Subsection 5A

Chapter 10

Geoengineering

Key points

- The scientific consensus remains that proposed novel geoengineering approaches are unproven in practice, and there is significant uncertainty about the impacts of pilot studies and upscaled experiments, especially where these experiments are planned over large ocean areas.
- Paris Agreement-compliant Intergovernmental Panel on Climate Change (IPCC) scenarios indicate that 7 gigatons of CO_2 ($GtCO_2$) to 9 $GtCO_2$ CO_2 removal (CDR) would be needed per year by 2050, in addition to reductions in greenhouse gas emissions. Currently only 2 $GtCO_2$ p.a. of conventional, low-durability terrestrial CDR has materialized.
- Monitoring, reporting and verification (MRV) protocols will be key to determining whether marine carbon dioxide (CO_2) removal (mCDR) approaches are effective.
- mCDR research studies may advance the state of key knowledge in the coming decade.
- Governance frameworks are limited and fragmented. Efforts to develop an international legally binding governance framework under the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and its 1996 Protocol (London Protocol) are progressing.

1. Introduction

This new chapter in the *World Ocean Assessment* outlines current understanding of and road maps for marine-based geoengineering. This is defined under the London Convention and Protocol as “a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe”.[1]

This chapter takes a broad remit, including marine-based: CO_2 removal (CDR): “human activity that captures CO_2 from the atmosphere and stores it for decades to millennia” (Smith and others, 2024), solar radiation modification (SRM) and structural engineering. Some countries are of the view that a cautious approach to SRM technologies is needed, as they carry numerous risks, not only for the environment but also with regard to geopolitical and security concerns.

Further reading on this subject can be found in the following documents:

- “The state of the science for marine carbon dioxide removal (mCDR) – a scientific summary for policymakers” (GESAMP, 2025[2]
- *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (NASEM, 2022)[3]

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[1] Resolution (LP.4(8) (not in force) (https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.4(8).pdf), available at https://www.imo.org/en/knowledgecentre/indexofimoresolutions/pages/ldc-lc-lp.aspx.

[2] Available at https://oceanrep.geomar.de/id/eprint/62361/.

[3] Available at www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration.

- *Principles for Responsible and Effective Marine Carbon Dioxide Removal Development and Governance* (Doney and others, 2025)[4]
- Ocean Visions high-level road map (Ocean Visions, 2023)[5]
- *Strategy for NOAA Carbon Dioxide Removal Research* (Cross and others, 2023)[6]
- *Guide to Best Practices in Ocean Alkalinity Enhancement Research* (Oschlies and others (eds), 2023b)[7]
- A code of conduct for marine carbon dioxide removal research Program (Boettcher and others, 2023)[8]
- The State of Carbon Dioxide Removal (Smith and others, 2024)[9]

The Paris Agreement (2015) sets a goal of limiting temperature increases to "well below 2˚ C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5˚ C above pre-industrial levels", which will require rapid, deep and sustained greenhouse gas reductions and ultimately the attainment of net zero CO_2 emissions by mid-century (IPCC, 2018; UNFCCC, 2023). A significant gap remains between international targets and the actions required to limit the extent of warming to 1.5˚ C (IPCC, 2023). All scenarios and action pathways that lead to achievement of the Paris goal require global net negative emissions, whereby the greenhouse gases taken up by land and ocean exceed the amount released to the atmosphere (Schipper and others, 2022). One proposed pathway for achieving this is the implementation of geoengineering approaches to counterbalance residual or harder-to-abate emissions (Pathak and others, 2022; IPCC, 2022) and their impact on global warming. That said, methodologies remain unproven in practice, requiring significant research abiding by the precautionary approach (Cooley and others, 2023). Furthermore, there is considerable debate around the definition and quantification of residual emissions (Buck and others, 2023).

The range of biological, chemical and physical processes that influence air-sea CO_2 exchange (see subsect. 5B, chap. 1) suggest that it may be possible to enhance the rate and capacity for ocean carbon storage through methods such as the implementation of mCDR techniques (NASEM, 2021) (see figure I). Some mCDR methods seek to enhance the diffusion of atmospheric CO_2 into seawater by increasing the production and/or storage of organic carbon or by altering the inorganic pool of dissolved carbon. Biological mCDR techniques, including direct nutrient addition or upwelling of nutrient rich waters to encourage primary production and the restoration of coastal vegetated ecosystems , potentially stimulate the conversion of dissolved CO_2 into plant matter through photosynthesis. Permanent or long-term removal requires the export or burial of the carbon such that its release back into the atmosphere following degradation is prevented. Deposition of terrestrial and marine biomass into the deep ocean for long-term storage is also proposed. Chemical mCDR approaches propose enhancing the capacity of the ocean to absorb atmospheric CO_2 either by increasing alkalinity, which forces the conversion of dissolved CO_2 into the more stable compounds (carbonate and bicarbonate ions), or by electrochemically removing the dissolved CO_2 for geological storage . In both cases the perturbations in seawater chemistry are

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[4] https://oceanpanel.org/wp-content/uploads/2025/06/OP_mCDR_Blue-Paper-1.pdf.

[5] https://oceanvisions.org/wp-content/uploads/2023/10/A-Comprehensive-Program-to-Prove-or-Disprove-Marine-Carbon-Dioxide-Removal-Technologies-by-2030_FINAL.pdf.

[6] https://sciencecouncil.noaa.gov/wp-content/uploads/2023/06/mCDR-glossy-final.pdf.

[7] https://sp.copernicus.org/articles/sp-oae2023-full-report.pdf.

[8] Available at www.aspeninstitute.org/publications/a-code-of-conduct-for-marine-carbon-dioxide-removal-research/.

[9] www.stateofcdr.org/.

designed to create an air-to-sea gradient that drives the absorption of more atmospheric CO_2 into the ocean . Physical mCDR approaches, including the downwelling of carbon-enriched surface waters, have also been suggested (GESAMP, 2025).

