Commissioned by

HIGH LEVEL PANEL *for* A SUSTAINABLE OCEAN ECONOMY

Blue Paper

Principles for responsible and effective marine carbon dioxide removal development and governance

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About the Ocean Panel

Established in 2018, the High Level Panel for a Sustainable Ocean Economy (Ocean Panel) is a unique initiative made up of serving world leaders who are building momentum for a sustainable ocean economy in which effective protection, sustainable production and equitable prosperity go hand in hand. By working collaboratively with a wide array of stakeholders, the Ocean Panel aims to identify bold solutions that bridge ocean health, wealth and equity and accelerate and scale responsive action worldwide.

This Blue Paper was prepared in support of the work of the Ocean Panel to provide a robust science and knowledge base and practical opportunities for action across issues central to the attainment of a sustainable ocean economy. The Blue Paper was developed by consensus of the authors who have balanced their individual academic and other perspectives. The arguments, findings and opportunities outlined in this Blue Paper represent the views of the authors alone. Ocean Panel members have not been asked to formally endorse the Blue Paper and should not be taken as having done so.

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Foreword

The world experienced the highest-ever anthropogenic carbon dioxide (CO_2) emissions in 2024, which was also the first year that the average global temperature exceeded 1.5 degrees Celsius (°C) above pre-industrial levels. The time left to bring global emissions under control is running out. Deep and rapid emissions reductions are needed—nearly a 50 percent reduction by 2030 to stay on track to limiting global temperature rise to 1.5°C.

Actively removing carbon dioxide from the atmosphere through CO_2 removal techniques will likely need to be explored to meet the goals of the Paris Agreement. Given the huge size of the global ocean, and its already key role in absorbing anthropogenic CO_2 emissions and associated excess heat, marine carbon dioxide removal (mCDR) techniques may offer hope. Proposed mCDR methods speed up or magnify the ocean's natural ability to absorb and/or store carbon through biological, chemical and physical processes. For example, ocean alkalinity enhancement, a chemical approach, proposes to reduce the acidity of the ocean, allowing for excess CO_2 in the atmosphere to dissolve into the ocean.

Although the first mCDR approaches and experiments were conducted over 30 years ago, the concept remains controversial among many because of continuing uncertainty regarding the efficacy, scalability, and environmental and social impacts of the approaches proposed. For example, meeting in Hangzhou, China in late February 2025, member countries of the Intergovernmental Panel on Climate Change could not reach consensus on the outline for the methodology report on Carbon Dioxide Removal Technologies and Carbon Capture, Utilization and Storage after disagreement on what form of carbon removal from the ocean, lakes and rivers to include. This reflected concern that the impacts of mCDR are not well understood, may be irreversible and are likely to be difficult to contain.

It is in this context that the High Level Panel for a Sustainable Ocean Economy (Ocean Panel) commissioned this Blue Paper. Ocean Panel members requested a synthesis of best available evidence on what is most effective and responsible when considering the development of mCDR technologies, alongside support in identifying valuable opportunities for action. The authors of this Blue Paper, who are internationally recognised subject experts, responded by bringing their learnings from diverse backgrounds, broad experiences and independent mindsets to the text of this document, and we thank them for this. This landmark paper provides readers with a synthesis of the state of knowledge and technical readiness for a broad spectrum of mCDR approaches, alongside an overview of key governance frameworks, concluding with a discussion of what governments can do to consider mCDR responsibly. Key priorities for action highlighted include expanding mCDR research capacity through the establishment of government research and development networks, including by developing coordinated test-bed networks, national lab approaches that support large-scale research, and public engagement hubs to help inform governments on their approaches to mCDR development. Countries considering mCDR are also encouraged to conduct a review of existing domestic laws to assess their sufficiency as a framework for mCDR activities. Countries could also benefit from increasing coordination and collaboration, both with industry and other governments, to share learnings to accelerate progress. They could also collectively support improvements to the international governance regime for the sector.

Responsible deployment of mCDR has the potential to help the global community reach the net-zero emissions targets that are required to meet the goals of the Paris Agreement. We call upon policymakers, researchers, the private sector and all other ocean stakeholders to consider the information and opportunities outlined in this paper. Doing so is a positive step towards the realisation of a sustainable ocean economy where effective protection, sustainable production and equitable prosperity go hand in hand.

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Highlights

- Alongside deep and rapid emissions reductions, removal of carbon dioxide from the atmosphere (known as carbon dioxide removal, or CDR) will likely be needed to help mitigate climate change. The ocean provides one potential option to scale CDR, but this potential comes with significant uncertainty about the efficacy, permanence, and environmental and social impacts of proposed approaches.
- The ocean is already among the planet's largest natural sinks of carbon dioxide (CO_2) from fossil fuel combustion and other human-caused CO_2 emissions. While dampening the rate of atmospheric CO_2 buildup and climate change, marine ecosystems are suffering from the uptake of excess CO_2 from human emissions (e.g. leading to ocean acidification).
- Marine carbon dioxide removal (mCDR) approaches seek to leverage the ocean's ability to safely store more carbon by augmenting or accelerating the ocean's biological, chemical and physical processes that take up CO_2 from the atmosphere, or by extracting CO_2 from seawater such that the seawater can take up additional CO_2 from the atmosphere.
- While the natural processes upon which mCDR approaches are based are well understood, the potential to scale mCDR to climatically relevant scales is highly uncertain. The state of knowledge is variable across approaches, and key knowledge gaps remain regarding efficacy, understanding of environmental and social impacts, permanence, cost, scale potential, readiness for deployment and other aspects. Decision-makers require more information on these parameters to inform choices about which mCDR approaches, if any, are appropriate for larger-scale deployment as part of a broad climate mitigation portfolio.
- Government investment in fundamental research of mCDR to understand environmental risk and climate feedbacks, and in development of mCDR approaches, is critical to address scientific and other knowledge gaps. Government investment is critical not only because mCDR is a suite of early-stage technologies, but also because it provides a public good of atmospheric pollution cleanup. Government funding for research and development (R&D) can be complemented and augmented by investments from industry and philanthropic organisations.
- While mCDR has received relatively little government funding for research and development and faces knowledge gaps related to both efficacy and the environmental and social impacts of different mCDR approaches, a range of entities, including companies, are developing mCDR technologies and starting to test them at sea.
- Ensuring mCDR field trials are conducted in a responsible manner will be critical to the long-term success of the sector. This includes robust monitoring of ecosystem response, reporting and verification (MRV); transparency and community engagement; and standardised research codes of conduct.
- While some existing international agreements and rules of customary international law may be relevant to mCDR activity, there is no purpose-built international governance framework specifically tailored to address all aspects of different mCDR approaches. Further, these frameworks bind only countries that have joined or ratified them. As such, they currently do not provide comprehensive governance. Some national governments are beginning to enact mCDR-specific regulations, but most have not.
- National governments have a critical role to play in the development and governance of mCDR including through investment in R&D for at-sea testing, among other research activities; adoption of requirements for recipients of government funding to meet certain standards of quality for at-sea activity (e.g. around MRV, transparency and public engagement); and assessment of current permitting and regulations to ensure they are fit-for-purpose for this emerging sector.

Executive summary

Purpose of report and section overview

This report is designed to inform policymakers and other stakeholders in governments that are interested in developing mCDR approaches. It provides a summary of the state of knowledge and technical readiness of proposed mCDR approaches, an overview of relevant governance frameworks and recommendations for what governments can do to develop mCDR responsibly.

The first section, 'State of knowledge and technology', presents the current range of biological, chemical and physical mCDR approaches, including how they remove carbon, their state of development and knowledge gaps. It also includes key development priorities that cut across all mCDR approaches, including around finance, MRV and scaling. Next, 'Governance considerations for the research or potential deployment of mCDR' summarises governance frameworks that apply to mCDR activity, including the United Nations (UN) Convention on the Law of the Sea, the London Convention and London Protocol, the Convention on Biological Diversity, the UN Framework Convention on Climate Change and Paris Agreement, and relevant rules of customary international law. The third section, 'How national governments can advance responsible mCDR', outlines what governments can do to develop mCDR responsibly in their national waters. It includes a discussion of public perceptions of mCDR, why governments have a critical role to play in supporting R&D and steps they can take to support responsible development of this new sector.

Key messages and findings

Marine CDR approaches can broadly be categorised as biological, chemical and physical approaches. Many of them do not directly remove CO_2 from the air but rather remove it from surface waters of the ocean and then rely on the re-equilibration of CO_2 from the air with dissolved CO_2 in the surface ocean. Additionally, there are a range of other CDR approaches that involve the marine environment in some capacity but are not considered a form of marine CDR—for example, sinking terrestrial biomass in the deep ocean. Some of these are discussed briefly since their impacts on the ocean are similar to those of mCDR approaches.

Chemical mCDR approaches—mainly ocean alkalinity enhancement and direct ocean carbon capture—are in the early stages of development, with most knowledge coming from modelling and a small number of trials in the marine environment (Table ES-1). Pilot studies are moving research beyond technology improvement to also focus on social acceptance and MRV processes. As chemical approaches seek to elevate the ocean's pH, impacts on ecosystems will be species specific and depend on the extent and duration of this change. Some approaches may introduce harmful trace minerals and require the movement of large amounts of water, both of which could impact marine species. MRV for chemical approaches can be more challenging for open-system approaches, such as those that add materials directly to the ocean, compared with closed-system approaches, which process and then discharge altered seawater with elevated CO_2 and can, therefore, more accurately measure atmospheric CO_2 removal.

Biological mCDR approaches include coastal ecosystem restoration (known as coastal blue carbon), enhancement of phytoplankton production and cultivation of macroalgae (Table ES-1). While coastal blue carbon provides limited scalability for carbon sequestration, conservation and restoration of blue carbon habitats have long been practiced for other objectives, such as increasing coastal resiliency. Phytoplankton enhancement can be stimulated by the addition of nutrients (nutrient fertilisation, e.g. iron, phosphate, nitrate) or by the upwelling of deep, nutrient-rich water (artificial upwelling). Carbon captured by phytoplankton and macroalgae from surface waters must be exported to the subsurface ocean as biomass or detritus prior to respiration of the carbon back to CO_2 if they are to be effective mCDR approaches.

Aside from coastal ecosystem restoration, biological mCDR techniques necessarily alter ecosystem composition—which can cause a range of impacts, from nutrient robbing, to changes in subsurface light, seawater oxygen, and turbidity, to altered seafloor chemistry. These impacts can happen at and beyond the site of mCDR activity. Measuring carbon removal and monitoring ecological and other impacts are challenging for biological approaches as they are less well understood than chemical approaches and can involve feedbacks that are difficult to model and monitor.

Even with the improvement in understanding of these mCDR techniques over recent years, their potential for implementation at climatically relevant scales remains highly uncertain. Chemical approaches are currently the most technologically advanced and scalable mCDR techniques based on field trials to date. Seaweed aquaculture is well established, though not widespread, and research efforts on macroalgal CDR are seeking to better understand the durability of biomass in the deep ocean. For mCDR to meaningfully contribute to global climate change mitigation efforts, we must significantly advance our technological capabilities and scientific knowledge of efficiency, environmental implications and monitoring requirements. Such effort must be coupled with the development of appropriate governance structures, financing mechanisms and societal engagement processes.

Despite the importance of controlled field trials for advancing our understanding of mCDR techniques, it remains challenging for both academic and commercial entities to conduct them because of the complexities associated with issuing permits and coordinating with regulatory bodies in the absence of clear governance mechanisms.

There are currently no dedicated international or national governance frameworks in place for mCDR research or deployment. However, several regimes are pertinent to protecting ocean environments or the climate and have, or could exert, influence over mCDR activities. These include the UN Convention on the Law of the Sea, the Biodiversity beyond National Jurisdiction Agreement, the London Convention and London Protocol, the Convention on Biological Diversity, and the UN Framework Convention on Climate Change and Paris Agreement, as well as various rules of customary international law.

While some principles of international law (known as customary rules) have near universal applicability to all states, international agreements bind only those states that have signed or ratified them. Some of the international agreements relevant to mCDR—most notably the London Convention and London Protocol—have fairly limited memberships, which may affect the ability of those agreements to establish a truly global governance regime for mCDR.

