap that will need to be met to limit warming (Rogelj et al., 2019) and (ii) the risks of climate change mitigation actions may be outweighed by the risks associated with changes in the natural system in the absence of mitigation activity.

In this article, we present an illustrative examination of the potential contributions of a broad range of coastal and ocean-based management options to mitigate the likely CO_2 emissions gap between now and 2100, using data synthesized from the literature. In parallel, we consider the legal, economic, and social frameworks likely to be needed to ensure the safe and timely development of mCDR to achieve maximum carbon drawdown at minimum risk. We further evaluate a series of natural ocean carbon cycle responses to climate change and other anthropogenic forcings to highlight the scale of change and potential risks of inaction with respect to marine climate change, and how these might amplify or counteract some of the benefits of mCDR systems over the coming decades.

A complementary paper by Bach et al. (2024) in this special collection highlights the importance of governability, additionality, and predictability in ensuring manageable, useful, and quantifiable mitigation action from mCDR in the near future. Here we take a longer view, considering the scale of CDR needed in 2030 to have a significant impact on carbon budgets in 2050 and beyond.

Methods

Carbon sequestration scenarios

We synthesized data from the literature to evaluate the maximum potential carbon sequestration (or emissions reduction) capacity of CBC systems and a series of mCDR techniques ranging from conservation and restoration of blue carbon ecosystems to "far field" ocean-based climate interventions, some of which are purely speculative. We calculated likely minimum and maximum sequestration potentials based on potential rates and capacities from the literature. Here we have grouped carbon protection/sequestration actions into three types, which have commonalities in geospatial extent, nature of action, and consequently our approach to scenario analysis: CBC, shelf carbon management, and whole ocean solutions, each of which is addressed separately below.

Coastal blue carbon

For CBC ecosystems, we applied an area-based analysis, considering the current best estimates of the loss rates of salt marsh, mangrove, seagrass meadows, and macroalgal beds globally and the per-unit area carbon stocks and sequestration rates of these ecosystems (Table S1). We used these data to calculate net carbon storage to 2100 under the following scenarios:

- (i) Business as usual: The current rate of loss of habitat (and the concurrent loss of carbon stock) is maintained until 2100, with the remaining habitat sequestering carbon at the rates in the literature (Figure S1, Table S2).
- (ii) Halt loss: All habitat is protected immediately so that the loss is halted, and this constant area is maintained until 2100, continuing to store carbon year on year (Figure S2, Table S2).
- (iii) Extreme restoration: There is a year-on-year increase in habitat areas through aggressive habitat restoration until 2050, at which point pre-World War II area has been restored. Each year the extant habitats fix carbon at the rates in the literature (Figure S2, Table S2).

The last scenario is unrealistic for salt marsh and mangrove because of the nature of historical habitat destruction (e.g., cities and port construction) that cannot be undone, and the enormous rate and scale of action that would be required to achieve complete restoration by 2050. On the other hand, sea level rise may present potential new land area for blue carbon habitats to develop or be developed, albeit at the loss of other freshwater habitats or alternative land use options (e.g., Fagherazzi et al., 2019). In any case, the economic and social cost of the additional carbon stored by restoration will be much higher than that of simply protecting what remains. Replanting kelp and seagrass, however, is limited mainly by the availability of labor and finance, and such restoration activities are already ongoing, albeit at a relatively small scale (e.g., Eger et al., 2020). Net carbon sequestration on the scale of the halt loss scenario might therefore be achievable by counterbalancing unavoidable loss with new or restored habitat to maintain a constant area.

Shelf carbon management

Details of carbon storage scenarios for three shelf carbon management options are presented in Text S3. The utilization of riverine nutrients for macroalgal aquaculture and subsequent long-term sequestration of harvested biomass (e.g., Lehahn et al., 2016) was evaluated as follows. Intensive macroalgal aquaculture in river plumes was assumed to capture 50% of anthropogenic nutrients and convert them into seaweed (C:N ratio 18). Linear growth was projected, achieving maximum capacity by 2050. The uncertainty range was estimated by future scenarios of nutrient flux in 2025 (minimum, 50% of current; maximum, 5× current; details in Table S3, Figure S3).

The literature is equivocal about how vulnerable sedimentary carbon is to trawling (e.g., Legge et al., 2020; Smeaton and Austin, 2022); however, possible significant carbon emissions associated with trawling could be prevented. We extrapolated lower end estimates of carbon loss per-unit area trawled from recent studies (e.g., Luisetti et al., 2019; details in Text S3) and applied them to the global shelf area, assuming that 10% by area is protected immediately. The uncertainty range was calculated by applying a range of observed carbon stock and sequestration rates for shelf sediments.

The final shelf carbon management option we considered is that of enhancing dissolved organic carbon export to the deep ocean through management of excess shelf nutrient inputs. Nutrient availability is known to affect the bioavailability of dissolved organic matter (DOM; Jiao et al., 2014), and interannual variability in DOM export is large (e.g., Chaichana et al., 2019). We assumed that a small fraction of this DOM export is manageable through nutrient control (e.g., by using macroalgal aquaculture to extract nutrients and decrease biodegradable fraction of DOM). The potential range of carbon storage was calculated from the range of shelf dissolved organic carbon export estimates. Given the highly uncertain nature of this approach and the need for considerable additional research before it could even be confirmed as a quantifiable carbon management strategy, we assumed that this approach could only be counted toward mitigation from 2040 onward.

Open ocean mCDR

We considered the following mCDR methods, taking literature values of maximum potential sequestration rates: open ocean seaweed cultivation (e.g., Lehahn et al., 2016; Table S4), ocean alkalinization, ocean iron fertilization, macronutrient fertilization, and artificial upwelling (e.g., Keller et al., 2014; Harrison, 2017; Table S5). Full details of scenarios and input data are provided in Text S4.