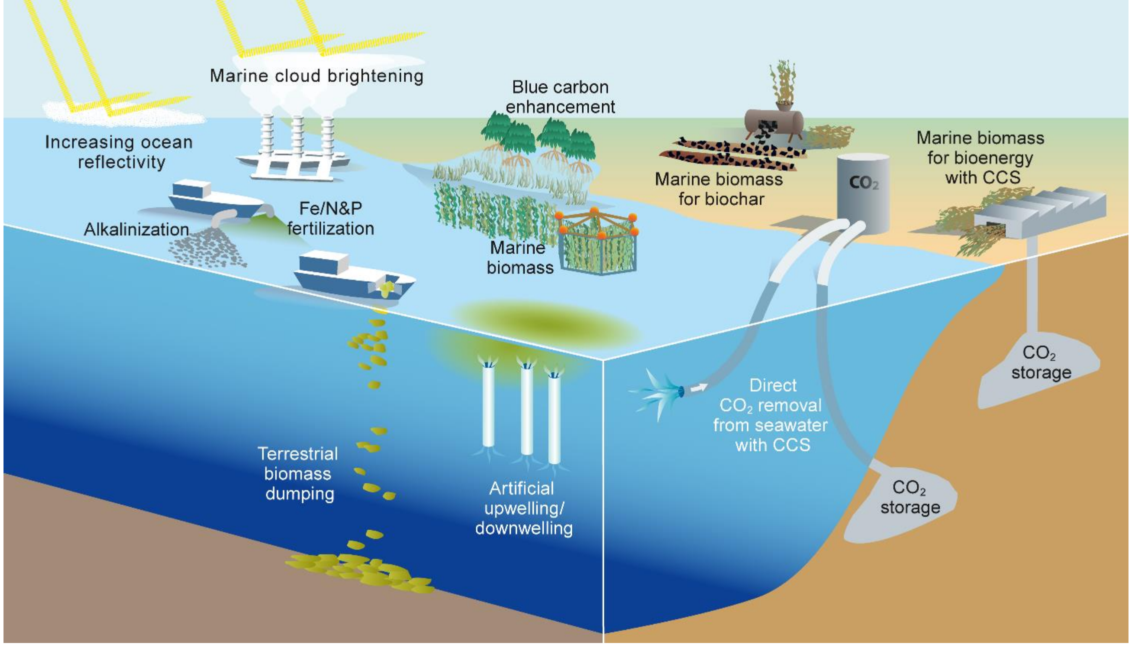
Ultimately, the successful long-term storage of CO_2 sequestered by CDR depends on either its incorporation into stable biogeochemical compounds in the ocean and ultimate burial in deep sediments (e.g. Boyd and others, 2024) or CO_2 capture and geological storage , which offers the most certainty for permanent CO_2 removal (IPCC, 2022). The placement of CO_2 saturated fluids on the deep seabed for long-term storage has also been considered (IPCC, 2005), as has the deposition of terrestrial biomass (Levin and others, 2023). All of the techniques have uncertain ecological impacts, long-term stability and legality.

Structural geoengineering techniques include the adoption of low-carbon manufactured building products and the design of marine structures to enhance biodiversity (UNEP 2023, Fennel and others, 2021, Dafforn and others, 2015, Firth and others, 2024). Such approaches may be relevant as coastal development (including for mCDR) progresses (see subsect. 5A, chap. 9).

Marine SRM approaches seek to explore increasing the albedo of the atmosphere or the ocean's surface, enabling more energy to be reflected away. Techniques include seawater sprays to stimulate cloud formation, sea ice enhancement, microbubbles and reflective foams (e.g. GESAMP, 2019); figure I). Ocean heat displacement and the use of more sustainable or biobased materials in ocean engineering have also been proposed as mechanisms for supporting decarbonization through the production of renewable electricity and CO_2 emission reduction during construction (GESAMP, 2019; NRC, 2006).

Figure I

Solar radiation modification and mCDR approaches

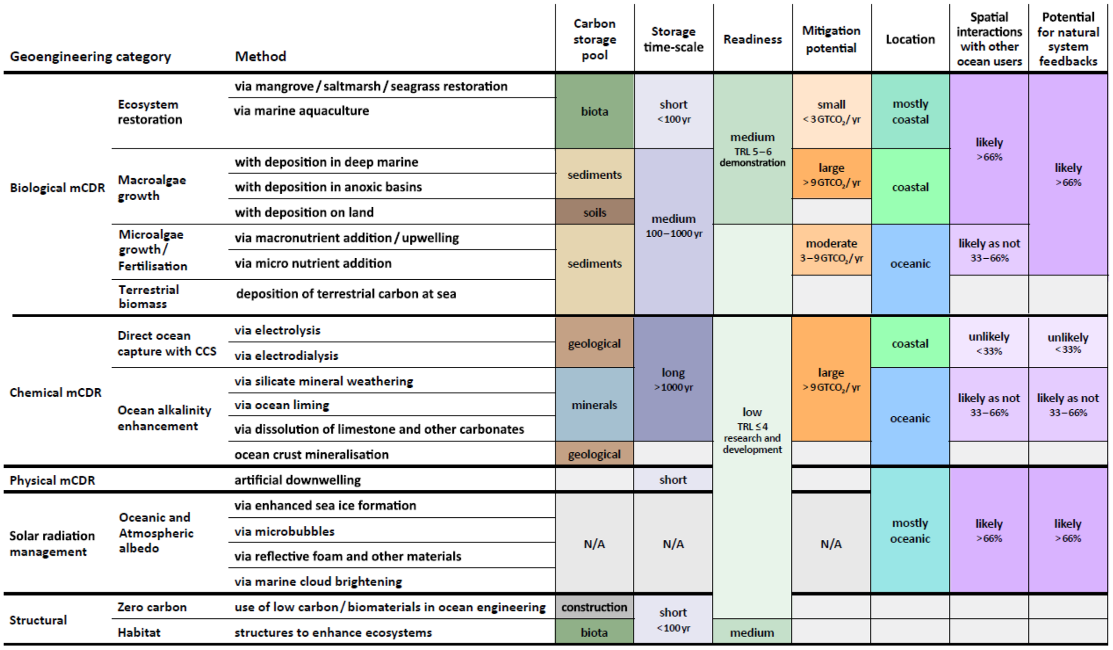


Source: Artwork, Rita Erven, Helmholtz Centre for Ocean Research Kiel (GEOMAR), Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0)