Although international law is not directly binding on private actors, it has a significant influence on domestic regulation of those actors' conduct. Few countries have domestic laws specifically addressing mCDR activities. Instead, most countries regulate those activities under general environmental laws, including laws enacted to implement the international agreements listed above.

Characteristics of 'responsible' mCDR, as recommended by non-governmental organisations and governments to date, include public engagement, robust monitoring and verification of removal, monitoring of environmental and social impacts, transparent sharing of project information, and the equitable distribution of impacts, among others. However, there is no consensus definition at present of what constitutes 'responsible'.

Members of the public are generally unfamiliar with CDR broadly, including mCDR. Within the limited understanding of CDR approaches, those that are considered 'natural' are more favourable. Engineered approaches that operate in closed systems are moderately preferable, and engineered approaches that operate in open systems (e.g. broadcasting materials into the environment) are least preferable. Public perceptions of mCDR approaches likely change with project scale. Preference among members of the public for small, decentralised CDR projects may conflict with the eventual need to reach large-scale deployment.

TABLE ES-1. **Summary of Technology Readiness Level and Scientific Readiness Level classification scheme for mCDR approaches and considerations associated with their implementation potentials**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	MATERIAL, ENERGY AND COST REQUIREMENTS	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS	OTHER CONSIDERATIONS
Ocean alkalinity enhancement Ocean liming Silicate and carbonate rocks Electrochemical	Established	Prototype	Recognised	Experimental	Prototype	Prototype	*Efficacy*: High *Durability*: Long *Sequestration potential:* Large–very large *Estimated cost at scale:* Medium–high
Direct ocean carbon capture Electrolysis Electrodialysis	Established	Prototype	Recognised	Experimental	Prototype	Prototype	*Efficacy*: High *Durability*: Long *Sequestration potential:* Large–very large *Estimated cost at scale:* Medium–high
Restoration of blue carbon ecosystems Mangroves Salt marshes Seagrass meadows	Demonstrated	Mature	Demonstrated	Mature	Established	Demonstrated	*Efficacy*: Low *Durability*: Short–medium *Sequestration potential*: Small *Estimated cost at scale*: Very high
Phytoplankton growth Iron fertilisation Nutrient (N,P) fertilisation Artificial upwelling	Demonstrated	Prototype (fertilisation) Conceptual (AU)	Recognised	Experimental (fertilisation) Conceptual (AU)	Recognised	Experimental	*Efficacy*: Medium *Durability*: Medium–long *Sequestration potential:* Medium–large *Estimated cost at scale*: Low to high, depending on technique
Macroalgal growth Seaweed farming and deposition into the deep sea *Sargassum* deposition into the deep sea	Demonstrated	Experimental	Recognised	Experimental	Recognised	Experimental	*Efficacy*: Medium *Durability*: Medium–long *Sequestration potential:* Medium–large *Estimated cost at scale*: Medium
Artificial downwelling Pumps and pipes Downwelling turbines	Theoretical	Conceptual	Theoretical	Conceptual	Theoretical	Conceptual	*Efficacy*: Low *Durability*: Medium–long *Sequestration potential*: Medium *Estimated cost at scale*: High

Notes: We adapted this Technology Readiness Level (TRL) and Scientific Readiness Level (SRL) classification scheme from the United Kingdom Research and Innovation's classification (UKRI n.d.), International Energy Agency groupings (IEA 2020) and European Space Agency definitions (ESA 2015).

TABLE ES-1. **Summary of Technology Readiness Level and Scientific Readiness Level classification scheme for mCDR approaches and considerations associated with their implementation potentials, continued**

CONCEPTUAL/THEORETICAL	TRL/SRL 1: basic principles conceived, observed and reported TRL/SRL 2: technological concept or application formulated
EXPERIMENTAL/RECOGNISED	TRL/SRL 3: analytical or experimental proof of concept TRL/SRL 4: basic validation in a laboratory environment
PROTOTYPE/ESTABLISHED	TRL/SRL 5: basic validation in a relevant environment TRL/SRL 6: prototype evaluation in a relevant environment
OPERATIONAL/DEMONSTRATED	TRL/SRL 7: prototype demonstration in an operational environment TRL/SRL 8: technology completed and qualified through test and demonstration
MATURE/QUANTIFIED	TRL/SRL 9: technology qualified through successful operation

Notes: The TRL and SRL scoring may vary for different implementation scenarios.

Efficacy: level of confidence that the approach will remove atmospheric CO_2 and increase ocean carbon storage. *Low; Medium; High*

Durability: likely duration over which CO_2 is expected to be removed from the atmosphere and stored away from the surface ocean. *Short (years–decades); Medium (decades–centuries); Long (centuries–millennia); Permanent (>10,000 years)*

Sequestration potential: anticipated maximum extent of net annual CO_2 removal that could be achieved with the approach if conducted globally at appropriate locations in the future. *Small (<0.1 Gt CO_2e/yr); Medium (0.1–1 Gt CO_2e/yr); Large (1–5 Gt CO_2e/yr); Very large (>5 Gt CO_2e/yr)*

Estimated cost at scale: approximate cost (dollars per tonne CO_2) for deployment at scale in the future, excluding the cost of MRV and associated development. *Low (<50 t/CO_2); Medium (50–100 t/CO_2); High (100–500 t/CO_2); Very high (>500 t/CO_2).*

The examples and considerations provided in this table are not exhaustive and are likely to vary by implementation method, setting and scale for each approach. Similarly, the TRL, SRL, efficacy, durability, sequestration potential and estimated cost of implementation may also vary by implementation scenario.

Abbreviations: TRL: Technology Readiness Level; SRL: Scientific Readiness Level; mCDR: marine carbon dioxide removal; CO_2: carbon dioxide; MRV: monitoring, reporting and verification; N: nitrogen; P: phosphorus; AU: artificial upwelling; Gt CO_2e/yr: gigatonnes of carbon dioxide equivalent per year; t/CO_2: dollars per tonne of carbon dioxide.

Sources: NASEM 2022; IPCC 2022a; Smith et al. 2024; and references therein.

Priorities for government action

Government-supported R&D is essential for addressing knowledge gaps and ensuring that scientific understanding of mCDR approaches remains ahead of commercial implementation. Government R&D into mCDR should be grounded in the concepts of sound science and technology; transparency, community engagement and equity; robust monitoring, reporting and verification; and established research codes of conduct that can complement, enhance and guide R&D supported by industry and private actors.

Carbon removal, including mCDR, includes a range of technologies in development that provide a public good of atmospheric pollution cleanup. Governments have a key role to play in supporting early research and development activities to inform decisions around which approaches could potentially be deployed in the future. If and when mCDR is found to be safe and effective, governments also have a role to play in facilitating both demand and supply—for example, by setting high standards for quality and procuring mCDR, and for compliance, which could also support voluntary mCDR markets by creating demand for high-quality projects with robust verification and environmental assessments.

Governments can create requirements for any publicly funded research or at-sea testing to ensure it is conducted responsibly, prioritising broad societal benefit while avoiding environmental and social pitfalls. Requirements around data sharing can also be included to ensure that learnings from publicly funded projects, including public-private partnerships to the extent practicable, are shared and can benefit others working in the mCDR space.

Governments should proactively review their existing domestic laws and evaluate whether they provide an effective governance framework for marine CDR. Governments should, where necessary and appropriate, adopt legal reforms to enable safe and responsible mCDR research in accordance with international law.

To ensure coordinated testing, governments can expand mCDR R&D capacity and establish mCDR R&D networks to evaluate the relative viability, uncertainties and trade-offs across systems. R&D networks could include 'test-bed' sites in national waters for streamlined trials of specific mCDR pathways; a national lab approach where governments proactively support mCDR research and innovation; and public engagement hubs where diverse actors coordinate research and engagement to understand public priorities and conditions of support for mCDR.

Test beds could speed up the testing of various mCDR techniques by allowing sites to be pre-permitted for field trials, standardising MRV and characterisation of the environmental safety of any mCDR technology, and more efficiently and effectively investigating and anticipating the social impact and acceptability of different siting and deployment options. An R&D network approach would also enable coordination across engineering as well as energy, materials and social sciences to address challenges presented by scaling up different options.

R&D networks and field test beds could be used to explore opportunities to develop mCDR approaches in conjunction with established marine and coastal activities, which could ease burdens around capital expenditure and MRV. Government-funded, coordinated public engagement as part of these networks could also inform how governments approach mCDR development, including developing an understanding of socially desired criteria for publicly funded projects.

As mCDR research and development progresses, countries should seek opportunities for coordination and collaboration to avoid duplication of efforts, share learnings to accelerate progress and increase capacity-building across borders.

Overall, governments interested in exploring or advancing knowledge on mCDR through R&D should consider the following:

- Funding basic and applied research, including at-sea tests, for the mCDR approaches that are most suitable within national jurisdiction to better understand the efficacy and environmental safety of mCDR techniques; this basic and applied research will help ensure that pressures to implement mCDR techniques do not get ahead of scientific understanding
- Funding efforts to improve monitoring and verification technologies and modelling capabilities
- Setting standards to ensure that government funding for mCDR research and development is done responsibly—including requirements for basic research; prior environmental impact assessments; robust monitoring, reporting and verification; transparency; minimisation of harm and maximisation of benefits; community engagement; and transparency—and works towards the development of environmental standards, criteria and precautionary thresholds
- Clarifying and streamlining permitting regimes to enable small-scale, rigorously monitored at-sea research tests
- Identifying opportunities for mCDR testing to be conducted in conjunction with existing coastal or marine activities to reduce permitting and financing burdens
- Developing data-sharing agreements that enable the sharing of knowledge gained from at-sea tests to facilitate advancement of the field and avoid duplication of efforts
- Pursuing mCDR R&D networks to advance research through field test-bed sites, a national lab approach and public engagement hubs
- Reviewing existing domestic laws and evaluating whether they provide an effective governance framework for marine CDR activities; in instances where this is not the case, improving national governance to ensure safe and responsible mCDR activity and adherence to international law
- Advocating for enhanced communication and coordination across international legal frameworks that are addressing mCDR activities to ensure that conflict among frameworks is reduced and that there are no regulatory gaps; initiating discussions in pertinent international fora, from the United Nations Ocean Conference to the UN General Assembly, would be salutary
- Encouraging states to ratify the London Protocol, including countries actively engaged in mCDR activities, such as the United States; Parties to the London Protocol are encouraged to engage with discussions concerning the marine geoengineering amendment to the agreement
- Seeking opportunities for coordination and collaboration to avoid duplication of efforts, share learnings to accelerate progress and increase capacity-building across borders

Introduction

The ocean covers 70 percent of the Earth and holds 42 times the amount of carbon that is contained in the atmosphere, serving as the planet's largest active carbon reservoir (Friedlingstein et al. 2024). As human-generated greenhouse gas (GHG) emissions continue to rise, the ocean plays a key role in dampening the impacts of climate change by taking up about 25 percent of anthropogenic carbon dioxide (CO_2) emissions and absorbing more than 90 percent of excess heat (Lindsey and Dahlman 2023; Friedlingstein et al. 2024). While the ocean plays this critical climate mitigation role, its impacts are causing ecosystem degradation from ocean warming, acidification and deoxygenation.

As the global community works to reduce GHG emissions—which must happen more rapidly and steeply than in recent years—there is scientific consensus that CO_2 removal is very likely to be needed in addition to deep and rapid emissions reductions to meet the global climate goal of limiting temperature rise to 1.5–2 degrees Celsius (°C), as agreed in the Paris Agreement (IPCC 2022b). Achieving this goal requires reaching net-zero CO_2 emissions by mid-century, and net-zero GHG emissions soon after. As global surface temperature rises closer to this 1.5°C limit, the role of carbon removal in addressing rising temperatures becomes clearer. Carbon removal will be needed to counterbalance any emissions that cannot be abated by the net-zero target date to reach net-zero. In the long term, carbon removal will be needed if net negative emissions are desired to reduce excess CO_2 in the atmosphere.