We did not consider technological or economic limitations or negative side effects that might prevent technologies from being deployed or limit their effectiveness. We therefore estimated "near-maximum" potentials, in keeping with previous studies (e.g., Keller et al., 2014). Therefore, we cannot say with any certainty that any of the mCDR mechanisms considered will produce any useful mitigation without socially or environmentally unacceptable consequences. Thus, the difference between the potential and actual mitigation capacity of mCDR is currently unknown and that must be accounted for in economic planning, policy, legislation, and governance.

Growth rates of mCDRs

We took the novel approach of considering the likely limits to the year-on-year growth of mCDR technology, based on data on economic and technological growth rates (Nagy et al., 2013; Iyer et al., 2015), to project the total sequestration potential of mCDR options to 2100. We assumed a maximum achievable growth rate of 11% year on year, based on the progression of high-investment, high-regulation, and high-infrastructure-cost technologies such as nuclear power (Iyer et al., 2017). This growth rate is consistent with the 12% growth rate used to project potential growth in CO_2 capture capacity for ocean alkalinity enhancement, based on other industrial growth data, by Renforth and Henderson (2017). Growth beyond this rate is likely to require a "war footing" and be sustainable only for relatively short times (Morgan, 1994; Lund, 2006). Deployment was assumed to start in 2030, following a period of intensive research and development in the remainder of the 2020s. This scenario inevitably shifts much of the CDR capacity toward the latter part of the century. **Figure 2** illustrates the trade-off between growth rate and starting sequestration capacity required to achieve a given total impact by a particular deadline. This balance between starting capacity and required growth rate also represents a trade-off between the risks of deploying close-to-megatonne-scale experimental activities (potential local-/regional-scale negative impacts) sooner and the "rushing" to gigatonne-scale activities (and potential global impacts) later.

Overall, very little engineered CDR capacity has been delivered to date (Smith et al., 2023). Bioenergy with carbon capture and storage, one of the most heavily researched and funded emissions reduction technologies, currently has an experimental operating capacity of about 1.5 Mt CO_2 yr^{-1} (Consoli, 2019), thus requiring an almost 1000-fold scale-up to be operating at a scale that would significantly impact the emissions gap in the second half of this century. This rapid scaling up is not inconceivable, but the requirement highlights the challenge for even the most "mature" of CDR techniques to make an impact by or soon after 2050. Even at a scale 10 times smaller (0.1 Gt CO_2 yr^{-1}), any process interacting with natural ocean systems has the potential to have other significant, potentially negative impacts on the Earth system, so the need for rapid implementation of governance frameworks to ensure the safe development of mCDR is clear.

Coastal blue carbon and marine carbon dioxide removal potentials

Figure 3 presents the results of our analysis of the potential cumulative carbon sequestration by the methods