Although the fundamental scientific principles of geoengineering approaches are well known, their technological maturity, environmental impact and potential for wide-scale implementation vary significantly (see figure II). Several recent synthesis reports outline the challenges and research gaps (see above), and while there is debate, the current consensus is that most of the techniques are not yet proven effective, safe or technologically mature enough to scale. Correspondingly, the level of investment in marine-based techniques remain considerably lower than terrestrial alternatives such as direct capture, bioenergy with CCS (BECCS) and biochar (Smith and others, 2024). Notwithstanding the London Protocol (see below), there are no binding international agreements that comprehensively and specifically address mCDR (Webb and others, 2023). Controlled pilot studies are starting to address some of the critical knowledge gaps in these approaches. GESAMP (2024) currently identify more than 39 mCDR initiatives aimed at sequestering carbon in the marine environment. Of these, the most numerous are macroalgae farming, ocean alkalinity enhancement, biomass sinking and ocean fertilization (28%, 20%, 18% and 15%, respectively). Crop wastes feature strongly in the biomass disposal category, alongside sargassum, accounting for a further four of the macroalgae farming initiatives. The development of monitoring, reporting and verification (MRV) protocols that assess carbon storage while accounting for local to global-scale marine processes, is another recognized research priority. Additional uncertainties regarding inter alia environmental impacts, resource use, societal acceptability and economic viability of marine geoengineering and mCDR approaches will need to be adequately addressed, with effective governance frameworks implemented, before considering deployment at climatically relevant scales. This chapter outlines the current challenges and priorities for marine geoengineering, including mitigation potential, environmental effects, impacts on communities, economic feasibility, governance and pathways for ensuring sustainable development.

Figure II

Status of mCDR and other marine geoengineering approaches and the potential changes



Geoengineering category		Method	Carbon storage pool	Storage time-scale	Readiness	Mitigation potential	Location	Spatial interactions with other ocean users	Potential for natural system feedbacks
Biological mCDR	Ecosystem restoration	via mangrove / saltmarsh / seagrass restoration	biota	short <100 yr	medium TRL 5–6 demonstration	small <3 GTCO$_2$/yr	mostly coastal	likely >66%	likely >66%
		via marine aquaculture							
	Macroalgae growth	with deposition in deep marine	sediments	medium 100–1000 yr		large >9 GTCO$_2$/yr	coastal		
		with deposition in anoxic basins							
		with deposition on land	soils						
	Microalgae growth/ Fertilisation	via macronutrient addition / upwelling	sediments		low TRL ≤ 4 research and development	moderate 3–9 GTCO$_2$/yr	oceanic	likely as not 33–66%	
		via micro nutrient addition							
	Terrestrial biomass	deposition of terrestrial carbon at sea							
Chemical mCDR	Direct ocean capture with CCS	via electrolysis	geological	long >1000 yr		large >9 GTCO$_2$/yr	coastal	unlikely <33%	unlikely <33%
		via electrodialysis							
	Ocean alkalinity enhancement	via silicate mineral weathering	minerals				oceanic	likely as not 33–66%	likely as not 33–66%
		via ocean liming							
		via dissolution of limestone and other carbonates							
		ocean crust mineralisation	geological						
Physical mCDR		artificial downwelling		short			mostly oceanic	likely >66%	likely >66%
Solar radiation management	Oceanic and Atmospheric albedo	via enhanced sea ice formation	N/A	N/A		N/A			
		via microbubbles							
		via reflective foam and other materials							
		via marine cloud brightening							
Structural	Zero carbon	use of low carbon / biomaterials in ocean engineering	construction	short <100 yr					
	Habitat	structures to enhance ecosystems	biota		medium				

Source: Based on Smith and others (2024) and Cooley and others (2023).

Note: Blank spaces indicate a lack of data.

2. Pressures and impacts

Chemical mCDR approaches

It is contended that chemical mCDR methods that increase the pH and/or alkalinity of seawater (either through mineral addition or electrochemical methods) have significant long-term carbon sequestration potential (NASEM, 2022; Kwiatkowski and others, 2023; Oschlies and others, 2023; Palmiéri and Yool, 2024; see also subsect. 5B, chap. 3). However, complex multi-scale ocean mixing processes, and the long timescales required for CO_2 diffusion into seawater (Jones and others, 2014), create significant uncertainty for their potential efficacy. Oceanic uptake of CO_2 might decrease in the future as a consequence of progressing ocean warming (enhancing outgassing), continuing ocean acidification (decreasing oceans' storage capacity) as well as potentially reduced CO_2 emissions due to successful climate policy (Gruber and others, 2023). Furthermore, any alteration to marine chemistry resulting in increased carbon storage will impose chemical gradients that exceed normal variability. Reducing these gradients by spreading operations over larger areas will have implications for both cost and monitoring and for the social acceptability of mCDR projects (Satterfield and others, 2023). Increasing seawater pH and alkalinity may not linearly enhance carbon storage. At a higher pH, bicarbonate saturation can reach a tipping point, reducing the efficiency of further CO_2 uptake and potentially leading to diminished or even negative effects on carbon drawdown (Suitner and others, 2024).

A large body of research describes ecosystem impacts arising from increasing levels of CO_2 leading to ocean acidification (Doney and others, 2020). Conversely, little work to date has looked at the ecological effects of increased alkalinity. Subhas and others (2022) and Ferderer and others (2022) both noted limited impacts on plankton communities during small-scale microcosm experiments but highlight the need for further research (Bach and others, 2024).