Carbon dioxide removal (CDR) refers to technologies or approaches that, through human intervention, remove CO_2 directly or indirectly from the atmosphere and store it durably (hundreds to thousands of years) (IPCC 2022a; Smith et al. 2024). This contrasts with carbon capture and storage (CCS), which captures emissions at a source before they enter the atmosphere and is a form of emissions reduction rather than carbon dioxide removal.

To reach the large-scale carbon removal that climate modelling scenarios indicate may be needed, a range of carbon removal approaches are beginning to be developed and deployed (Smith et al. 2024). While many of these are on land (e.g. direct air capture, bioenergy with carbon capture and storage, biochar), a suite of carbon removal approaches has been proposed, and in some cases tested, to leverage the carbon storage capacity of the ocean (NASEM 2022; Hoegh-Guldberg et al. 2023; Doney et al. 2025). These are referred to as marine carbon dioxide removal (mCDR) approaches. They aim to accelerate or augment natural biological or chemical processes in the ocean to store carbon durably and in ways that minimise negative impacts on marine ecosystems.

Carbon removal approaches on land have seen significant increases in policy support in the past five years, including through investments in research and development (R&D), demonstration projects in the field and early deployment, as well as development of carbon accounting rules and mechanisms to drive demand for purchasers of CDR credits (WRI 2022; European Commission n.d.). While there has been some early public investment in mCDR research and development, mCDR approaches have not yet seen commensurate policy support to their terrestrial counterparts (NOAA OAP 2023; DAM n.d.). Private sector activity and investment have also increased over the past several years, with dozens of mCDR project developers working on early-stage research to project implementation (Service 2024).

A suite of marine carbon dioxide removal (mCDR) approaches has been proposed, and in some cases tested at sea, to leverage the ocean's natural biological and chemical processes to store more carbon.

Increased policy attention on mCDR is critical because many unknowns remain about the efficacy and impacts of various mCDR approaches—whether they remove carbon effectively and over what time period, and what impacts they have on ecosystems and people (Hoegh-Guldberg et al. 2023).

As countries, companies and others work towards meeting climate goals, the pressure to use the ocean for mCDR will likely only increase due to sustainability limits on land CDR (Deprez et al. 2024). In this context, governments have a critical role to play in supporting the R&D of mCDR approaches to understand whether they can help address the climate crisis. Governments must also develop and improve governance and regulatory frameworks for this new sector to ensure that research trials and potential future deployments—if mCDR approaches are shown to be safe and effective—are done responsibly (Lebling et al. 2022).

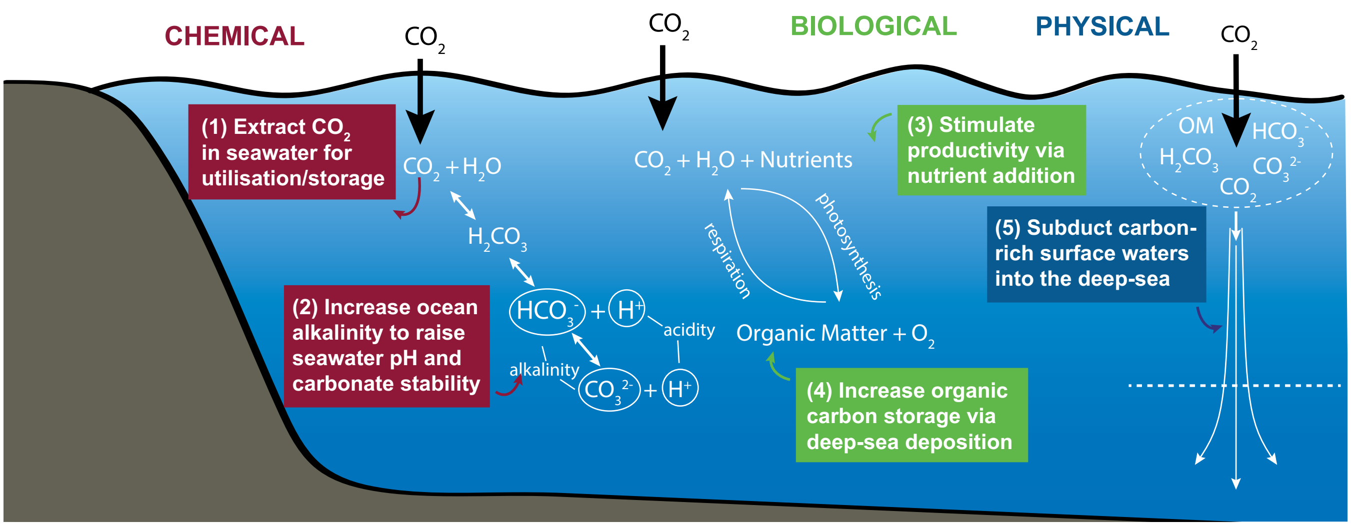
While there is no consensus definition of what constitutes responsible research and deployment, it generally includes public engagement, robust measurement and verification of removal and monitoring of environmental and social impacts, transparent sharing of project information, and the equitable distribution of impacts and benefits (Box 3). Developing proactive and comprehensive governance frameworks will help ensure that mCDR activity is maximising climate benefits and minimising negative impacts on the environment and people, which, in turn, can help build public understanding and trust in the development and decision-making process for this sector (Lebling et al. 2022).

State of knowledge and technology

1.1 Overview

The ocean's ability to help regulate atmospheric CO_2 reflects a natural drive for equilibrium between the partial pressure of CO_2 (pCO_2) in the surface ocean and the overlying atmosphere. The surface ocean shows significant regional and seasonal variations in the pCO_2 as it is dependent on physical (temperature), chemical (marine carbonate system) and biological conditions. Once CO_2 gas has dissolved into seawater, a series of reactions converts it into carbonic acid (H_2CO_3), which further dissociates into more stable bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) (Figure 1). Collectively, the sum of these carbon-containing ions (CO_2, H_2CO_3, HCO_3^- and CO_3^{2-}) is termed the dissolved inorganic carbon (DIC) content of seawater, with HCO_3^- as the dominant form at seawater pH (about 8). Adding more CO_2 into seawater increases the DIC concentration and increases the acidity (H^+ concentration) of the ocean, lowering the pH (the process of ocean acidification). Conversely, removing CO_2 from seawater reduces DIC and acidity. The co-dependency of these processes reflects the buffering capacity of the marine carbonate system and they jointly enable the ocean to store more carbon than the atmosphere, making marine environments the largest exchangeable carbon reservoir on Earth's surface.

FIGURE 1. **Summary of the scientific concepts behind the archetypal mCDR processes**



Notes: **Chemical methods** seek to increase the absorption of atmospheric CO_2 into seawater by adjusting the buffering capacity of the ocean. This can be achieved in the following ways:

1. Extracting CO_2 (in all forms) from seawater before returning the DIC-depleted solution back into the ocean and sequestering the captured CO_2 in geological reservoirs
2. Adding alkalinity into seawater to increase the stability of the HCO_3^- ion, forcing the dissolved CO_2 and H_2CO_3 species to convert into HCO_3^-

Biological methods increase the pCO_2 gradient between seawater and the overlying atmosphere by converting dissolved CO_2 into organic carbon via photosynthesis and either delaying or shifting to the deep sea the degradation of that organic matter back into DIC by either

3. stimulating huge increases in productivity through nutrient addition, which overwhelms degradation processes in near-surface environments; or
4. increasing the storage of biomass in sediments and/or deep-sea environments.

Physical methods (5) aim to increase CO_2 absorption by transporting carbon-rich surface waters (both DIC and organic carbon) into deep-water environments that are isolated from the atmosphere over longer time scales.

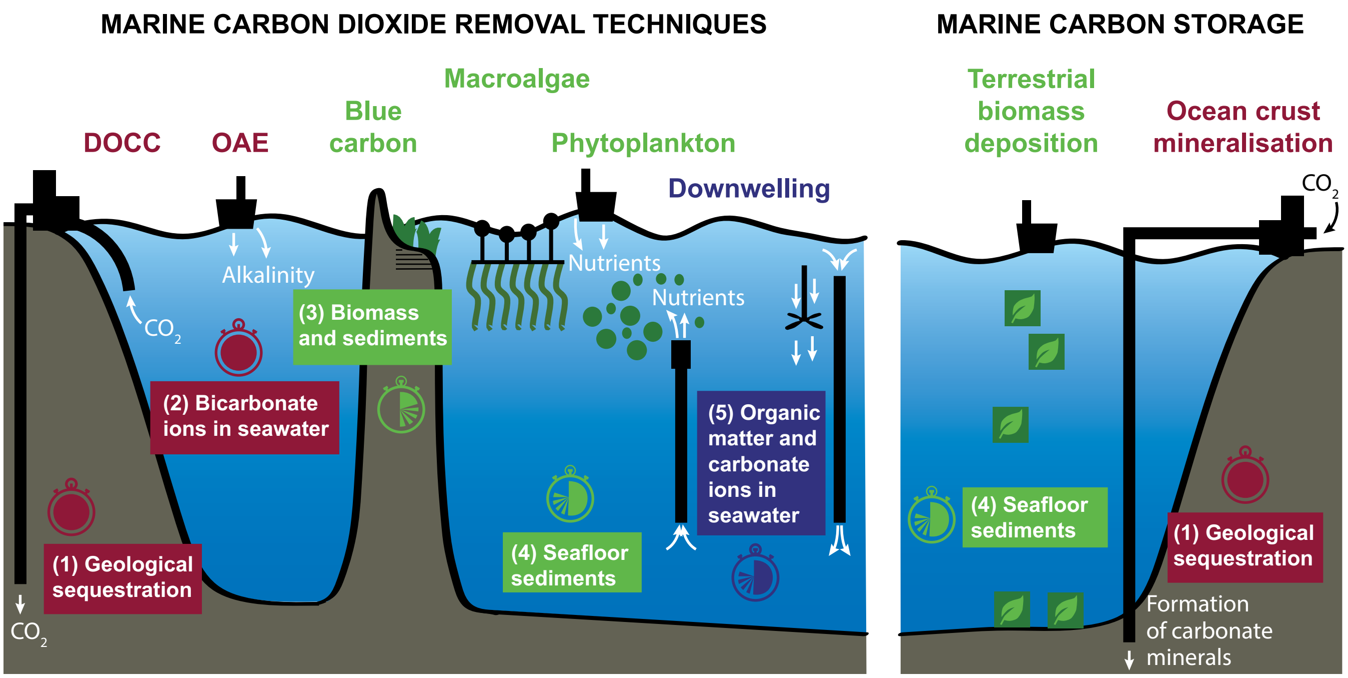
Abbreviations: mCDR: marine carbon dioxide removal; CO_2: carbon dioxide; DIC: dissolved inorganic carbon; HCO_3^-: bicarbonate ion; H_2CO_3: carbonic acid; pCO_2: partial pressure of CO_2; H_2O: water; H+: hydrogen ion; CO_3^{2-}: carbonate ion; O_2: oxygen; OM: organic matter.

Source: Authors.

Current atmospheric pCO_2 levels drive a global air-sea flux of anthropogenic CO_2 into the ocean of 2.1–2.4 billion tonnes (gigatonne, Gt) of carbon per year (DeVries et al. 2023). Marine CDR processes seek to increase the rate at which the ocean is absorbing atmospheric CO_2 by actively decreasing the pCO_2 of surface water. This can be achieved through chemical, biological or physical techniques (Figure 1). Chemical approaches use the carbonate buffering capacity of the ocean by either adding alkalinity to neutralise the acidity of the ocean (lowering the amount of CO_2 dissolved in seawater) or extracting CO_2 directly through ex situ processing, with subsequent utilisation or storage of the purified CO_2 gas. Biological approaches primarily rely on the absorption of dissolved CO_2 into marine phytoplankton or macroalgae (seaweed) through photosynthesis, with techniques seeking to enhance both the rate of production, export to deep water or the seafloor and preservation of organic matter, thereby minimising the return of the trapped carbon back to the atmosphere during degradation. Physical approaches transport the carbon-rich surface waters into deep-sea settings where the carbon components cannot re-exchange with the atmosphere over millennial time scales. Other proposed techniques, such as terrestrial biomass deposition and mineralisation of the oceanic crust, also seek to use marine environments to store captured CO_2 (Figure 2) but are not considered mCDR because they do not increase the absorption of CO_2 into seawater.