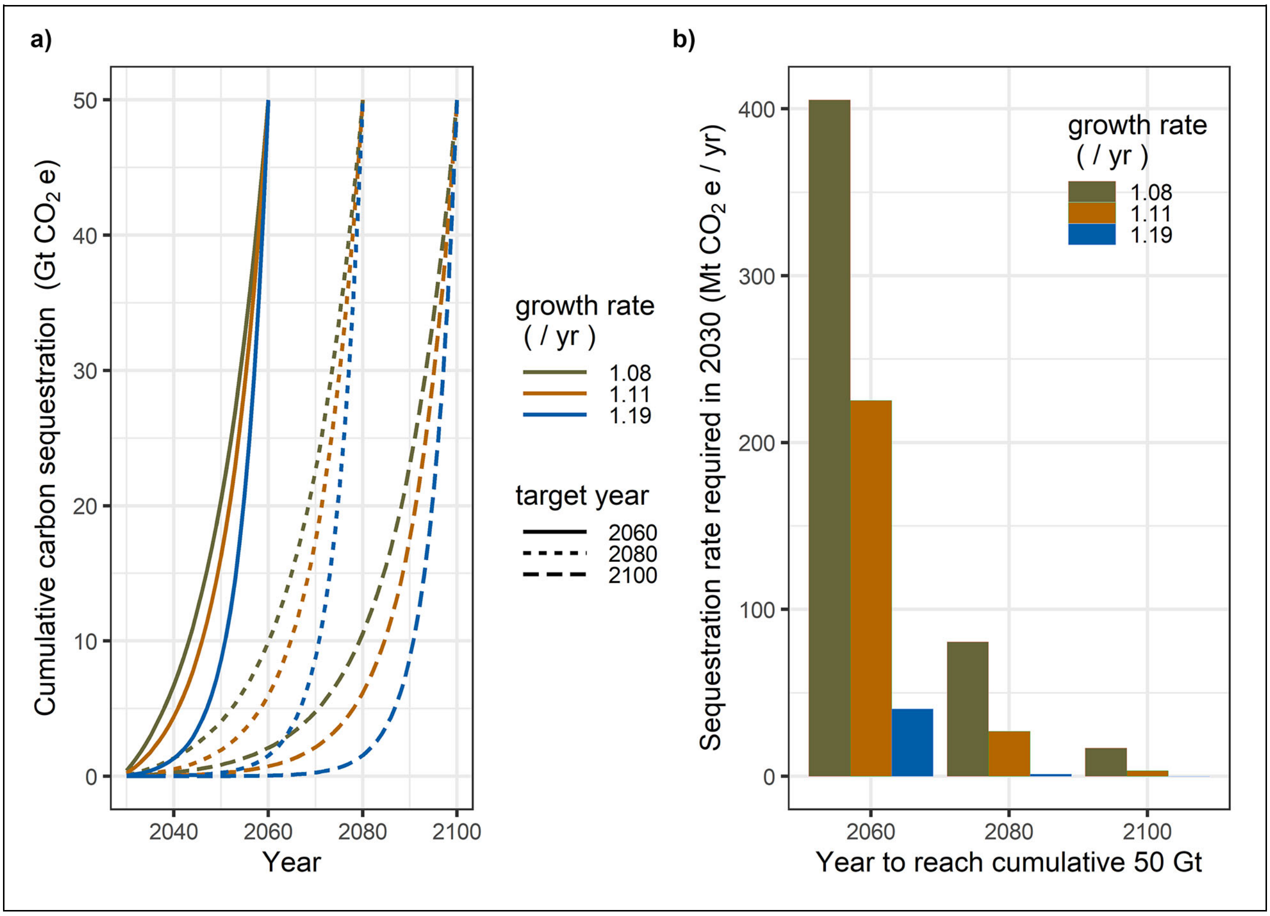

Figure 2. Growth rate and starting capacity in 2030: key determinants of timescale to achieve sequestration capacities. We calculated cumulative sequestration trajectories (left panel) for a hypothetical carbon dioxide removal (CDR) technique or a set of techniques for an arbitrary total sequestration rate of 50 Gt CO_2e to be achieved by a target year of 2060, 2080, or 2100 under annual growth rates of 8% (moderate), 11% (realistic but rapid), and 19% ("war footing"); see Text S5 for details. The starting capacity in 2030 required to achieve the targeted sequestration timescale is shown in the right panel. This analysis highlights that sequestration rates on the order of tens of Mt CO_2e per year are needed by 2030 for any realistic chance of achieving a significant impact by or before 2080. For example, given that bioenergy with carbon capture and storage currently has an experimental operating capacity of about 1.5 Mt CO_2 yr^{-1} (Consoli, 2019), a rapid (10–100 fold) upscaling of CDR will be needed by the end of the decade to make a significant contribution to the emissions gap before 2080.

considered, up to 2100, compared with the projections of the emissions gap at 2030 and 2050. We found that only two options have the potential to make a substantial contribution to carbon budgets over the next two to three decades: (i) conservation, protection, and restoration of coastal and shelf habitats (the bottom three color bands on **Figure 3**) and (ii) using the established technology of near-shore macroalgal aquaculture to sequester carbon from riverine nutrients (light green color block on **Figure 3**). Even these options can make only a relatively small contribution to meeting short-term emissions gaps and come with significant uncertainties regarding their additionality and predictability (e.g., Bach et al., 2024). Even under our most optimistic of scenarios, only toward the end of the century, and then only if the more controversial and extreme forms of action such as ocean fertilization are adopted at maximum potential scale, is mCDR potentially able to make a significant (i.e., 50% or greater) contribution to closing the projected emissions gap.

Unproven and potentially dangerous technologies would need to be deployed and operating at the level of sequestering tens of millions of tonnes of carbon per year, within a decade, if they are to be relied upon to scale up and play a significant role in CO_2 sequestration post 2050. The range of total CO_2 sequestration estimates is broadly consistent with the potential contribution of mCDR projected by a recent independent assessment of CDR technologies and pathways (Rocky Mountain Institute, 2023).

Coastal blue carbon contribution

Protecting, conserving, and (potentially) restoring coastal ecosystems has many benefits aside from carbon storage. However, even under the most optimistic assumptions, with active restoration of large areas, coastal ecosystems can probably only mitigate some tens of gigatonnes of CO_2, that is, at most 10% (and more likely <1%) of the emissions gap to 2100 (**Figure 3**). This projection is in line with the estimate in the IPCC Special Report on the Ocean