Estimates of chemical mCDR potential have been reported in the range of 3 $GtCO_2\ yr^{-1}$–30 $FtCO_2\ yr^{-1}$ (Köhler and others, 2013; Renforth and Henderson, 2017; Feng and others, 2017), but current pilots operate at the scale of tons. CDR activities would need to increase in both number and capacity by orders of magnitude, accompanied by increased environmental impacts and process uncertainties, within a relatively short timescale (Ocean Visions, 2023; Boyd and others, 2024).

Apart from sequestration and impact potential, the scalability of chemical mCDR approaches will depend on the deployment location (open ocean or coastal), deployment strategy (e.g. choice of alkalinity source), delivery mechanism, infrastructure needs (e.g. ships, systems for electrochemical stripping) and feasibility, energy requirements, raw materials and contamination, collectively making a full life-cycle analysis imperative (Eisaman and others, 2023).

Biological mCDR approaches

The conservation and expansion of macroalgal coastal ecosystems such as salt marshes (sect. 4, subchap. 5I), mangroves (sect. 4, subchap. 5H), seagrass meadows (sect. 4, subchap. 5G) and kelp forests (sect. 4, subchap. 4I) protects biodiversity, stabilizes coastal habitats and act as carbon sinks, with an estimated storage potential of less than 3 $GtCO_2\ yr^{-1}$ (UNFCCC Ocean Dialogue, 2023; Canadell and others, 2021; Erlania and others, 2023; Krause-Jensen and Duarte, 2016; do Amaral Camara Lima and others, 2023; Yau and others, 2023).

Macroalgae aquaculture can potentially contribute to mCDR if it leads to long-term carbon storage but will compete with phytoplankton for nutrients (Berger and others, 2023). Alternatively, such aquaculture can contribute indirectly to reducing climate pressures through food and product provision, improving water quality (Krause and others, 2022; Duarte and others, 2022) and mitigating local ocean acidification and deoxygenation (Guang Gao and others, 2022; Xi Xiao and others, 2021; Dinghui Zou, 2005). Deposition on deep ocean sediments of harvested macroalgae, or terrestrial biomass, may significantly increase carbon sequestration and its climatic benefits (e.g. Wu and others, 2023), although the potential scalability and durability remains uncertain (Berger and others, 2023). Other post-harvest uses of macroalgae (feed additives to reduce ruminant methane emissions, biofuels and plastic substitutes) have additional climatic benefits (Kinley and others, 2020), while the removal and use of beach wrack for agricultural soil improvement can have a positive impact on carbon sink efficiency if done sustainably (Lanari and others, 2024). Crucially, impacts on habitats and populations stemming from the alteration of the ecosystem must be considered (Ross and others, 2023; Chopin and others, 2024; Hyndes and others, 2022). Deposition of shells from shellfish aquaculture has also been proposed as a mCDR technique by restoring alkalinity, although the efficiency of the process has been questioned, and full life cycle assessments are yet to be conducted (e.g. Boyd and others, 2024).

Microalgal mCDR methods are aimed at increasing primary productivity through fertilization using micronutrients, such as iron fertilization, or macronutrients (e.g. nitrogen, phosphorous) through the upwelling of deep nutrient rich waters. Iron fertilization has been shown to promote the local growth of phytoplankton, particularly diatoms, but an increase in the amount of carbon that reaches the deep ocean is not generally observed (Boyd and others, 2007; Martin and others, 2013; Jiang and others, 2024). Iron fertilization may also lead to widescale changes in nutrient distribution, reduced interior oxygen concentrations and decreases in ecosystem biomass in the tropics with implications for fisheries (Tagliabue and others, 2023). Concerns such as these led Parties to the London Convention and London Protocol to issue a statement of concern in 2007 (IMO, 2007), leading to the adoption of a resolution in the following year that introduced the first international controls on ocean fertilization activities (IMO, 2008). Further research is needed, following the London Protocol 2013 guidelines for scientific research to better assess the efficacy, impacts and feasibility of this approach (Buesseler and others, 2024). Fertilization through the upwelling of nutrient-rich waters has been shown have scalability constraints, with the CDR potential of the approach thought to be limited to 0.1 $GtCO_2$ y^{-1} (Koweek, 2022; Yool and others, 2009).

Physical mCDR approaches

Artificial downwelling has been proposed as a method to accelerate the sinking of carbon carrying biomass to the deep ocean, driven by pumps or increased salinity gradients (NASEM, 2022), with only regional tests conducted (Stigebrandt and others, 2015). Primarily proposed as a method by which to counter deep ocean hypoxia, impacts and efficacy in sequestering carbon are unknown. Impacts on local temperature, salinity and plankton communities can be envisaged, and model studies have suggested that downwelling is highly unlikely to be competitive (Zhou and Flynn, 2005).

Structural geoengineering

Traditionally, coastal and marine developments involve the construction of rigid infrastructures such as seawalls, piers, ports as well as wind farms and oil platforms. These constructions, although needed for a wide range of societal demands, have considerable environmental impacts, including habitat loss. The production of building materials also generates carbon emissions (Fennel and others, 2021).

Geoengineering approaches can be applied in this context to promote low-carbon sustainable development practices aimed at mitigating environmental impacts from both existing and new marine infrastructure. Biobased materials are emerging as a solution for decarbonization through the responsible management of carbon cycles, with the potential for reducing construction-related emissions by up to 40% by 2060 (UNEP, 2023; Fennell and others, 2021). This approach involves using alternative raw materials, cement chemistries and fuels in the production process. Other approaches, such as eco-engineering, may also be viable alternatives, through the design of structures to promote the colonization of carbon-capturing organisms (Dafforn and others, 2015b; Firth and others, 2024).