While the natural processes on which these mCDR techniques are based are well understood, their potential for large-scale enhancement of the air-sea CO_2 flux is less clear. Critical scientific and technical uncertainties include the efficacy of the process and associated time scales for enabling atmospheric

FIGURE 2. **Proposed methods for marine carbon dioxide removal and storage**



Notes: Principal techniques proposed for conducting mCDR (left) and examples of approaches that seek to increase carbon storage in marine settings (right). Chemical mCDR techniques include direct ocean carbon capture (DOCC) and ocean alkalinity enhancement (OAE). Biological mCDR techniques include blue carbon ecosystem restoration, macroalgal cultivation and deposition, and phytoplankton fertilisation. Physical mCDR techniques include artificial downwelling. Marine carbon storage approaches discussed in this report include mineralisation of the oceanic crust (Box 1) and the deposition of terrestrial biomass in deep-sea environments. The primary location and form in which the captured carbon is stored from each approach is also indicated:

1. Supersaturated fluids and gas in geological reservoirs
2. Dissolved carbonate ions in seawater (primarily bicarbonate; HCO_3^-)
3. Organic carbon within biomass or coastal sediments
4. Organic carbon within deep-sea environments and seafloor sediments
5. Organic carbon and dissolved carbonate ions in deep-sea environments

Stop watches represent the indicative durability associated with each storage form (short, medium, long and permanent).

Abbreviations: mCDR: marine carbon dioxide removal; DOCC: direct ocean carbon capture; OAE: ocean alkalinity enhancement; CO_2: carbon dioxide.

Source: Authors.

CO_2 removal; permanence of the technique (durability of the removed CO_2); scalability of the approach and the cost of doing so (including enabling monitoring, reporting and verification, or MRV, of the approach). The potential ecological and environmental risks and/or co-benefits of conducting, and up-scaling, mCDR approaches are also largely unknown, although the interconnectivity and interdependency of oceanic environments mean that any intervention is likely to have environmental impacts (Levin et al. 2023).

Resolving these knowledge gaps requires coordinated interdisciplinary evaluation of both the potential climatic benefits and ecological impacts of the proposed approaches. Advancements in our understanding of the scientific efficacy (Boyd et al. 2024) of mCDR approaches are currently primarily being driven by small-scale pilot studies run by commercial entities, though natural analogues also provide opportunities for evaluating at-scale implementation potential (Bach and Boyd 2021; Subhas et al. 2023). This section reviews the technological principles behind the main mCDR approaches and what is currently known regarding their potential environmental impacts, co-benefits and monitoring requirements. We also identify the information needed to responsibly progress mCDR as well as the financial requirements and sociotechnical considerations (Cooley et al. 2023a) associated with this.

1.2 Chemical approaches

1.2.1 Ocean alkalinity enhancement

Ocean alkalinity enhancement (OAE) leverages the ocean's natural ability to act as a carbon sink by raising the chemical capacity of seawater to neutralise acids and store carbon in stable, non-volatile forms such as bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions (Figure 1) (Oschlies et al. 2023). This is achieved by adding alkaline materials or using electrochemical methods to alter seawater chemistry. Depending on the initial air-sea CO_2 gradient, OAE can either enhance CO_2 uptake or reduce emissions from the ocean to the atmosphere.

There are three main approaches to OAE (Eisaman et al. 2023):

1. Ocean liming: This involves the addition of quicklime (CaO) or hydrated lime ($Ca(OH)_2$) to surface waters. Quicklime is produced through the calcination of limestone at high temperatures, a process that releases CO_2. To achieve net carbon negativity, the CO_2 emitted during production must be captured and stored and the heat required for calcination decarbonised. Once added to seawater, lime reacts to increase alkalinity, but the process must be carefully managed to avoid issues like calcium carbonate precipitation, which can reduce the intended benefits by removing alkalinity.

2. Silicate and carbonate rocks: Pulverised silicate or carbonate rocks, industrial by-products like slag or their dissolution products can be added to the ocean to enhance alkalinity. These materials dissolve slowly, requiring fine pulverisation to ensure they remain in the surface layer long enough to influence atmospheric CO_2. Materials can also be placed on the seafloor within near-shore environments, or react with CO_2 in facilities that are coupled with CCS prior to the discharge of alkaline solution into the ocean. One idea is to add materials through wastewater treatment plants (Cai and Jiao 2022). While less energy intensive than lime production, the dissolution process varies by material type and environmental condition. Additionally, this approach raises concerns about the ecological effects of trace metals (e.g. nickel, chromium) present in some materials.

3. Electrochemical methods: Electrochemical OAE involves extracting acids from seawater and discharging alkaline solutions back into the ocean. This process increases seawater alkalinity and promotes CO_2 uptake. The acid by-products, typically hydrochloric acid, must be carefully managed to avoid environmental harm and to avoid return in any acidic form to the surface ocean where it would negate the delivered carbon dioxide removal. Renewable energy sources are crucial for powering these processes to ensure overall carbon negativity.

1.2.2 Direct ocean carbon capture

Direct ocean carbon capture (DOCC), also known as direct ocean capture or direct ocean removal, also uses seawater carbon chemistry to facilitate atmospheric CO_2 removal (Aleta et al. 2023). Rather than enhancing the capacity of seawater to hold dissolved carbon, DOCC involves removing carbon directly from seawater. This is achieved by converting the dissolved carbonate and bicarbonate ions back into CO_2 and extracting the CO_2 from the water as a gas. The seawater is then allowed to 'refill' with CO_2 from the atmosphere, such that, after equilibration with the atmosphere, seawater chemistry is returned to normal. The CO_2 extracted from seawater will need to be stored or utilised in such a way that it will not return to the atmosphere. Options include underground storage in disused oil and gas reservoirs, saline aquifers or salt caverns, or mineralisation within bedrock (Box 1).

Bicarbonate and carbonate can be converted to CO_2 through seawater acidification. At around a pH of 4, the alkalinity of the water (which describes its ability to buffer CO_2 by converting it to carbonate and bicarbonate) drops to zero. After CO_2 removal, the alkalinity must be returned to ambient levels through the addition of a base, so that the seawater can again store carbon as carbonate and bicarbonate. Alternatively, a catalyst such as carbonic anhydrase can be used to speed up the conversion of carbon from dissolved carbonate and bicarbonate into CO_2 during degassing, avoiding the need for an acid or base addition (Digdaya et al. 2020). In both approaches, the seawater would have a higher pH caused by the reduction in the concentration of carbonic acid until CO_2 has been reabsorbed from the atmosphere.

Commercially available acid and base can cause the alkalinity swing required for DOCC. However, current research is primarily focused on developing electrochemical approaches to generate the required

products to reduce the life cycle carbon emissions and enhance the tractability of those emissions. Bipolar membrane electrodialysis generates the acid and base by the electrochemical dissociation of water (H_2O) into hydrogen ions (H^+) and hydroxide ions (OH^-) across a bipolar membrane. The H^+ and OH^- combine with the sodium (Na^+) and chloride (Cl^-) that are naturally present in the seawater and move across charge-selective membranes to balance the charge generated at the bipolar membrane. This forms hydrochloric acid (HCl) and sodium hydroxide (NaOH) in two separate streams that can be used to deliver the alkalinity swing. Other approaches have

BOX 1. **Marine carbon storage through mineralisation of the oceanic crust**

Carbon storage beneath the seabed through mineral carbonation involves injecting CO_2 into basaltic rock formations below the ocean floor, where it reacts with minerals to form stable carbonate solids.[a] This method provides a permanent and secure form of CO_2 sequestration by converting it into solid minerals like calcite and magnesite. It can qualify as a CDR approach when combined with chemical methods such as DOCC or direct air capture. However, it does not qualify as CDR if the CO_2 originates from the combustion of fossil fuels (it is then considered CCS).

The primary target for this technique is oceanic basalt, known for its high reactivity due to its rich content of calcium, magnesium and iron silicates. The carbonic acid formed by CO_2 dissolution into seawater accelerates the dissolution of basalt minerals, releasing cations that react with the dissolved CO_2 to form stable carbonates. This storage method is considered highly secure since the resulting carbonates are chemically stable for millions of years, eliminating the risk of CO_2 leakage. Furthermore, the vast oceanic crust offers significant storage capacity, with potential estimates in the range of hundreds of billions of tonnes of CO_2. However, challenges such as technical complexity, the high cost of deep-sea operations and the need for comprehensive environmental monitoring remain. Despite these challenges, the permanent sequestration of captured carbon through mineral carbonation is regarded as a promising strategy for supporting climate change mitigation.[b]

Notes: [a] Goldberg et al. 2008; Snæbjörnsdóttir et al. 2020. [b] Oelkers et al. 2023; Kopf et al. 2024.

been investigated, including an approach where rather than moving Cl^- across an anion exchange membrane to balance the charges generated by the dissociation of H_2O, the Cl^- is donated and accepted from bismuth and silver electrodes (Kim et al. 2023).

1.2.3 Potential environmental impacts

OAE and DOCC share common environmental impact risks associated with elevated pH and reduced pCO_2 within the modified seawater (Figure 3). Point source discharge from OAE or DOCC could cause pH increases of over one unit locally, risking significant impacts on marine organisms until ocean mixing reduces the pH and, over a longer period, air-sea CO_2 exchange. These acute near-source impacts become more significant as activity scales up, but in all situations can be minimised or made negligible away from the point of application by matching the mCDR activity to the local oceanographic mixing regime.

The tolerance of organisms to elevated pH is species specific (Wilkie and Wood 1996) and likely depends on both the intensity and duration of exposure, with many examined species not surviving above a pH of 10 (Hansen 2002). However, some species suffer well below this pH (Goldman et al. 1982; Pedersen and Hansen 2003). Phytoplankton growth appears to have an upper pH limit of around 9 (Pedersen and Hansen 2003; Berge et al. 2012). Macroalgae and seagrass face similar challenges to phytoplankton, with photosynthesis generally declining as pH surpasses 8.5, and ceasing above 9 (Mvungi et al. 2012). Some macroalgae can acclimate (Middelboe and Hansen 2007), but sustained high pH can alter species dominance, diversity and ecosystem functioning, ultimately impacting ecosystem services (Figure 3). Low dissolved CO_2 concentrations and high pH have also been shown to impact coccolithophores (Bach et al. 2011). Reduced CO_2 can also elevate blood pH in crabs (Cripps et al. 2013) and fish (Wilkie and Wood 1996), necessitating costly physiological adjustments.

These direct impacts on species have ecosystem-level consequences, which in turn impact ecosystem services (Figure 3). For instance, pH disruption to photosynthesis impacts primary production, which in turn impacts biological carbon sequestration, food production, water quality and other services. The addition of quicklime to the marine environment has been tested to control sea urchin populations in kelp forests (H.K. Strand et al. 2020; Christie et al. 2024), and the results of these applications can provide insights into possible OAE effects on marine fauna. Overall, while certain taxa can tolerate transient high-pH, low-pCO_2 conditions, at-scale OAE or DOCC activity that results in persistent near-field carbon chemistry changes will need to undergo a careful environmental impact assessment, for which a greater body of marine impact evidence will be required.