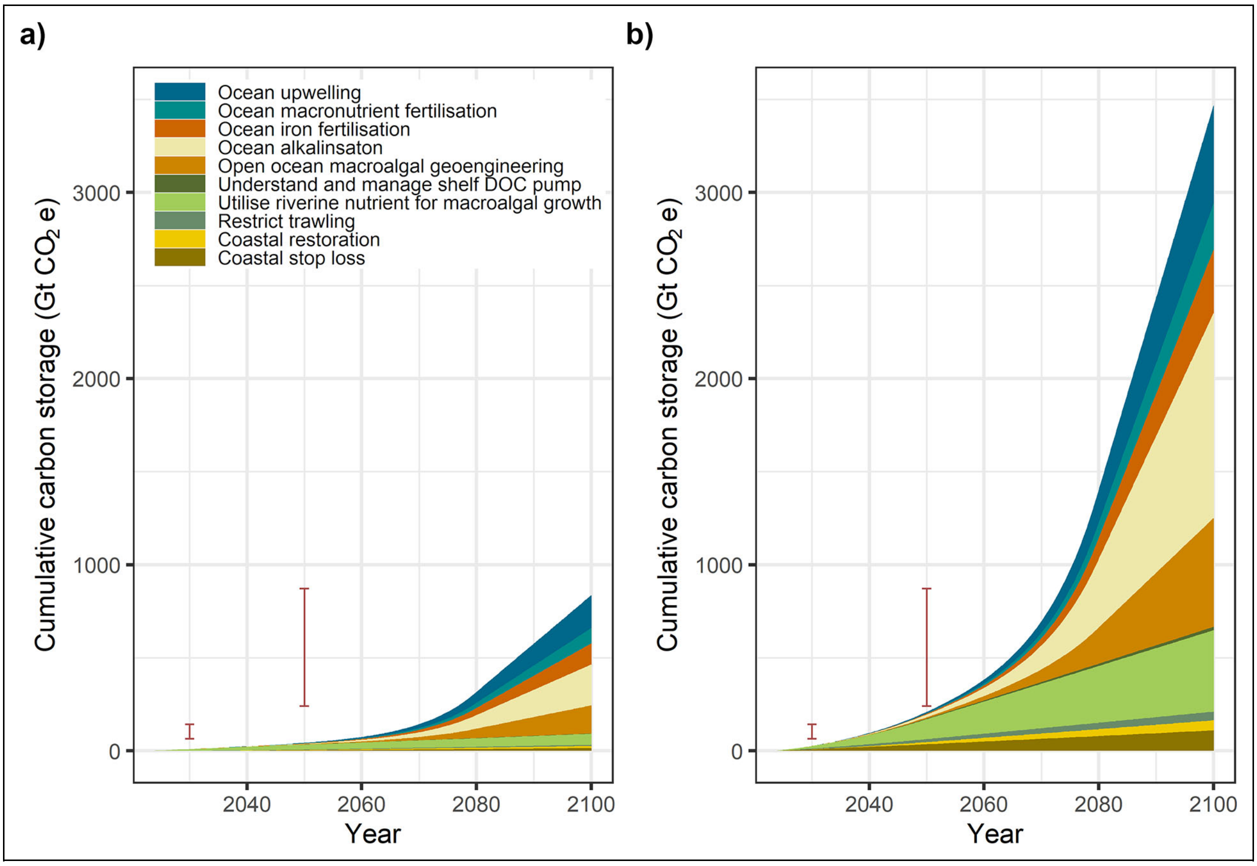

Figure 3. Evaluation of potential cumulative carbon mitigation for a series of coastal or marine mitigation actions. Based on literature values for current loss rates and potential sequestration rates (detailed in Texts S2–S4) and scenarios of growth (Text S5), we calculated the potential cumulative carbon impact of the (color coded) coastal blue carbon and marine carbon dioxide removal actions considered. Coastal blue carbon benefits are presented for the "stop loss" scenario and additional "restore" scenario (main text, method) with the four habitats (saltmarsh, mangrove, seagrass, and wild macroalgae) collated together for simplicity (see Figures S1 and S2 for by-habitat breakdown). The left panel shows the potential carbon storage capacity taking minimum estimates of sequestration rates, and the right panel shows the maximum estimate of potential storage capacity (details in Texts S2–S4). Note that, in both cases, the values presented are "potential" carbon impact; that is, the projections do not account for technological limitations or negative impacts on the marine system which might mean that particular techniques are not viable. In both panels, red whiskers show the likely magnitude of the cumulative emissions gap in 2030 and 2050, based on data from UNEP (2023; see **Figure 1**). DOC indicates dissolved organic carbon.

and Cryosphere in a Changing Climate, which suggests that only 0.5% of excess CO_2 could be stored as blue carbon (Bindoff et al., 2019). In 2030 or 2050, the likely potential contribution is an even smaller percentage of the carbon emissions gap.

The largest *potential* carbon gain in the conservation and restoration of coastal habitats (Figure S2) is in the protection/restoration of wild-growing macroalgae (kelp and other seaweeds), which cover large areas and are seeing substantial losses due to exploitation, shifting temperature ranges, and other environmental drivers such as pollution (e.g., Duffy et al., 2019; Pessarrodona et al., 2023). While not storing sedimentary carbon in situ, a small percentage of macroalgal primary production may be sequestered as organic carbon in shelf sediments, or as unreactive dissolved organic carbon in the marine carbon pool, on a climate-relevant timescale (Krause-Jensen and Duarte, 2016; Krause-Jensen et al., 2018). This percentage is highly uncertain (with a lower bound of zero), so further research is needed to understand carbon flows through macroalgae before it can feature in CO_2 emissions mitigation strategies (e.g., Legge et al., 2020). Other studies have highlighted possible net CO_2 release from kelp ecosystems, emphasizing the need for extensive further study before allocating CDR "credit" to kelp restoration efforts (Bach et al., 2021; Gallagher et al., 2022).

Shelf carbon management

Near-shore macroalgal aquaculture has the largest potential in our analysis to sequester carbon between now and at least 2070. This method would harvest some or all of the grown seaweed (Table S3) in order to sequester the carbon, not relying on the highly uncertain natural sequestration processes detailed in the previous section.

However, the upper end estimates assume humankind will fail to mitigate its huge perturbations to the nitrogen cycle and continue to increase the eutrophication of shelf seas. Clearly, ceasing this pollution (and the carbon emissions associated with fertilizer production) would be preferable, but it would substantially reduce the potential for macroalgal production (and thus the risk of negative impacts on natural systems; e.g., Campbell et al., 2019). Nonetheless, macroalgal aquaculture seems the most high-potential/low-risk option currently available of the mCDR methods considered.

In addition, we estimate that protecting 10% of global shelf sediments from disturbance from trawling might potentially provide an extra 6–49 Gt CO_2e of long-term carbon storage, although a large uncertainty is associated with this estimate because of the degree to which sedimentary carbon stocks are uncertain and geospatially variable (e.g., Legge et al., 2020; Smeaton and Austin, 2022). However, while only making a small and uncertain contribution to the emissions gap problem, the protection, conservation, and restoration of continental shelf systems can be considered "low regret" options (as defined for CBC systems by Gattuso et al., 2021).

Whole ocean mCDR

From 2070 onward, there is the potential for large-scale open ocean mCDR to contribute a significant amount of carbon sequestration (cumulatively 500–2500 Gt CO_2e by 2100), with open ocean macroalgal aquaculture and ocean alkalinization offering the largest potential gains. The former relies on hitherto unproved technology for growing seaweed in the deep ocean and also would require a considerable amount of the global ocean surface (approximately 1%–3% to achieve the range of potential carbon sequestration in **Figure 3**), with all the associated risks and trade-offs. This area is only one-tenth of the 9%–33% of the global ocean coverage proposed by the source papers (de Ramon N'Yeurt et al., 2012; Lehahn et al., 2016), with carbon sequestration scaled accordingly, but is still, in our opinion, pushing the limits of what might be feasible, environmentally sound, or socially acceptable (noting that publication of a negative emissions "solution" in the peer-reviewed literature does not mean that it is safe, feasible, or even worth pursuing; e.g., Johnson et al., 2008). Nonetheless, as with coastal macroalgal aquaculture, this open ocean approach at some scale could potentially provide a relatively safe and low risk, measurable carbon sequestration and is therefore likely to be a subject of increasing study and commercial development in the coming years.

The ocean alkalinization scenarios presented are based on estimates of the potential for physical addition of soluble alkaline materials to the surface ocean to stimulate carbon uptake or inhibit natural carbon release (e.g., Keller et al., 2014; Renforth and Henderson, 2017). This proposition is an attractive one because it is predictable and quantifiable based on physical chemistry, with biological processes not directly involved in the resulting sequestration. Ocean alkalinization nonetheless represents a huge global-scale perturbation of Earth's natural systems and so cannot reasonably be undertaken without extensive research, monitoring, governance, and legislation.