Implementing a large-scale transition to circular and biobased materials in the built environment involves significant risks. Without careful planning, decarbonization can lead to unintended ecological impacts, if biobased materials are not sourced sustainably (UNEP, 2023). In addition, it can worsen unfair labour practices and result in uneven economic shifts during industry transitions (Lehne and Preston, 2018).

Solar radiation modification in marine environments

Unlike CDR approaches which reduce atmospheric CO_2, the root cause of warming, SRM works by reflecting incoming solar radiation, purporting to cause a cooling effect (MacMartin and others, 2018). While theoretically effective, there is potential to generate adverse impacts on climate, weather, ecosystems and air quality with geopolitical implications (Jones and others, 2013; Jones and others, 2018; NASEM, 2021; UNEP, 2023; Mengis and others, 2016). From an ocean perspective, changing the heat and light reaching the surface ocean may alter ecosystems by changing hydrodynamics, nutrient supply to the photic zone and photosynthetically available radiation. The effect on carbon cycles is highly uncertain (Cao, 2018; Zarnetske and others, 2021). Consequently, at present, SRM is a controversial approach, with no international consensus on research pathways (UNEP, 2023) or successful calls to establish international scientific review and governance processes to ensure an equitable, transparent and rigorous body of knowledge (UNEP, 2023).

Monitoring, reporting and verification

An acute challenge for geoengineering is establishing protocols that deliver sufficient knowledge into the efficacy and impact potential of each method and generate trust in regulators, publics and markets (e.g. Ho and others, 2023; Boyd and others, 2023). The time and spatial scales over which geoengineering interventions may be realized complicates such protocols, and the potential lag between mCDR implementation and carbon drawdown presents a challenge for financing.

Joint model and observation approaches to MRV for mCDR are recommended (Fennel and others, 2023), so that predictive models can establish the likelihood of success of a given intervention, while being appraised by observations. However, models have inherent uncertainties, which cannot be completely resolved by cost-limited observations, suggesting that complete certainty will be elusive (Bach and others, 2023) and the risks must be carefully considered in advance of any trials.

From an observational perspective, environmental sensors and their deployment options (e.g. autonomous platforms such as Biogeochemical-Argo floats, gliders and drones) are generally well established (e.g. Yin and others, 2021; Lichtschlag and others, 2021). However, their capability for measuring key parameters for conducting market- and regulatory-acceptable MRV at and beyond initial deployment locations is yet to be proven. Similarly, the financial costs and carbon emissions of at-sea monitoring are currently considered to be prohibitive for at-scale implementation and remain a focus of ongoing research activities.

Modelling capability among scientists is relatively well established, falling into two broad categories.

- High-resolution local and regional scale models, that address single or clusters of geoengineering/mCDR operations, assessing dispersal, ecosystem impact, local sequestration efficacy and advection to deep water (Khangaonkar and others, 2024).
- Global ocean or Earth system models that assess the long-term effectiveness of upscaled geoengineering /mCDR approaches, which consider the biotic and abiotic carbon cycles and macroscale hydrodynamics and operate on decadal to millennial scales (Oschlies and others, 2023; Bach and others, 2023).

Lack of fully comprehensive biodiversity in standard marine models may restrict the ability to accurately simulate biological mCDR or specific impacts. While the marine carbonate system is well understood, care must be taken that the chemical parameterizations still hold for mCDR interventions and are applied in both observational and modelling studies (Dupont and Metian, 2023; Schulz and others, 2023).

MRV for mCDR is a rapidly growing area of research drawing on natural analogues (Subhas and others, 2023) and small-scale field trials (Cyronak and others, 2023). Decision-support tools (Chay and others, 2022) also provide high-level frameworks with which to indicate confidence levels for various approaches, although the status of current certification practices remains complex, diverse and inconsistent (Arcusa and Sprenkle-Hyppolite, 2022). By contrast, protocol development for SRM is in its infancy.

3. Socioeconomic considerations

Societal perceptions

Public attitudes towards mCDR and geoengineering are divergent (Jebari and others, 2021). On the one hand, there is theoretical support for strategies to reduce CO_2. On the other, opposition emerges when specific projects are proposed, owing to uncertainties about their risks and reversibility, as well as governance shortcomings (Cox and others, 2022). This tension is further compounded by the divide between “natural” and “engineered” solutions, as public perceptions are heavily influenced by how technologies are framed (Bertram and Merk, 2020).

Conditional supporters favour mCDR technologies, but their acceptance is typically contingent on the perception of co-benefits, controllability and alignment with conservation efforts (Bertram and Merk, 2020). For example, in countries such as the United States, Canada and the United Kingdom, where prior knowledge of CDR remains very low, public support can waver depending on actual or perceived risks and benefits (Cox and others, 2020). This type of support is particularly evident in responses to different approaches: ecosystem-based solutions, such as blue carbon management, tend to receive more public support, while engineered methods such as ocean fertilization face significant resistance (Jinnah and others, 2021).

Less controversial approaches which align with traditional conservation methods, such as wetland restoration and algal farming, tend to receive general (or unconditional) support. Acceptability follows from perceived co-benefits, e.g. food security and enhanced biodiversity (Were and others, 2019). These nature-based solutions are preferred globally, especially where local livelihoods are intertwined with ecosystems (Bertram and Merk, 2020). However, even supporters of climate mitigation express concerns about the potential social, economic or environmental impacts. These concerns grow when interventions appear intrusive or large scale, particularly with engineered solutions such as ocean alkalinity enhancement (Bertram and Merk, 2020).

In the global North, concerns are often centred around environmental risk and governance, with public preference leaning towards small, localized projects (Bertram and Merk, 2020; Baum and others, 2024).

In the global South, large-scale projects intended to offset emissions in the global North often raise ethical issues regarding land use and sovereignty (Zeng and others, 2021; Hickel and Slamersak, 2022). Concerns about exploitation and inequity in the global South are further fuelled by fears of wealthier nations' reliance on technological fixes rather than reducing their emissions at the source (Jinnah and others, 2021). This amplifies opposition in areas where the risks associated with new technologies are perceived as disproportionately impacting poorer nations (Satterfield and others, 2023). This resistance to mCDR projects is not confined to one region but is observed globally, reflecting a scepticism towards interventions considered disruptive or overly risky.