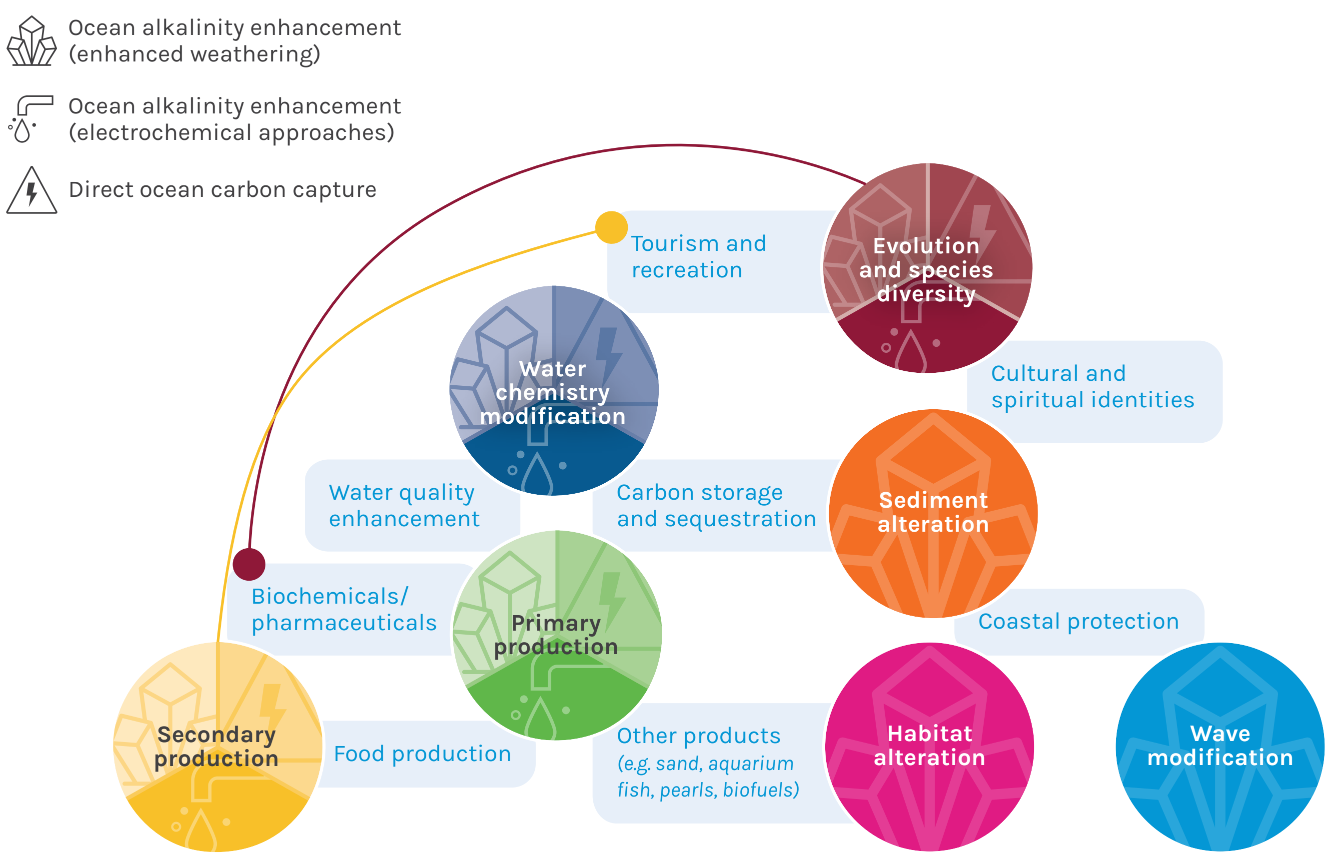
In addition to impacting carbonate chemistry, mineral-based OAE risks elevating trace chemical concentrations in the seawater downstream of application. Some additions, such as silica or iron, may alleviate nutrient stress in certain areas (with potential impacts to primary and secondary production), and the addition of elements such as calcium and magnesium in a dispersed way is unlikely to have significant impacts. However, it is possible that elements such as nickel or chromium would be added to the marine environment in toxic concentrations (Bach et al. 2019). Comprehensive studies are needed to evaluate and mitigate these risks. The addition of olivine structures as a coastal alkalinity enhancement and coastal protection strategy act via wave modification but will also alter habitats and sediments (Figure 3).

Electrochemical approaches operating at climatically relevant scales will also require very large seawater intake and discharge infrastructure. For example, DOCC would require more than 12,000 cubic metres of seawater to be processed per tonne of CO_2 removed. Building and operating such infrastructure, especially in sensitive areas, can pose significant environmental impacts. Furthermore, processing of the volumes of water required to deliver meaningful carbon removal has implications for marine organisms (including fish, invertebrates and planktonic algae) that could be entrained and killed in seawater intake (Gallo et al. 2025).

1.2.4 Monitoring, reporting and verification requirements

Accurate and reliable MRV systems are essential for quantifying the CO_2 removed and stored by OAE and DOCC (Fennel et al. 2023; Ho et al. 2023). The fundamental challenge is that CO_2 is not removed from the atmosphere at the point of mCDR application, other than in very specific cases that involve the pre-equilibration of CO_2 in shore-based

FIGURE 3. **Potential ecosystem impacts for chemical marine carbon dioxide removal**



Note: The figure shows potential ecosystem impacts (to species, structures or processes) associated with the main chemical marine carbon dioxide removal methods discussed in this paper. Changes to the key ecosystem components, indicated by the coloured circles, may affect associated ecosystem services, shown in the connected light blue boxes. Ocean alkalinity enhancement has been subcategorised into enhanced weathering and electrochemical approaches due to the different potential impacts associated with each technique.

Source: Authors.

or ship-based facilities (La Plante et al. 2023). In addition to this, mixing quickly dilutes the signal as it moves away from the point of application, making direct observation of the perturbed chemistry or air-sea CO_2 flux challenging. This can be addressed by a combination of observations in the near field, and spanning a larger area, numerical modelling to determine whether low pCO_2 water remains in contact with the atmosphere for long enough to reach the air-sea equilibrium, and importantly, that it is not being physically transported into the interior of the ocean. Additional verification challenges also exist, particularly for mineral-based OAE, to demonstrate the following: that the added minerals are dissolving to add the required alkalinity; that the alkalinity is not being precipitated out as other minerals; and that any impacts on biological systems are not counteracting the CDR being delivered through the perturbation in carbonate chemistry.

Scientists have been observing and modelling ocean–carbon cycle perturbations to understand the natural operation of the Earth system for decades, so there is no fundamental barrier to verifying the larger signals associated with deliberate seawater carbon chemistry manipulation. The remaining challenges arise from the geographical locations, often coastal, where mCDR techniques could be applied, and operationalising the advanced numerical models and innovative observational techniques that are needed.

1.2.5 Summary

The theoretical potential of both OAE and DOCC is substantial, with estimates suggesting they could sequester billions of tonnes of CO_2 annually (Table 1). As context, global CO_2 emissions from fossil fuels and land use were just over 40 billion tonnes in 2023 (Friedlingstein et al. 2024). However, demonstrating that this removal and that operation will be safe with respect to the marine environment present challenges (NASEM 2022; Doney et al. 2025; Halloran et al. 2025).

Field trials have begun to provide valuable insights into the practical challenges of project operation, alkalinity delivery, potential carbonate precipitation and ecological impacts. The first commercial-scale OAE project was proposed in 2024, targeting 100,000 tonnes of CO_2 removal per year, using electrochemical acid removal and the introduction of CO_2 into alkalinity-enhanced water prior to release, as a form of pre-equilibration. To date, research in DOCC has primarily been on technology and engineering, initially focused on the electrochemistry required to generate the alkalinity swing (Willauer et al. 2011; Digdaya et al. 2020; Kim et al. 2023) then system energetics (Eisaman et al. 2018; Eisaman 2020). Two in situ pilot plants that were built in California and the United Kingdom (UK) in 2023 and 2025, respectively, are beginning to drive research to move beyond the technology and assess the potential marine impacts, MRV and social acceptance. Nevertheless, scaling OAE and DOCC from experimental stages and early projects to a climatically relevant level remains an ambitious goal that will require significant advancements in science, technology, governance and societal engagement.

Key areas for future research include developing cost-effective and energy-efficient methods for alkalinity generation and addition, and energy-efficient seawater CO_2 removal and purification; assessing the acute and long-term ecological impacts and climatic feedbacks; refining MRV systems; and exploring the socio-economic dimensions of deployment.

Scientists have been observing and modelling ocean–carbon cycle perturbations to understand the natural operation of the Earth system for decades, so there is no fundamental barrier to verifying the larger signals associated with deliberate seawater carbon chemistry manipulation.

TABLE 1. **Technology Readiness Level and Scientific Readiness Level classification scheme for chemical mCDR approaches and considerations associated with their implementation potentials**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	MATERIAL, ENERGY AND COST REQUIRE-MENTS	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS
Ocean alkalinity enhancement Ocean liming Silicate and carbonate rocks Electrochemical	**Established** Marine carbonate systematics are well understood. Uncertainties persist in mineral dissolution rates and the implications of strong chemical gradients close to the point addition. *Efficacy:* High *Durability:* Long *Sequestration potential:* Large–very large	**Prototype** Small-scale field trials are being conducted with further in situ experiments planned. The scalability of the approaches taken in these pilot studies remains unclear.	**Recognised** Substantial material and energy requirements are associated with the acquisition, preparation, transportation and deployment of alkalinity sources, though they vary by technique. Electrochemical methods are expected to have high energy demands and will generate acidic waste. *Estimated cost at scale:* Medium–high	**Experimental** Elevated seawater pH and strong chemical gradients may negatively impact organisms. Mineral-based methods may introduce harmful trace minerals; impact nutrient availability, which affects phytoplankton and the wider food web; and yield precipitates that reach the seafloor. The seawater intake and discharge required for electrochemical methods may affect ecosystems (plankton entrainment and mortality).	**Prototype** Sensors and platforms are available for conducting in situ observations of marine carbonate chemistry. Challenges persist in linking the added alkalinity to CO_2 removal from the atmosphere (as this does not necessarily happen at the point of application), though advanced numerical modelling approaches are being developed.	**Prototype** One of the more advanced mCDR techniques with field trials is starting to address key knowledge gaps. *Limiting factors:* Efficacy and environmental impacts; costs and MRV methods for implementation at scale; social acceptance

TABLE 1. **Technology Readiness Level and Scientific Readiness Level classification scheme for chemical mCDR approaches and considerations associated with their implementation potentials, continued**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	MATERIAL, ENERGY AND COST REQUIRE-MENTS	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS
Direct ocean carbon capture Electrolysis Electrodialysis	**Established** Marine carbonate systematics are well understood. Uncertainty with the potential implications of strong chemical gradients close to the point discharge. *Efficacy:* High *Durability:* Long Sequestration potential: Large–very large	**Prototype** Small-scale field trials are being conducted with further in situ experiments planned. The scalability of the approaches taken in these pilot studies remains unclear.	**Recognised** Substantial material and clean-energy requirements are associated with the extraction and subsequent transportation and long-term storage of CO_2. *Estimated cost at scale:* Medium–high	**Experimental** Strong chemical gradients at the point of discharge may negatively impact marine organisms. Seawater intake (plankton entrainment and mortality) and discharge may affect ecosystems.	**Prototype** Sensors and platforms are available for conducting in situ observations of aspects of marine carbonate chemistry. Challenges persist in determining the rate of CO_2 removal from the atmosphere (if this does not happen prior to discharge), though advanced numerical modelling approaches are being developed.	**Prototype** One of the more advanced mCDR techniques with pilot plants and field trials is starting to address key knowledge gaps. *Limiting factors:* Cost and clean energy requirements associated with the CO_2 extraction process and CO_2 storage; potential environmental impacts; MRV methods for implementation at scale

Notes: We adapted this Technology Readiness Level and Scientific Readiness Level classification scheme from the United Kingdom Research and Innovation's classification (UKRI n.d.), International Energy Agency groupings (IEA 2020) and European Space Agency definitions (ESA 2015).