Clearly, if we are to rely on mCDR at any scale to meet the Paris Agreement goals, policymakers must act immediately to put systems in place to incentivize safe and responsible research, field testing, monitoring, and ultimately the adoption of the least damaging, most beneficial approaches to harnessing the ocean's capacity to sequester additional CO_2, including those approaches not yet discovered or anticipated. Below, we assess the current state of legal and economic frameworks addressing mCDR, identify shortcomings, and make recommendations.

Natural system responses

Extensive observational and modeling work over decades has demonstrated the complexity of the ocean carbon cycle and the difficulty in predicting the net effect of the many interacting responses of ocean carbon system components to rising CO_2 and other perturbations (e.g., Lomas et al., 2010; Boyd, 2015; Heinze et al., 2015; Rödenbeck et al., 2015; DeVries et al., 2017). More complex, higher order, or indirect responses are the hardest to predict and are least likely to be captured by climate scenario modeling and, therefore, are most likely to be omitted from emissions gap estimates (Rogelj et al., 2019). We present a non-exhaustive analysis of natural system responses to climate change and other relevant anthropogenic forcings in **Table 1**, along with likely non-CO_2-related side effects of these responses, to highlight the potential negative effects of CO_2-absorbing natural responses (e.g., loss of natural calcifying organisms such as coral reefs).

An additional important effect is the weakening and possible reversal of ocean and land sinks in response to reduced atmospheric CO_2 concentrations due to CDR. This weakening will potentially affect CDR's effectiveness and require additional CDR deployment to compensate by the end of the century under low-emissions scenarios (Jones et al., 2016). We do not attempt to quantify this effect but assume that it is accounted for in the uncertainty in the magnitude of the emissions gap to 2100.

The concept of additionality is detailed in the paper by Bach et al. (2024, part of this special feature "Boundary Shift: The Air-Sea Interface in a Changing Climate"). Additionality considers, holistically, the net climate change mitigation potential of an action compared with the "baseline" in the absence of that action. The above concepts highlight that both the baseline and the additionality of any mitigation action may vary, depending on the natural system response to climate change and to mitigation efforts, and that the additionality may vary over time for a given mitigation action on a particular climate trajectory. Quantifying these second-order responses is beyond the scope of this article and requires coordinated, ongoing modeling and observation efforts as part of the governance of CDR in the coming years and decades.

Policy, legal, and economic drivers and barriers

In order to facilitate positive climate actions, it is necessary to have enabling legislation and policy drivers, viable economic mechanisms and governance frameworks that

Table 1. Examples of ocean carbon system responses to climate change and other anthropogenic forcings not currently accounted for in emissions scenarios

Natural System Response	Net Additional Carbon Storage (+) or Loss (−) to 2100 (Gt CO_2e)[a]	Outcomes and Side Effects Beyond Carbon Response
Shelf denitrification of anthropogenic nitrogen inputs (from fertilizer)	Up to 81	Ongoing benefit of removal of anthropogenic nutrients. Nitrous oxide production, negative climate, and environmental impacts of fertilizer production and application
Weakening of ocean carbon pump	−238 to 10	Changing ecosystem structure. Unknown effects
Decrease in coral net calcification to zero by 2070 and subsequent net dissolution	3.3 to 41	Catastrophic loss of coral ecosystems
Loss of planktonic calcification	1.8 to 17	Change in pteropod community, second-order effects on carbon export, community change, and so on
Dissolution of magnesium-rich carbonates on continental shelf	0 to 293	Mediation of ocean acidification. Potential loss of calcifying organisms such as coralline algae

[a]Details of calculations of gigatonnes of CO_2 equivalents (Gt CO_2e) and references used are provided in the Supplemental Materials (Text S6).

incentivize best practice and ensure rigorous evaluation of carbon sequestration benefits (e.g., Macreadie et al., 2022). Under the Paris Agreement, States have pledged to make NDCs containing their intended achievements "to strengthen the global response to the threat of climate change" (UNFCCC Articles 2 and 3), including both emissions reductions and CDR (Borth and Nicholson, 2021). However, whether CDR, or even restoration of coastal ecosystems, is consistent with previous international laws is not immediately clear. The 1982 United Nations Convention on the Law of the Sea is essentially permissive regarding climate intervention in the marine environment, and the UNFCCC also appears fundamentally to support mitigation through climate intervention (UNFCCC Article 3(3)). However, some forms of action, such as ocean iron fertilization, would be in contravention of the London Protocol on pollution and dumping at sea (1972/1996), although a moratorium on the same is arguably contrary to the UNFCCC (specifically UNFCCC Article 3(3); Scott, 2014). Restoration of CBC ecosystems is potentially at odds with international biological diversity law, because the creation of one ecosystem may be to the detriment of another.

Neither the London Protocol amendments (1996) nor international environmental law is currently able to provide a framework that can address the ethical, policy, and legal issues related to climate intervention (Scott, 2013). Considering that the only regulation developed specifically for climate intervention on the international level—the amendments of the London Protocol—are a decade old and have not yet entered into force, application of legally binding rules that enable climate intervention and CBC ecosystem protection from the perspective of climate change might take too long, certainly on the international level. Thus, countries must develop their legislation in this direction and incorporate it into their NDCs as examples for others.

Socioeconomic incentives are seen as key to the successful implementation of CBC and mCDR systems (e.g., Herr et al., 2017; Bellamy, 2018). Carbon markets are a key component of this incentivization and are seen as the main vehicle for delivering CDR to meet Paris Agreement goals. However, these markets are fragmented, internally inconsistent, and do not necessarily recognize key properties of *durable* and *additional* storage, potentially undermining the value of the markets (Michaelowa et al., 2023). The notable recent example of the large majority of carbon credits issued by Verra, the world's leading carbon standard for the voluntary offset market, allegedly not being representative of real reductions in CO_2 emissions (Greenfield, 2023), highlights the risk of the current "gold rush" atmosphere in removal markets potentially tainting carbon markets with scandal and compromising their value (Michaelowa et al., 2023). Beyond these common issues, there are specific challenges for CBC and mCDR systems, and these are dealt with separately below.