Also significantly influencing public acceptance of mCDR is the perceived urgency of climate change (Bellamy, 2022). Openness towards mCDR does not equate to uncritical acceptance. Comfort with specific technologies varies depending on perceived risks and uncertainties. While solutions such as coastal restoration and direct air capture tend to be more favoured, experimental technologies such as ocean fertilization and ocean alkalinity enhancement face greater scepticism, largely owing to concerns about environmental impacts and the permanence of carbon storage (Cox and others, 2024; Nawaz and others, 2023). Generally public support for geoengineering techniques such as SRM are lower than those for mCDR, with concerns about controllability, reversibility and a preference for mitigation techniques over temperature management (NASEM, 2021). These disparities reflect how risks and uncertainties associated with those technologies, as well as climate vulnerability, inequity and development priorities, shape regional attitudes towards climate intervention technologies.

Economic potential and sustainability

The economic potential of geoengineering depends on integration into carbon markets, providing financial incentives and fostering new industries. The co-benefits from certain mCDR techniques could include supporting sectors such as tourism and fisheries, contributing to a "blue growth" strategy. This is the case notably for ecosystems restoration.

However, integrating CDR into markets entails significant risks. A primary concern is mitigation deterrence, where reliance on credits substitutes for, rather than complements, emission reductions (Trencher and others, 2024). Neglecting the mitigation hierarchy – whereby emission avoidance and reduction should precede reliance on removals – risks fostering overreliance on market mechanisms and delaying decarbonization (Caldecott and Johnstone, 2024).

Further risks concern the environmental and social integrity of carbon markets, including challenges such as the risk of low-quality credits misrepresenting actual emission reductions (Trencher and others, 2024). On the supply side, challenges include ensuring additionality, permanence, accurate monitoring, avoidance of double counting and independent verification (Kreibich and Hermwille, 2021). On the demand side, credible claims and protections against greenwashing are essential (Trencher and others, 2024). Without double-claiming prevention, the voluntary carbon market (VCM) may struggle to encourage genuine mitigation efforts. Accurate MRV is essential for maintaining market credibility, as inadequate MRV creates uncertainties about the actual carbon removal achieved. As environmental conditions change, it becomes challenging to assess the true impact of CDR projects, leading to credits that may not accurately reflect real carbon removal. Issues of additionality also arise when projects receive credits for carbon removal that would have happened without market incentives (Betz and others, 2023).

VCM, provided that solid guardrails are established, such as those established in the standards and methodologies of the Paris Agreement Crediting Mechanism, could provide a valuable means for financing climate action and sustainable development, especially for projects in vulnerable areas. Smaller-scale projects such as the Mikoko Pamoja (mangrove restoration) project in Kenya, funded through the VCM, offer a promising opportunity for small island developing States (Kairo and others, 2018), although VCM for projects in developing States is more suited to ecosystem restoration, as opposed to other geoengineering approaches such as ocean alkalinity enhancement or ocean fertilization. This approach can be especially effective when combined with organic certification in areas with existing aquaculture, generating revenue through carbon credits, supporting local livelihoods and community development.

To tackle challenges of accurately measuring carbon sequestration within restoration (Macreadie and others, 2019), regional and international networks such as the Blue Forests Project,[10] the Blue Planet fund[11] and the Blue Carbon Initiative,[12] are developing best practices to effectively utilize international carbon finance (OECD, 2020), although this currently applies to habitat restoration rather than geoengineering.

Overall (i.e. not mCDR specific), carbon credit issuances are currently increasing exponentially (37 million tons CO_2 by July 2025 - CDR.fyi[13]), while retirements of carbon credits have plateaued (Sylvera, 2024). The economic feasibility of the carbon market hinges on developing MRV capacity and a combination of technical readiness, storage verification, supportive policies and strategies to mitigate carbon leakage (emissions reductions in one region that lead to increased emissions elsewhere, Schroeder and Stracca, 2023), while maintaining industry competitiveness (IFC, 2023).

Generally, the global carbon market is bolstered by policies and mechanisms facilitating emissions reductions and promoting sustainable investment (IFC, 2023). Carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems such as the European Union Emissions Trading System, incentivize companies to reduce emissions. The idea of integrating carbon removals into the European Union ETS is gaining traction (Meyer-Ohlendorf, 2023).

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[10] https://gefblueforests.org/.

[11] https://icai.independent.gov.uk/html-version/blue-planet-fund-review/.

[12] www.thebluecarboninitiative.org/.

[13] www.cdr.fyi/.

Supportive policies are applied to encourage market participation. On 10 April 2024, the European Parliament approved the Carbon Removals and Carbon Farming (CRCF) Regulation,[14] creating the first European Union-wide framework for certifying carbon removals, carbon farming and carbon storage. It sets quality standards, tackles greenwashing and promotes investment in carbon removal technologies and sustainable farming to support the European Union's climate goals.

Various levels of implementation for sustainable ocean-based economy programmes, including established official development assistance, involve key mechanisms such as conservation trust funds, blue carbon payments and private sector concessions. Improving practices that facilitate carbon sequestration by ocean ecosystems offers economic opportunities through emerging blue carbon markets. These activities require a robust framework for successful carbon investing, including precise measurement and verification (World Bank, 2023).

4. Sector-relevant governance

Governance of marine geoengineering and CDR spans international, regional and domestic frameworks. Currently, there are no binding international laws specifically governing marine geoengineering or CDR, but various general international agreements and rules of customary international law may apply (e.g. United Nations Convention on the Law of the Sea; International Tribunal for the Law of the Sea, advisory opinion on climate change and international law, 2024; International Court of Justice, advisory opinion on the obligations of States in respect of climate change, 2025) (see also sect. 3). Non-binding instruments, including a 2010 resolution of the Parties to the Convention on Biological Diversity, which applies to geoengineering broadly (e.g. decision X/33 (2010)) and widely agreed conventions have bridged regions (e.g. International Law Commission, Prevention of Transboundary Harm from Hazardous Activities;[15] Oxford Principles on Geoengineering[16]).