Conceptual/theoretical	TRL/SRL 1: basic principles conceived, observed and reported TRL/SRL 2: technological concept or application formulated
Experimental/recognised	TRL/SRL 3: analytical or experimental proof of concept TRL/SRL 4: basic validation in a laboratory environment
Prototype/established	TRL/SRL 5: basic validation in a relevant environment TRL/SRL 6: prototype evaluation in a relevant environment
Operational/demonstrated	TRL/SRL 7: prototype demonstration in an operational environment TRL/SRL 8: technology completed and qualified through test and demonstration
Mature/quantified	TRL/SRL 9: technology qualified through successful operation

Efficacy: level of confidence that the approach will remove atmospheric CO_2 and increase ocean carbon storage. *Low; Medium; High*

Durability: likely duration over which CO_2 is expected to be removed from the atmosphere and stored away from the surface ocean. *Short (years-decades); Medium (decades-centuries); Long (centuries-millennia); Permanent (>10,000 years)*

Sequestration potential: anticipated maximum extent of net annual CO_2 removal that could be achieved with the approach if conducted globally at appropriate locations in the future. *Small (<0.1 Gt CO_2e/yr); Medium (0.1–1 Gt CO_2e/yr); Large (1–5 Gt CO_2e/yr); Very large (>5 Gt CO_2e/yr)*

Estimated cost at scale: approximate cost (dollars per tonne CO_2) for deployment at scale in the future, excluding the cost of MRV and associated development. *Low (<50 \$t/CO_2); Medium (50–100 \$t/CO_2); High (100–500 \$t/CO_2); Very high (>500 \$t/CO_2).*

The examples and considerations provided in this table are not exhaustive and are likely to vary by implementation method, setting and scale for each approach. Similarly, the TRL, SRL, efficacy, durability, sequestration potential and estimated cost of implementation may also vary by implementation scenario.

Abbreviations: TRL: Technology Readiness Level; SRL: Scientific Readiness Level; mCDR: marine carbon dioxide removal; CO_2: carbon dioxide; MRV: monitoring, reporting and verification; Gt CO_2e/yr: gigatonnes of carbon dioxide equivalent per year; \$t/CO_2: dollars per tonne of carbon dioxide.

Sources: NASEM 2022; IPCC 2022a; Smith et al. 2024; and references therein.

International collaborations and multi-disciplinary approaches will be essential to addressing these knowledge gaps and accelerating progress.

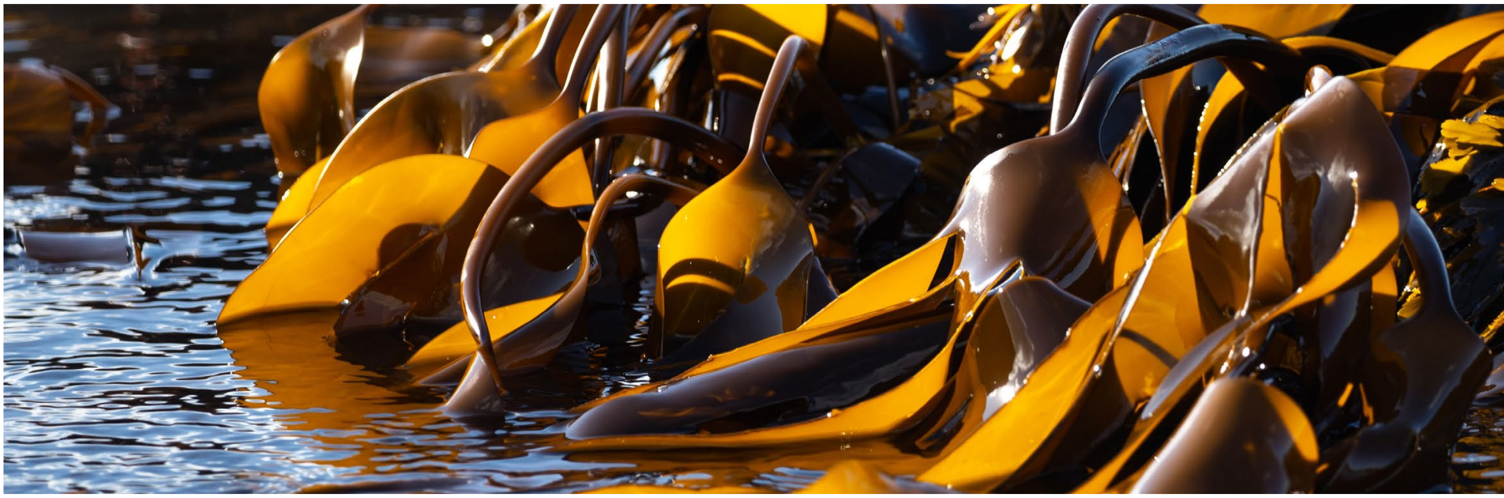
1.3 Biological mCDR approaches

1.3.1 Restoration of blue carbon ecosystems

Mangroves, wetlands and seagrass beds, commonly termed 'blue carbon' ecosystems, are coastal marine ecosystems that trap and sequester carbon with high efficiency and are amenable to management (IPCC 2019). Beyond carbon storage, healthy blue carbon ecosystems provide multiple co-benefits such as shoreline protection, space for recreation and tourism, habitat space for biodiversity and nursery habitats for fish species (Schindler Murray et al. 2023). These benefits mean that protecting and restoring blue carbon ecosystems may be met with less public concern than other mCDR methods, and that CDR does not have to be, and typically has not been, the primary driving factor for enabling their sustainable management. Scientific understanding, governance frameworks and other management considerations are covered in detail within the Ocean Panel's *Blue Carbon Handbook* (Schindler Murray et al. 2023).

The sustainable management and restoration of blue carbon ecosystems is considered an mCDR technique because these ecosystems actively remove atmospheric CO_2 via photosynthesis and convert it into organic carbon that can be accumulated within the sediments. Worldwide, blue carbon ecosystems store an estimated 6–12 gigatonnes of carbon dioxide equivalent (Gt CO_2e) (Cifuentes-Jara et al. 2015; Kauffman et al. 2020), while the restoration of degraded blue carbon ecosystems globally could contribute to carbon sequestration at a rate of up to 0.212 Gt CO_2e per year (/yr) by 2050 (Hoegh-Guldberg et al. 2023). Although our ability to quantify these carbon stocks and fluxes and to map blue carbon ecosystems using remote-sensing tools has improved over recent years (Simpson et al. 2022), key scientific knowledge gaps remain, including the role and dynamics of other greenhouse gases like methane (CH_4) and nitrous oxide (N_2O), the effect of disturbance on carbon release (Macreadie et al. 2021) and the sequestration potential of restored blue carbon ecosystems (IPCC 2019).

Internationally adopted greenhouse gas accounting guidelines exist under the Intergovernmental Panel on Climate Change (IPCC) for blue carbon ecosystems in the IPCC Wetlands Supplement (IPCC 2013), allowing them to be accounted for in national greenhouse gas inventories, biennial transparency reports and nationally determined contributions under the Paris Agreement. However, many countries lack detailed data (known as IPCC Tier 2 and Tier 3 data) on carbon stocks and fluxes in their national blue carbon ecosystems (Schindler Murray et al. 2023). Since 2024, this accounting has been encouraged and, in the future, certain Parties may decide to make this accounting mandatory (e.g. under the European Union [EU] regulation on land use, land-use change and forestry (Schindler Murray et al. 2023).[1] Because coastal blue carbon ecosystems lie at the intersection of land and sea areas, their



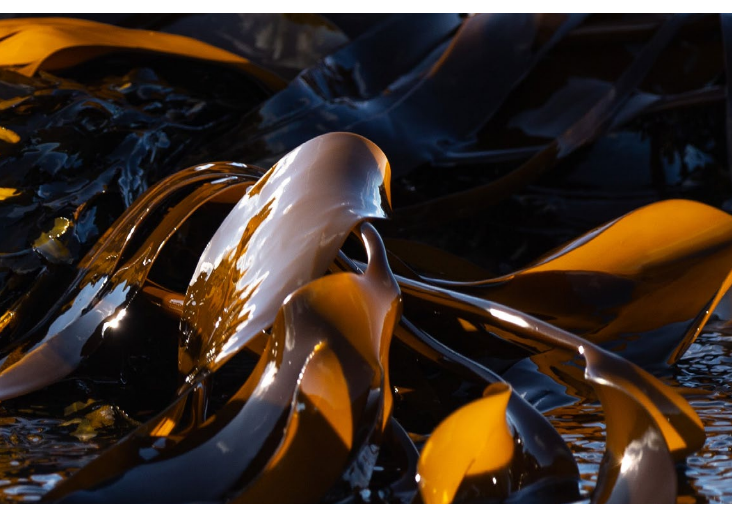
management is governed by a web of frameworks, agreements and initiatives that require coordinated and integrated approaches for high-quality outcomes (Schindler Murray et al. 2023).

Market-based blue carbon projects are currently located across 29 countries, encompassing about 1.5 million hectares of ongoing and proposed blue carbon ecosystem restoration and conservation (Perera et al. 2024). The 11 registered projects with ongoing credit issuances claim to represent a cumulative emissions abatement of 154 million tonnes of CO_2 over their crediting periods (Perera et al. 2024).

1.3.2 Phytoplankton growth

Phytoplankton carry out most marine primary production within sunlit surface waters and their rate of photosynthesis is often limited by the availability of nutrients such as nitrogen or iron. Thus, the addition of these nutrients is expected to enhance primary production, and hence CO_2 removal, as some portion of the embodied carbon in phytoplankton biomass is exported to the deep ocean for storage (known as the biological carbon pump) (Berzaghi et al. 2025). Nutrient fertilisation can occur via external additions (known as ocean fertilisation) or via the transfer of deep nutrient-rich waters to the surface (known as artificial upwelling). In both cases, the objective is to fundamentally alter marine plankton ecosystems, enhancing biological productivity to increase downward carbon export.

Iron is most often targeted for ocean fertilisation because it takes relatively small amounts to cause phytoplankton growth. Thirteen ocean iron fertilisation experiments, conducted between 1990 and 2009, successfully demonstrated the potential to enhance primary production and decrease dissolved inorganic carbon in surface waters, though 10 of the experiments resulted in little increase of carbon flux to deep water (Buesseler et al. 2024). This evidence of retention, or respiration, of the CO_2 fixed by phytoplankton within surface waters or shallow subsurface ocean raises uncertainty regarding the potential effectiveness of fertilisation for long-term carbon sequestration. Modelling studies indicate that strategies that increase open-ocean biological carbon export to depth will have a largely short-term influence on atmospheric CO_2 levels as about 70 percent of the captured carbon will be transported back to the surface ocean within 50 years (Siegel et al. 2021). To sequester carbon for at least 100 years (Buesseler et al. 2024), carbon must sink to 500–1000 metres (or more) depending on location.



By design, an intended consequence of iron fertilisation is the restructuring of plankton food webs to enhance carbon export, and the possible deployment of the technique at scale is viewed by many as controversial because of uncertainties and the sense of irreversibility of the potential, and as of yet poorly characterised, ecological impacts (Strong et al. 2009; Cooley et al. 2023a). Other areas of uncertainty that impact the potential efficacy of ocean iron fertilisation include iron bioavailability and retention time, the sensitivity of phytoplankton to iron limitation, the influence of viruses and other microorganisms comprising the microbial carbon pump (the formation of long-lived, recalcitrant dissolved organic carbon) and non-biological carbon cycles (Jiang et al. 2024; Jiao et al. 2024).

Despite these knowledge gaps, ocean fertilisation has the largest estimated CO_2 removal potential among biological mCDR approaches. If applied globally and continuously to all ocean high-nutrient, low-chlorophyll regions, it could sequester up to 1 Gt CO_2e/yr (NASEM 2022). This potential has prompted significant interest in the approach, and various fertilisation technologies are currently in development around the world. For example, one approach introduces particles with a nutrient core and gravity-controlled shell designed to sink as phytoplankton aggregate around the particle. Other approaches include the removal of harmful algae blooms; simulation of whale faeces, which naturally fertilise the surface ocean; and growth of diatom culture in photobioreactors. Different forms of iron (e.g. ferrous sulphate, manufactured nanoparticles, rice husks, clays) and different modes of delivery (including pumping from vessels, liquid or powder aerosol spray, or electrochemical dissolution of metal plates) involving autonomous underwater vehicles, planes and ships (Buesseler et al. 2024) are also being explored.