Coastal blue carbon

While CBC ecosystems are starting to be considered and accounted for under the UNFCCC (e.g., Luisetti et al., 2020), progress toward effective universal protection of and incentivization for coastal ecosystems lags at least a decade behind that for tropical forests (Herr et al., 2016). Extant CBC ecosystems are increasingly well protected under national laws (Bell-James, 2023; Susanti and Yanti, 2023), and the recent Nature Restoration Law of the European Union provides a framework for active restoration activities (European Climate, Infrastructure and Environment Executive Agency, 2023). However, there are still many gaps in protection, locally and nationally (e.g., Susanti and Yanti, 2023), and the need for enabling legislation to facilitate integrated landscape-scale restoration of coastal habitats has been identified as significant, for both carbon storage and wider ecosystem services (Bell-James, 2023). However, to what extent international law requires states to restore marine areas is unclear (Akhtar-Khavari and Richardson, 2019). From a policy perspective, deciding on the historical trajectory of the ecosystem and thus to what state the ecosystem should be restored is difficult (Akhtar-Khavari and Telesetsky, 2016).

The total economic value of coastal and marine ecosystem services is usually significantly higher than the economic value of carbon sequestration and storage services alone (Milon and Alvarez, 2019). Carbon markets are limited when assessing the socioeconomic benefits of carbon-storing ecosystems because they do not account for the many co-benefits associated with these ecosystems beyond carbon storage (Herr et al., 2016), although co-benefits may feature in corporate offsetting decisions, which voluntary carbon markets tend to reflect in higher prices than compliance markets.

A recent analysis by Macreadie et al. (2022) has identified key development needs in the governance of CBC ecosystems: (i) principles and good practice for the equitable and sustainable sharing of benefits; (ii) legislation that enshrines carbon trading systems that are linked to land tenure and ownership of the sequestered carbon; (iii) filling numerous research gaps regarding different sources and sinks of greenhouse gases and the technologies and protocols for monitoring carbon storage and ecosystem co-benefits; all of which lead to (iv) the stakeholder-led establishment of quality assurance requirements for financial markets.

Protection and management of shelf carbon, including sedimentary stocks and mitigation of nutrient impacts from large-scale macroalgal aquaculture, may share some commonalities with protection and management of CBC in that they have non-carbon co-benefits (ecosystem health, fisheries productivity, valuable by-products, etc.) and would largely sit on the emissions reduction side of the CO_2 balance sheet, although there are substantial gray areas relating to natural baselines and what constitutes new carbon storage (e.g., macroalgal uptake) versus reduced emissions (nutrient reduction and impacts on the shelf carbon pump). Furthermore, transboundary issues relating to the transport of carbon storage services across geopolitical boundaries via shelf sea circulation is a complicating factor in the governance and attribution of carbon benefits (Luisetti et al., 2019; Luisetti et al., 2020). Thus (as must be the case with all CBC and CDR actions), case-specific evaluation of the biogeochemical and ecological context of actions to protect existing or sequester additional carbon in shelf seas is essential, including the potential positive and negative carbon feedbacks arising from connectivity between land use and ocean use (e.g., Burrows et al., 2014; European Environment Agency, 2022).

Marine carbon dioxide removal

Removing marine carbon dioxide differs from CBC in that, in most cases, there are few or no co-benefits beyond those arising from the direct impacts of mitigating climate change (e.g., ocean acidification). Given the international nature of mCDR projects (transboundary impacts; much CO_2 uptake is likely to be in the open ocean), there is a need for more top-down governance for mCDR than for CBC or terrestrial carbon projects (Bellamy and Geden, 2019), which presents a significant challenge given the disconnect between the need for rapid action and the slow-moving nature of international law. Meanwhile, interest and activity from the private sector in mCDR opportunities is growing rapidly (Lebling et al., 2022a; Loomis et al., 2022), which makes governance and regulatory frameworks all the more urgent.

Current academic efforts (e.g., Loomis et al., 2022), proposed legislation (Webb and Silverman-Roati, 2023), and even semi-commercially focused roadmaps for CDR implementation (Rocky Mountain Institute, 2023) are focused on research activities, rather than implementing global-scale climate impacts, highlighting the immaturity of the potential technologies and actions. These are essential first steps, but a regulatory framework for both deployment, measurement reporting, and validation and associated carbon markets is also needed urgently. How the emerging commercial mCDR sector is addressing the legal and regulatory gaps in their activities currently is not clear (although we assume that they would welcome regulation, as this de-risks their activities).

The economic mechanisms to incentivize engineered mCDR are even less developed than those for the protection and restoration of natural carbon-storing ecosystems. Some studies have suggested that the only feasible financing mechanism for mCDR activities would be a massive public subsidy by richer nations (Honegger and Reiner, 2018; Bednar et al., 2019; Fajardy et al., 2019). While the traded cost of carbon and discount rates apply, the financing challenge is as significant as the technological challenges of implementing gigatonne-scale climate interventions (e.g., Honegger and Reiner, 2018; Bednar et al., 2019). mCDR projects also present large economic risks and pitfalls (Neimark et al., 2016). Current knowledge gaps pose the risk that seemingly promising approaches that garner significant investment may subsequently be discovered to do unacceptable harm to natural or human systems and therefore require termination to limit further damage. As well as the huge associated financial risk, this risk of failure also comes with the moral hazard of relying on mitigation technologies instead of maximizing emissions reductions, only to find that the mitigation technologies are ineffective.