Marine geoengineering could implicate various provisions of the United Nations Convention on the Law of the Sea,[17] including those governing marine scientific research and protection of the marine environment, particularly as marine scientific research has been interpreted as encompassing marine geoengineering research (Brent and others, 2019; Webb and others, 2023). Under articles 192 and 194 (1), the Convention includes an obligation to protect the marine environment by taking all measures "necessary to prevent, reduce and control" marine pollution. Other provisions include the obligation not to transform one type of pollution into another (United Nations Convention on the Law of the Sea, art 195; International Tribunal for the Law of the Sea, advisory opinion, 2024). This has some implications for geoengineering both directly in association with the introduction of substances or energy into the ocean (Ghaleigh and Boyle, 2016; Reynolds, 2018; Webb and others, 2023) and also indirectly through its application to reduce greenhouse gas emissions. In its advisory opinion, the International Tribunal on the Law of the Sea determined that greenhouse gas emissions into the atmosphere constitute marine pollution and thus States have an obligation to reduce emissions under the Convention.

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[14] https://www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/ENVI/DV/2024/03-11/Item9-Provisionalagreement-CFCR_2022-0394COD_EN.pdf.
[15] https://legal.un.org/ilc/texts/instruments/english/draft_articles/9_7_2001.pdf.
[16] See www.oxfordmartin.ox.ac.uk/geoengineering.
[17] https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

The modernizing London Protocol, an extension to the London Convention (1972), entered into force in 2006 but has not been ratified by all Convention Parties, and thus the two instruments continue to operate jointly. While the Convention is generally more permissive of dumping of wastes, the Protocol takes a more precautionary approach, prohibiting the dumping of all wastes and other matter, except those on the "reverse list" in annex 1. In 2006, CO_2 was added to annex 1 to the Protocol, thereby enabling sub-seabed carbon storage , subject to purity standards and risk assessment procedures, amended in 2009 to allow export of CO_2 to other countries for storage. The amendment is yet to enter into force but has been provisionally applied since 2019. Furthermore, in 2012, the governing bodies for the Convention and Protocol adopted specific guidelines for the assessment of Carbon Dioxide for disposal into sub-seabed geological formations (LC 34/15, annex 8) to guide its implementation. These instruments have implications for some forms of mCDR.

In 2008, the Parties to the London Convention and Protocol adopted a non-binding resolution on ocean fertilization, declaring that "ocean fertilization activities other than legitimate scientific research should not be allowed" (resolution LC-LP.1, adopted on 31 October 2008). In 2010, the Parties adopted an assessment framework for evaluating proposed scientific research projects, requiring (among other things) ex ante environmental review and ongoing monitoring and management of risks (resolution LC-LP.2, adopted on 14 October 2010). This approach to ocean fertilization of permitting some legitimate scientific research but restricting commercial deployment was codified in a formal amendment to the London Protocol in 2013 (resolution LP 4(8), adopted on 18 October 2013). The amendment is yet to enter into force but is intended to establish a governance framework for certain marine geoengineering and CDR activities listed in a new annex 4 (Röschel and Neumann 2023). Currently, only ocean fertilization is listed.

In 2022, Parties to both the London Convention and the London Protocol committed to evaluate four marine geoengineering techniques – ocean alkalinity enhancement, biomass cultivation for carbon removal, marine cloud brightening and surface albedo enhancement – for potential listing under the 2013 amendment (London Convention, 2022). While that process remains ongoing, in 2025, the Parties issued a statement on marine geoengineering.[18]

The United Nations Framework Convention on Climate Change (UNFCCC, 1992) does not contain explicit references to geoengineering. It contains references to "removal by sinks", language repeated in the Paris Agreement (UNFCCC, 2015). The Convention defines "sink" as "any process, activity or mechanism which removes a greenhouse gas…from the atmosphere" (UNFCCC, 1992). The recognition of the ocean's critical role in climate action under Convention has evolved significantly over time.

While yet to enter into force, the 2023 Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction[19] may have implications for marine geoengineering and CDR activities. For example, Part III outlines a framework for establishing area-based management tools, and Part IV outlines detailed

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[18] See the summary of the forty-seventh Consultative Meeting of Contracting Parties to the London Convention and the twentieth Meeting of Contracting Parties to the London Protocol (LC 47/LP 20), available at https://www.imo.org/en/mediacentre/meetingsummaries/pages/lc-47-lp-20.aspx.

[19] See https://www.un.org/bbnjagreement/en.

environmental assessment requirements, which could be used to control where and how marine activities are conducted (Webb, 2024).

In addition, potentially relevant to marine geoengineering and CDR are international agreements governing shipping, such as the International Convention for the Prevention of Pollution from Ships Convention),[20], global human rights conventions and regional seas conventions including the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)[21] and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention),[22] the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention)[23] and the Convention on the Protection of the Black Sea Against Pollution (Bucharest Convention)[24].

Emerging domestic governance frameworks

To date, decisions relating to CDR and other marine geoengineering activities have often been regulated under domestic environmental laws, including (although not restricted to) laws enacted to implement the London Convention and Protocol and other international agreements; however, regulation varies significantly between countries (Silverman-Roati and Webb, 2023). For example, in the United States, the federal Marine Protection, Research, and Sanctuaries Act – i.e. the domestic law implementing the Convention – governs many marine activities. Other federal, state, tribal and local laws may also apply to some projects. The laws of a few countries allow research for marine geoengineering or CDR, subject to permitting and other requirements (Silverman-Roati and Webb, 2023). At least one other country, Australia, has taken steps to implement the 2013 London Protocol Amendment revising its Environment Protection (Sea Dumping) Act 1981, but the revisions will not take effect until the London Protocol Amendment enters into force.