Unlike ocean fertilisation, artificial upwelling (AU) involves moving deep, nutrient-rich water to the surface using a continuous pumping mechanism powered by renewable energy (e.g. wave energy). However, this upwelling process also carries elevated levels of dissolved CO_2 from organic matter respiration to surface waters, potentially resulting in the outgassing of CO_2 to the atmosphere (Yool et al. 2009) and reducing or eliminating the CDR efficacy of the approach (Jürchott et al. 2024). The natural upwelling of deep, carbon-rich water has also been shown to exacerbate ocean acidification along the west coast of North America (Feely et al. 2008; Anderson et al. 2022), while the transfer of cold, often more saline, water to the surface may reduce natural stratification and limit CO_2 isolation from the surface, potentially altering radiation and circulation in ways that exacerbate warming (Oschlies et al. 2010; Kwiatkowski et al. 2015). At this time there are no proof-of-concept trials demonstrating that AU could sequester carbon at sufficient ocean depths (NASEM 2022), and model simulations suggest that AU is unlikely to support significant carbon removal by phytoplankton (0.05 Gt CO_2e/yr) or macroalgae (0.1 Gt CO_2e/yr) (Koweek 2022).

BOX 2. **Marine carbon storage through the deposition of terrestrial biomass**

Multiple terrestrial biomass deposition approaches have been proposed and are currently being explored by companies. These include sinking bundles of leftover agricultural material (i.e. sugarcane fibre and corn stover) into deep, oxygen-poor basins; the deposition of agricultural and forest residues into oxygen-poor deep marine environments; and the deposition of hardwood and softwood forestry residues into deep-sea environments. While terrestrial-derived material like woodfalls, leaves and shipwrecks do naturally get transported to the deep sea following storms, the scale of terrestrial carbon deposition activities for CDR purposes would likely exceed natural processes and the terrestrial biomass may have different properties than marine biomass in terms of how easily marine organisms can break it down. In addition, terrestrial organic matter may contain chemicals from agricultural or forestry processing practices that could be considered a form of pollution when added to the marine environment.

1.3.3 Macroalgal growth

Macroalgae, or seaweed, have a long history of cultivation for human use, especially in Asia where there is already large-scale commercial seaweed aquaculture. Seaweed is used in agricultural feed, human food, cosmetics and bioplastics, and is now also being grown for use as biofuel and biochar (Farghali et al. 2023). Aside from use in biochar production, growing macroalgae for use in products is not CDR since the organic matter within the macroalgae needs to be durably stored for centuries or more (Krumhansl and Scheibling 2012; Pessarrodona et al. 2022). Additionally, although the deposition of terrestrial organic material such as crop residues (S.E. Strand and Benford 2009) in marine environments is not a form of mCDR, the approach shares many similar logistical, environmental and monitoring considerations as macroalgal growth and deposition (Box 2).

Macroalgal ecosystems are some of the most productive in the ocean, with primary productivity in kelp forests (0.03 to 5.8 kilogrammes of carbon per square metre per year [kg $C/m^2/yr$]) (Mann 1973; Cebrian 1999) comparable to that of tropical rainforests (around 2.2 kg $C/m^2/yr$) and wetlands (about 2 kg $C/m^2/yr$) (Zheng et al. 2003). However, 8–61 percent of carbon assimilated into macroalgal biomass is estimated to be lost through erosion and breakage of seaweed before harvesting (Pessarrodona et al. 2024), and much of this biomass will be decomposed and remineralised back to CO_2 by microbial respiration (Brunner et al. 2024). Actively depositing organic matter onto the seafloor may help increase storage potential, with durability estimates of years to decades if deposited in shallow coastal shelf regions, and centuries or longer if deposited in deep-ocean settings (Pessarrodona et al. 2024). However, shipping large quantities of macroalgae from farms to the open ocean for deposition in either deep-water or anoxic settings raises logistical challenges as well as challenges related to MRV and demonstrating that the carbon stays sequestered for appropriate time scales.

Actively depositing organic matter onto the seafloor may help increase CO_2 storage potential, with durability estimates of years to decades if deposited in shallow coastal shelf regions, and centuries or longer if deposited in deep-ocean settings.

Scaling macroalgal growth to climatically significant (Gt CO_2e/yr) mCDR levels will require cultivation across large areas of the coastal ocean or in open-ocean settings (Pessarrodona et al. 2024). Both locations present complications, as coastal macroalgal farming will face competition with other maritime industries (including fishing and aquaculture, renewable energy, and shipping) while open-ocean farming has logistical challenges associated with tethering, seeding and harvesting the seaweed in offshore, dynamic systems as well as concerns regarding nutrient supply and disruption of natural ecosystems and relation to global marine conservation goals. These challenges mean that few companies are investigating macroalgal growth as an mCDR approach.

However, several projects are investigating the potential to remove a problematic free-floating seaweed (*Sargassum*) by sinking it to the deep ocean. *Sargassum* naturally forms huge rafts in the tropical ocean that can smother beaches and create anoxic conditions as it rots in the nearshore environment (Zhang et al. 2023). Depositing the seaweed in deep-sea environments before it impacts the coastline may help improve local conditions while facilitating CDR (Hu et al. 2021), though the long-term fate of the deposited carbon and its potential impacts on deep-sea communities is not yet well understood.

Advancing macroalgal growth as an mCDR approach requires more research into the carbon storage potential and environmental impacts associated with the deposition of large amounts of algae as well as the potential impacts of continued climate and ocean change on the technique. For example, recent modelling suggests that the CDR efficiency of macroalgal growth will be constrained by ocean dynamics and biogeophysical drivers over short time frames (about five years) while macronutrient limitations are likely to cap efficiency over longer time frames (approximately 25 years) (Berger et al. 2023). Studies also show that large-scale macroalgal farming can result in nutrient robbing that causes substantial competition with phytoplankton (Arzeno-Soltero et al. 2023; Berger et al. 2023).

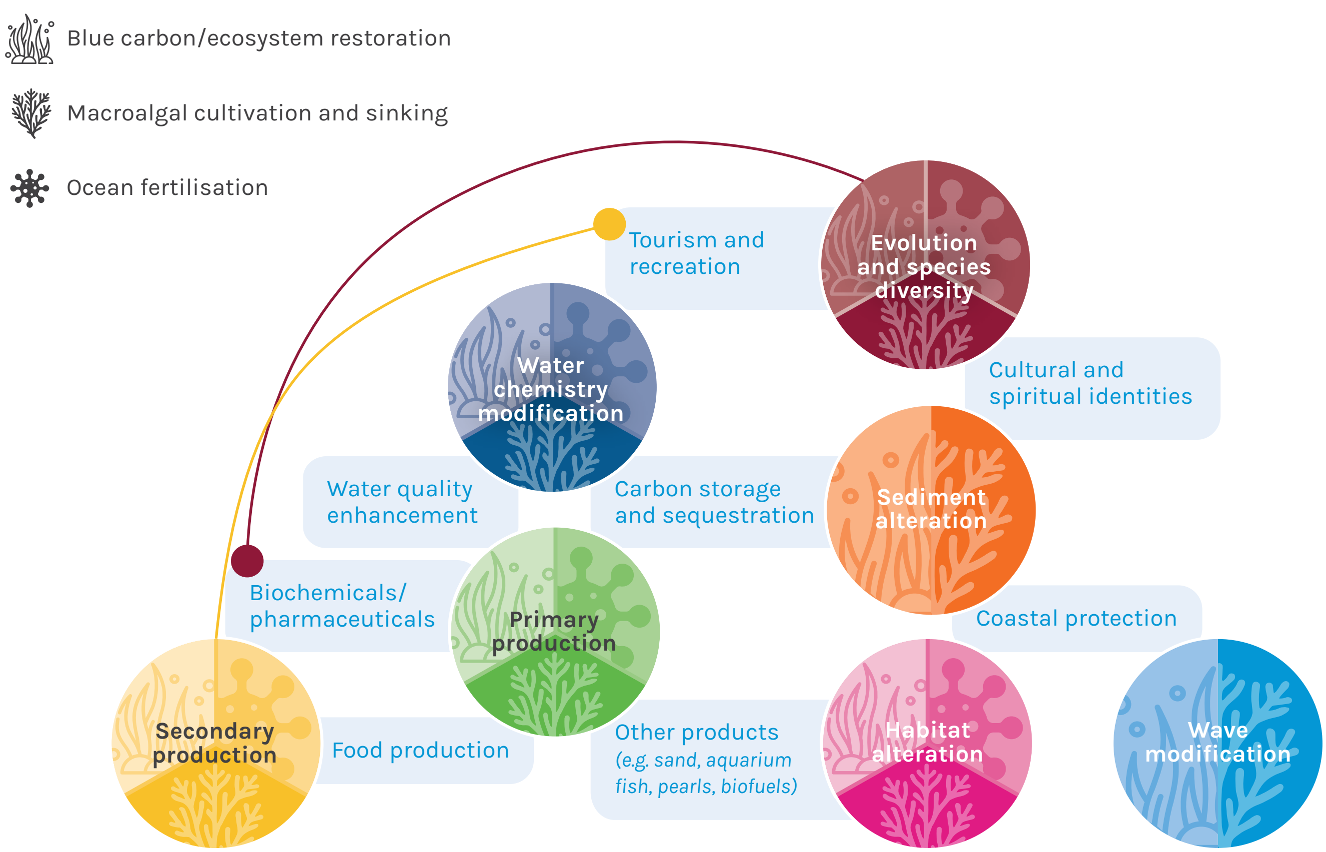
1.3.4 Potential environmental impacts

Implementing biological mCDR approaches at climatically relevant scales will inherently alter environmental and ecosystem processes, with potential effects on biodiversity, habitats, nutrient and biogeochemical functioning, and other ecosystem services (Figure 4). Increased phytoplankton and macroalgal growth may benefit some consumers and enhance finfish and shellfish production by increasing primary production and creating habitats, in the case of macroalgae. However, changes in surface reflectance, light penetration and turbidity regimes, and midwater and seafloor chemistry (oxygen, carbon dioxide, nitrous oxide, hydrogen sulphide) from the decay of phytoplankton blooms, altered nutrient regimes and the release of dissolved organic matter will likely have negative consequences both locally and further afield (Figure 4). Both macroalgal farms and phytoplankton blooms will also change surface albedo relative to seawater, with the potential for positive and negative effects that are difficult to discern (Bach et al. 2019). Ocean fertilisation may produce additional greenhouse gases (methane and nitrous oxide) whose effects may offset or even cancel out the intended CDR benefits, and may also induce loss of oxygen in the water column and cause toxic algal blooms (Williamson et al. 2012; Yoon et al. 2018). Negative impacts may also not arise until after the mCDR activity is complete and may appear in areas outside of where the activity is conducted, highlighting the importance of continuous monitoring.

Nutrient robbing is a major concern for biological mCDR approaches. Large-scale macroalgal cultivation may remove nutrients that would have otherwise fuelled phytoplankton production and associated food webs and fisheries (Arzeno-Soltero et al. 2023; Berger et al. 2023). Similarly, nutrient displacement may also occur if large-scale ocean fertilisation removes nutrients destined for the subtropics and tropics, resulting in losses in primary production and fish biomass as well as implications for coral reef ecosystems (Tagliabue et al. 2023). Nutrient fertilisation may favour larger phytoplankton species, or nitrogen-fixing species, altering the type of consumers at higher trophic levels (Jürchott et al. 2024). At the seafloor, accumulated biomass in the form of seaweed, crop or wood waste, or particulate matter from phytoplankton (Duarte et al. 2023) is likely to smother or bury benthic fauna, with microbial decay creating anoxia and generating toxic hydrogen sulphide and methane or other greenhouse gases (Levin et al. 2023). Special consideration to ecological deep-sea impacts is needed given that macroalgae deposition, ocean fertilisation, and terrestrial biomass deposition all target the deep sea to store removed carbon (Gallo et al. 2025). Stopping fertilisation would alter the biological carbon pump and could lead to outgassing of previously sequestered carbon (Oschlies et al. 2025). Increased infrastructure and ship use may lead to competition with other maritime uses (e.g. offshore renewable energy and fishing) and increase noise pollution (Duarte et al. 2021).