Currently, there are almost no monitoring, reporting, and verification (MRV) standards for mCDR processes (Palter et al., 2023), although grassroots efforts like the Guide to Best Practices in Ocean Alkalinity Enhancement Research has a section on MRV (Ho et al., 2023). Scientists are also developing open-source tools for independent evaluation and MRV of mCDR (e.g., see the non-profit research organization [C]Worthy, Boulder, Colorado, https://cworthy.org). Such initiatives are an opportunity for the mCDR community to develop the frameworks needed for MRV practices with a high level of integrity, by applying the lessons learned from both successful and problematic protocols that have been developed in terrestrial CDR projects.

In June 2023, some companies involved in mCDR activities began marketing CO_2 removal services to potential buyers of carbon credits to offset their emissions (Palter et al., 2023). Such commercial activity highlights the urgent need to develop methods for carefully quantifying the net carbon removal rates and storage durability of the various mCDR techniques (Palter et al., 2023), and full engagement between commercial, policy, and academic/research communities is essential.

While the details of particular issues may differ somewhat, the key enabling actions proposed by Macreadie et al. (2022) for CBC actions are largely transferrable to mCDR. The need for equitable and sustainable distribution of benefits, a robust legal (and regulatory) framework, independent scrutiny of the underpinning science, and quality assurance to support financial mechanisms are all needed for mCDR. In addition, financial mechanisms to share the risk of failure and support the rollback of actions that turn out to be ineffective or damaging are also essential in the case of mCDR, given the poor level of knowledge of the potential impacts.

Recommendations

Given the need for action *as soon as safely possible* in order for mCDR to make a useful contribution to mitigating the impacts of climate change when it is most needed (i.e., from 2050) and the clear gaps in regulation and governance, action is urgently required from policymakers. For any CBC or CDR action to occur in a safe and successful manner, it must be scientifically sound, legal, supported and regulated by policy, publicly acceptable, economically viable, and just and equitable (e.g., Fyson et al., 2020; Macreadie et al., 2022). Economic and legal frameworks must continually evolve in good time to facilitate the scale of deployment of CDR technologies required. As new ocean-based or terrestrial solutions are proposed and developed, they will likely continue to challenge these frameworks, and they must therefore be adaptive to continue to facilitate the safe and timely deployment of CDR. There are clear first steps outlined above to begin to facilitate this deployment, but, as knowledge and evidence grow, and the required magnitude of future CDR evolves, governance structures will need to adapt, including to a future phase-down of CDR as climate is stabilized.

Despite the risks, mCDR will likely be desired by policymakers and increasingly adopted by "climate tech" companies. We therefore propose an adaptive management and legislative development process, which engages the public, policymakers, scientists, investors, and businesses in the development and deployment of mCDR (**Figure 4**). This cycle would see stepwise scaling up of carbon storage capacity from research deployments to large-scale action in a "ratchet" mechanism for each individual technology/intervention. A governance and evaluation framework would be necessary, which would evaluate continually the social and environmental impacts and ensure net benefits, while prioritizing research and upscaling activities for the most promising selection of potential technologies (e.g., Bellamy, 2018). Furthermore, as with other aspects of climate policy and management, full and proper engagement with the public would be an essential part of ensuring a just and democratic utilization of globally shared environmental resources (e.g., Bellamy, 2018; Nemet et al., 2018; Cox et al., 2021; Cooley et al., 2023) and to prevent vested interests in powerful economies from benefiting disproportionately (e.g., Dunlap and Fairhead, 2014). Such a governance effort cannot be achieved without extensive investment at all levels in the knowledge exchange, brokerage, and management necessary to facilitate it (e.g., Johnson et al., 2020).

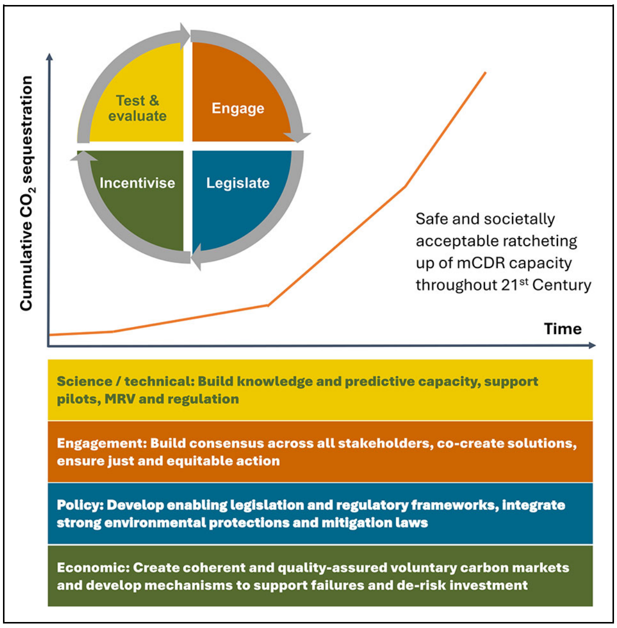

Figure 4. Governance cycle facilitating safe, acceptable development of marine carbon dioxide removal (mCDR) through this century. MRV indicates monitoring, reporting, and verification.

Achieving comprehensive and integrated governance is an enormous challenge. We propose here that a key first step is international support and funding for an inclusive knowledge exchange forum for all stakeholders to engage with and begin the co-creation of the necessary governance structures. Such a forum could potentially be coordinated through an international scientific body such as the Surface-Ocean Lower-Atmosphere Study (SOLAS, https://www.solas-int.org/), given the necessary funding and governance supports (Johnson et al., 2020).

Economic incentives and carbon valuation will also need to adapt if mCDR is to be deployed safely and effectively. Without a mechanism to value the future carbon sequestration potential by actions taken now, the lag time on the development cycle of mCDR will likely be too great to achieve safe, large-scale carbon sequestration in the second half of this century without wholesale economic restructuring to a permanent war footing. Action is needed immediately to boost progress to a level where normal economic growth can take mCDR to climate intervention scales of action in useful timescales. Already very difficult to envision is any way in which mCDR can contribute significantly to climate change mitigation by 2050 without taking extreme risks with the ocean system and the immediate investment of trillions of dollars in untested and unproven technologies. Legislation for mCDR, therefore, needs to encompass both the protection of the marine system and the governance and economic frameworks necessary to address the many challenges associated with the rapid research, development, and deployment cycle needed to maximize the potential benefit from the safe development of climate mitigation actions using ocean and coastal systems.