By contrast, other countries have implemented regulation that is more restrictive than the 2013 London Protocol amendment. For example, in Germany, the High Seas Dumping Act prohibits any addition of substances to the ocean in connection with marine geoengineering and/or CDR, with only a limited exception for certain ocean fertilization research (Proelss and Steenkamp, 2023).

See also section 3 of the present *Assessment*.

5. Sustainability pathways

The ability of mCDR to make a meaningful contribution towards global targets is theoretically plausible but not yet established. Nevertheless, interest and efforts on the research and development of various techniques has accelerated significantly since the publication of the World Ocean Assessment II, delivering a rapidly evolving knowledge base. Generically, motivations and challenges identified are

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[20] https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

[21] www.ospar.org/convention.

[22] https://helcom.fi/about-us/convention/.

[23] https://www.unep.org/unepmap/who-we-are/barcelona-convention-and-protocols.

[24] http://www.blacksea-commission.org/_convention.aspwww.blackseacommission.org/Official%20Documents/The%20Convention/Overview/.

diverse and sometimes opposing, but may be broadly summarized as environmental, social, economic, regulatory and technical.

There can be potential co-benefits of certain macroalgal mCDR approaches, for example in protecting biodiversity, creating gender positive roles and providing food and other resources (Larson and others, 2021; Zhang and others, 2022). Development of macroalgae approaches for mCDR will require a sustainability framework that emphasizes the critical importance of environmental limits and constraints imposed by nature and ecological impacts (Boyd and others, 2023) and incorporates performance indicators, ensures societal acceptance and enables policymaking that takes into consideration marine space allocation and reduces regulatory barriers (Cordell and others, 2009; Krause-Jensen and Duarte, 2016; Herrero and others, 2021). Conversely, biological mCDR methods based on the stimulation of phytoplankton productivity are thought to offer fewer direct co-benefits and have greater potential for disruptive ecosystem feedbacks, by altering the magnitude and geography of marine primary production (Tagliabue and others, 2023).

Concentrating mCDR deployments in designated offshore marine areas could provide infrastructural, economic and environmental benefits through a multi-use approach (Schupp and others, 2019) reducing user conflicts. Seaweed farming, for instance, adapted to local conservation targets can contribute to the goals of marine protected areas (MPAs), all while providing jobs and revenue to local communities (Le Gouvello and others, 2017).

Motivations and challenges derived from the United Nations regional workshops

	Motivations	*Challenges*
Environmental	☐ Addressing climate change and the Paris Agreement goals ☐ Reducing ocean acidification, greenhouse gas levels and emissions ☐ Preserving marine ecosystems, biodiversity and ecosystem services ☐ Sea level change management ☐ Understanding impacts of geoengineering on ecosystems ☐ Nature-based solutions	☐ Life-cycle assessment, including lack of feasibility studies and post implementation impact understanding ☐ Potential for and lack of assessment of significant negative impacts, including technological limitations
Social	☐ Quality of life for future generations ☐ Sustainable communities ☐ Application of traditional knowledge	☐ Social licence to operate, awareness and education ☐ Ethical and moral challenges – managing finite resources, who benefits and who pays, transnational impacts

Economic	☐ Limiting economic threats of climate change ☐ Lowering cost of geoengineering/CDR and capacity-building	☐ Lack of incentive, financing and funding for capacity-building, especially in the least developed countries and small island developing States
Governance	☐ Development of regulations, legislation and policies ☐ International cooperation and dissemination	☐ Lack of consistent policy, regulations, monitoring and standards ☐ Interactions between landlocked and coastal States
Technical	☐ Technology development, innovation and excellence in research and development ☐ Technology for exploration and sustainable exploitation of natural resources ☐ Digital toolboxes to evaluate solutions	☐ Deep ocean exploration and monitoring

Several small-scale pilot studies assessing potential chemical mCDR approaches are currently in progress (Ocean Visions 2024; GESAMP, 2024). Independent scientific oversight of these, in conjunction with the application of the London Protocol requirements, including the research assessment framework, as well as the proposed approaches to upscaling, will be crucial to maximize learnings in the next few years. Any move to upscale from pilot studies will require a full life-cycle assessment such that carbon emissions from energy, transport and installation are offset against carbon sequestered. As upscaled trials will span local and national jurisdictions to the open ocean, international coordination will be necessary to ensure that those experiments do not harm the environment and human societies.

There remains little consensus on testing, development, monitoring or regulation of SRM, with this controversial approach not considered as mitigation when the terminology of the Intergovernmental Panel on Climate Change (IPCC) is applied. Nevertheless, funding and research and development is likely to increase in this sector over the coming years.

In summary, a number of uncertainties remain with regard to marine CDR and geoengineering techniques, including:

- Their impacts on marine ecosystems and coastal areas.
- Their effectiveness in the long-term removal and storage of CO_2, including ensuring that they do not reduce the ocean's natural CO_2 storage capacity.
- The energy and resources needed for deployment at scale and the effects on terrestrial ecosystems, including conflicts over, for example, minerals use and mining.
- There are currently no reliable technical means to monitor, report or verify (MRV) the CO_2 that would be absorbed and sequestrated, especially considering the complexity and existing knowledge gaps about the ocean carbon cycle.

The key enablers for sustainable research progress are:

- Scientifically endorsed, standardized and accessible MRV approaches.
- Responsive and transparent funding mechanisms, ensuring that commercial interests do not influence the design, conduct and outcomes of the research activities.
- Collaboration and transparency for research will be required for geoengineering approaches to demonstrate feasibility (or lack thereof) and upscale effectively and safely if they are proven safe, effective and realistic.
- Global policy that prioritizes addressing knowledge gaps, equity concerns, risk perception and precautionary governance to strengthen understanding and control for mCDR and geoengineering research.

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