Conclusion

The degree to which coastal and marine systems might play a role in future climate change mitigation is ultimately a policy decision. The protection and restoration of CBC habitats have the potential to mitigate a few percent of excess CO_2 emissions between now and 2100, with substantial co-benefits and a very low risk of negative consequences, by utilizing already existing frameworks (e.g., Luisetti et al., 2019; Laffoley, 2020; Luisetti et al., 2020; Hilmi et al., 2021; Hilmi et al., 2023a), although steps are still needed to make CBC sequestration activities safe, just, and quality-assured (Macreadie et al., 2022). Although progress has been slow to date, protection and restoration nonetheless represent the "low-hanging fruit" of marine carbon mitigation. There is still work to be done on understanding the variability in net carbon storage of these CBC habitats under different conditions and the flows and fate of carbon from macroalgal growth. There is also debate in the literature about the partial negation of carbon storage benefits by the release of the strong greenhouse gases methane and nitrous oxide (e.g., Al-Haj and Fulweiler, 2020; Rosentreter and Williamson, 2020; Williamson and Gattuso, 2022). While CBC ecosystem protection and restoration is a climate change "no brainer," to what extent any carbon mitigation activities can be relied upon is much less certain, and extensive research and monitoring work is necessary for accurate predictions to feed into climate change mitigation scenarios. Furthermore, the market incentivization of the protection and restoration/expansion of coastal ecosystems relies largely on the carbon markets, which currently undervalue the cost of carbon emissions and have been argued to be unfit to incentivize positive actions with the required urgency (Rosenbloom et al., 2021). Therefore, we currently rely on governmental and charitable funding to ensure that the opportunity to protect and sequester additional coastal carbon is fully realized, while market mechanisms catch up and are able to support operationalized carbon action in the future (e.g., Honegger et al., 2021; Kuwae et al., 2022; Michaelowa et al., 2023).

Other management and protection options in shelf seas may be possible to potentially mitigate further tens to hundreds of gigatonnes of CO_2 by 2100. These options include the restriction of trawling to limited areas of shelf seas (via, e.g., broader and better-enforced marine protected areas) and the management of nutrient inputs to shelf seas (via either reduced inputs or targeted macroalgal aquaculture at or near river mouths). These actions also appear to have few negative consequences and are for the most part analogous to protection or restoration. There is substantial uncertainty, however, about the likely efficacy of these actions on carbon storage, and the mechanisms for incentivizing such activities are less clear. Therefore, research, monitoring, and financing programs are needed to evaluate and facilitate the inclusion of these actions in climate change mitigation targets.

Beyond the coastal conservation actions, large-scale ocean climate interventions (i.e., mCDR) may collectively have the potential to sequester sufficient carbon to offset a meaningful proportion of excess emissions in the latter part of this century. However, there are likely to be unintended (potentially catastrophic) consequences from these actions, as well as substantial social and economic costs (e.g., Larkin et al., 2018; NASEM, 2019; Gattuso et al., 2021; Williamson et al., 2022). The risk is high that ultimately they will not sequester the amount of carbon projected. The likelihood of negative outcomes can be reduced by effective governance, and so the economic incentive mechanisms and appropriate legislation urgently need to be put in place to allow well-regulated and safe research and development of these potential carbon mitigation technologies.

Current legal and regulatory frameworks are insufficient to protect the marine environment from the potential negative effects of mCDR and are also a potential barrier to the safe and expedient development of any potentially beneficial mCDR technologies and trials. New international and national legislation is needed for marine carbon mitigation activities. This legislation must be adaptive to the evolving needs of society and nature, as the emissions pathway and Earth system response play out, and to the new and unforeseen technologies and strategies that will develop and their associated challenges and pitfalls.

The ability to incentivize climate-positive action around mCDR is limited by the focus and scale of economic mechanisms and frameworks currently in place to drive positive action for the climate and the environment. The larger the scale of ambition for coastal and marine systems to contribute to carbon mitigation, the greater the need for substantial socioeconomic restructuring, that is, to a war footing in the short term, and ultimately to a future economy in which carbon sequestration is financially beneficial. However, we currently have no precise figures on the likely scale of safely deployable mCDR, no regulations, and therefore no real possibility of effectively including these new projects in the carbon markets. We need to respond to this problem quickly, correctly, and using reasonable scenarios (effectiveness of methods, specificity of projects, carbon sequestration time, socioeconomic impacts on coastal populations, etc.). Methods will have to be put in place to establish a rigorous quantification of the various issues, and many experts, regulators, economists, investors, practitioners, and stakeholders will have to be mobilized. Above all, political agreement on governance frameworks is essential and urgent.

Legal instruments

1. United Nations Convention on the Law of the Sea 21 *International Legal Materials* 1261 (1982).

2. Convention on Biological Diversity 31 *International Legal Materials* 822 (1992).
3. United Nations Framework Convention on Climate Change 31 *International Legal Materials* 849 (1992).
4. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention), 1972: Final Act, 1996 Protocol and Resolutions 36 *International Legal Materials* 1 (1997)
5. Paris Agreement 55 *International Legal Materials* 740 (2016).

Supplemental files

The supplemental files for this article can be found as follows:

Figures S1–S3. Text S1–S6. Tables S1–S5.Docx

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Competing interests

The authors declare no competing interests.

Author contributions

MJ led the scenario modeling effort with support from HT, CM, NM, DA, and PS. Legal and Economic review and assessment was conducted by EVD, NH, LL, and LDA. DTH advised on carbon cycle and negative emissions. MJ led authoring effort and created figures. All authors contributed to the conception, writing, and editing of the manuscript and approved the submission.

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