In contrast to phytoplankton and macroalgal growth, the ecosystem co-benefits associated with blue carbon ecosystem management and restoration are numerous (e.g. biodiversity, coastline protection, nursery grounds) (see Figure 4) and may outweigh the CDR benefit. However, large-scale expansion of blue carbon projects can also lead to increased competition for coastal areas, potentially displacing local communities or coastal subsistence activities

FIGURE 4. **Potential ecosystem impacts for biological marine carbon dioxide removal**



Note: This figure shows the potential ecosystem impacts (on species, structures and processes) associated with the main biological marine carbon dioxide removal methods discussed in this paper. Changes to the key ecosystem components, indicated by the coloured circles, may affect the associated ecosystem services, shown in the connected light blue boxes.

Source: Authors.

(see the 'Local communities and social safeguards' section within the *Blue Carbon Handbook* [Schindler Murray et al. 2023]).

1.3.5 Monitoring, reporting and verification requirements

The complexity of marine biological interactions and processes means that the predictability of carbon sequestration remains a major challenge for mCDR approaches involving phytoplankton and macroalgae (Bach et al. 2024). Monitoring, reporting and verification (MRV) for nutrient fertilisation is especially challenging because of the large spatial scales involved, the complex effects of ocean conditions and circulation, the variability in system responses, and limited holistic understanding of carbon cycle processes. Assessing carbon sequestration efficiency requires quantifying additionality, whereby changes in carbon removal from biological manipulation must subtract the anticipated extent of sequestration expected without the intervention, which is particularly challenging in biological mCDR scenarios where nutrient robbing might occur (Bach and Boyd 2021). Another additionality concern involves the extent to which unintended environmental and ecological consequences of mCDR application reduce naturally occurring carbon cycling and sequestration.

Other MRV considerations associated with macroalgal growth include better understanding the rapid rate of biomass turnover, the fate of the dissolved and particulate organic carbon in a dynamic ocean, and the spatial and temporal patterns of atmospheric-ocean CO_2 exchange at, and beyond, cultivation sites (Hurd et al. 2022). Similarly, MRV for phytoplankton growth will require monitoring throughout the water column in addition to satellite tracking of blooms, using techniques including sediment traps, underwater video profilers, autonomous gliders and floats with transmissometers, and particle backscatter and fluorescence sensors (Yoon et al. 2018), which are expected to increase the cost of conducting ocean fertilization three- to fourfold (NASEM 2022).

Technological advances have enhanced the use of satellites and remote-sensing tools such as drones for monitoring the coverage, and in some cases the health, of mangroves, wetlands and seagrass beds in actionable blue carbon ecosystems (Carpenter et al. 2022; Malerba et al. 2023; Chowdhury et al. 2024). However, additional in situ data are needed to monitor the belowground sedimentary carbon stocks (Mazarrasa et al. 2021; Simpson et al. 2022; Holmquist et al. 2024). Thus, monitoring and verification is still a costly process and capacity-building for MRV is needed (Schindler Murray et al. 2023). Nevertheless, specific blue carbon verification methodologies already exist to support the emerging voluntary carbon market for blue carbon projects (Friess et al. 2022) such as those developed by Verra, for mangrove forests (VM0007, v1.6) and tidal wetland and seagrass beds (VM0033, v2.0), by Plan Vivo and under the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism.

1.3.6 Summary

Biological mCDR approaches seek to enhance the photosynthetic uptake of CO_2 in coastal blue carbon ecosystems (mangroves, seagrasses, wetlands), macroalgae and phytoplankton and to sequester the resulting fixed carbon such that it cannot reenter the atmosphere. Co-benefits are high for blue carbon ecosystems, but co-benefits and trade-offs are less well understood for the other biological approaches. Estimates of sequestration potential range from 0.1 to 1 Gt CO_2e/yr, with blue carbon sequestration potential being the most limited because it is possible in only coastal areas rather than the open ocean. Each approach has uncertain efficacy stemming from scientific knowledge gaps about the interaction of and variability in biological, biogeochemical and physical processes in the ocean. The methods also differ in their technological readiness levels, with blue carbon restoration having the highest maturity, followed by macroalgal growth and finally phytoplankton growth (Table 2). Concerns exist about the environmental risks associated with greatly enhancing phytoplankton and macroalgal growth, including changes in ocean chemistry, consequences for marine life, ecosystem functions and associated services (Figure 4). Whereas, for blue carbon ecosystem restoration, the key risks are primarily socio-economic and relate to competition for coastal areas and the potential displacement of local communities.

TABLE 2. **Technology Readiness Level and Scientific Readiness Level classification scheme for biological mCDR approaches and considerations associated with their implementation potentials**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	MATERIAL, ENERGY AND COST REQUIRE-MENTS	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS
Restoration of blue carbon ecosystems Mangroves Salt marshes Seagrass meadows	**Demonstrated** The processes that influence organic carbon accumulation in coastal ecosystems are relatively well understood. Knowledge gaps remain on the spatial and temporal heterogeneity in sequestration and the extent to which other greenhouse gas emissions (CH_4, NO_x) and carbonate production may impact efficacy. *Efficacy:* Low *Durability:* Short–medium *Sequestration potential:* Small	**Mature** Blue carbon and ecosystem restoration management strategies are well established and supported by a large network of international organisations.	**Demonstrated** Low energy requirements minimise costs when implemented for wider ecosystem benefits. Trade-offs with other marine spatial uses need to be considered. *Estimated cost at scale:* Very high	**Mature** The management and restoration of blue carbon environments have an array of recognised ecosystem benefits that may outweigh the net CDR benefit. Potential negative impacts from mismanagement (e.g. perturbations in O_2 availability, release of other greenhouse gases) are also well characterised.	**Established** While the carbon content of coastal sediments can be directly measured, it is extremely challenging to quantify the additional extent of atmospheric CO_2 uptake into blue carbon ecosystems as a function of management interventions.	**Demonstrated** While blue carbon management is technologically the most mature mCDR approach with well-characterised co-benefits, it has limited potential for at-scale implementation as an mCDR strategy alone. Limiting factors: MRV methods for linking the management intervention to atmospheric CO_2 uptake; understanding of the impact of CH_4 and N_2O release and carbonate production on CDR efficacy

TABLE 2. **Technology Readiness Level and Scientific Readiness Level classification scheme for biological mCDR approaches and considerations associated with their implementation potentials, continued**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	MATERIAL, ENERGY AND COST REQUIRE-MENTS	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS
Phytoplankton growth Iron fertilisation Nutrient (N, P) fertilisation Artificial upwelling	**Demonstrated** The general mechanisms that influence the ocean's 'biological pump' are well understood but spatial variability is significant. The potential for manipulation at scale and the efficacy of carbon sequestration in manipulated settings remain uncertain. *Efficacy:* Medium *Durability:* Medium–long *Sequestration potential:* Medium–large	**Prototype (fertilisation)/ Conceptual (AU)** 13 iron fertilisation field trials were conducted between 1990 and 2009. Further iron and nutrient fertilisation trials are currently being planned or assessed. While some AU approaches have been proposed and tested in nearshore settings, no scalable approaches have so far been developed or demonstrated.	**Recognised** Substantial material and energy requirements are associated with placing the nutrients into the photic zone (including shipping, aerial deployment and/or in situ infrastructure). *Estimated cost at scale:* Low–high	**Experimental (fertilisation)/ Conceptual (AU)** The intentional modification of marine phytoplankton productivity is expected to have an array of cascading environmental impacts, though their severity and ecological consequences if conducted at scale remain unknown. The anticipated impacts include biodiversity changes, downstream nutrient robbing, seawater chemistry perturbation (including O_2 reduction and N_2O production), adjusted sea surface albedo and effects from nutrient dispersal infrastructure (ships/pipes).	**Recognised** Phytoplankton productivity can be monitored using both in situ and remote observation (satellite) techniques. However, it is very challenging to relate the extent of phytoplankton activity to carbon export and atmospheric CO_2 removal, owing to the large spatial scales involved, effects of marine circulation, carbon tracing through the food web and water column and delay in CO_2 uptake into seawater.	**Experimental** Despite its prominence in mCDR discussions and potential for implementation over large spatial scales, several critical knowledge gaps and uncertainties remain. *Limiting factors:* Environmental impacts and efficacy if conducted at scale; MRV approaches that account for natural system variability; cost and infrastructure requirements; social acceptance

TABLE 2. **Technology Readiness Level and Scientific Readiness Level classification scheme for biological mCDR approaches and considerations associated with their implementation potentials, continued**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	MATERIAL, ENERGY AND COST REQUIRE-MENTS	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS
Macroalgal growth Seaweed farming and deposition into the deep sea *Sargassum* deposition into the deep sea	**Demonstrated** Seaweed farming is established for other sectors, and the processes that control growth and CO_2 uptake are well understood. However, the potential for increasing seaweed growth at scale, plus the efficacy of carbon sinking and burial in manipulated settings, remains uncertain. *Efficacy:* Medium *Durability:* Medium–long *Sequestration potential:* Medium–large	**Experimental** Commercial seaweed farms are already operational. Field trials and technologies for depositing harvested seaweed in deep-sea settings are currently in development.	**Recognised** Substantial material and energy requirements are likely associated with farming at scale due to the need for nutrient replenishment in surface waters and deposition of the harvested material into deep-sea environments. *Estimated cost at scale:* Medium	**Experimental** Seaweed farming may create beneficial habitats for other species and marine sectors (e.g. fisheries) but may also impact nutrient availability and seawater chemistry with detrimental consequences for phytoplankton-based food webs due to nutrient robbing. The deposition of harvested material into deep-sea environments is also likely to impact seafloor ecosystems, with potential effects including physical smothering and expansion of oxygen-deficient conditions. The infrastructure associated with the cultivation and/or deposition process (e.g. ships, lines, nutrient pipes) may also conflict with other sectors and uses.	**Recognised** The amount of carbon harvested in seaweed can be measured, but it is difficult to relate that to atmospheric CO_2 uptake into seawater. The fate of carbon deposited into deep-sea environments is also very challenging to monitor, and significant uncertainty exists in the nature and scale of MRV required for deep-sea deposition.	**Experimental** While seaweed farming can be considered a mature technology, its potential use for mCDR is unproven and significant uncertainties exist on the wider ecological consequences if conducted at scale. *Limiting factors:* Environmental impacts, both in surface and deep-sea settings; MRV requirements; cost and infrastructure requirements

Notes: We adapted this Technology Readiness Level and Scientific Readiness Level classification scheme from the United Kingdom Research and Innovation's classification (UKRI n.d.), International Energy Agency groupings (IEA 2020) and European Space Agency definitions (ESA 2015).

Conceptual/theoretical	TRL/SRL 1: basic principles conceived, observed and reported TRL/SRL 2: technological concept or application formulated
Experimental/recognised	TRL/SRL 3: analytical or experimental proof of concept TRL/SRL 4: basic validation in a laboratory environment
Prototype/established	TRL/SRL 5: basic validation in a relevant environment TRL/SRL 6: prototype evaluation in a relevant environment
Operational/demonstrated	TRL/SRL 7: prototype demonstration in an operational environment TRL/SRL 8: technology completed and qualified through test and demonstration
Mature/quantified	TRL/SRL 9: technology qualified through successful operation

TABLE 2. Technology Readiness Level and Scientific Readiness Level classification scheme for biological mCDR approaches and considerations associated with their implementation potentials, continued

Notes, continued: **Efficacy:** level of confidence that the approach will remove atmospheric CO_2 and increase ocean carbon storage. *Low; Medium; High*

Durability: likely duration over which CO_2 is expected to be removed from the atmosphere and stored away from the surface ocean. *Short (years–decades); Medium (decades–centuries); Long (centuries–millennia); Permanent (>10,000 years)*

Sequestration potential: anticipated maximum extent of net annual CO_2 removal that could be achieved with the approach if conducted globally at appropriate locations in the future. *Small (<0.1 Gt CO_2e/yr); Medium (0.1–1 Gt CO_2e/yr); Large (1–5 Gt CO_2e/yr); Very large (>5 Gt CO_2e/yr)*

Estimated cost at scale: approximate cost (dollars per tonne CO_2) for deployment at scale in the future, excluding the cost of MRV and associated development. *Low (<50 \$t/CO_2); Medium (50–100 \$t/CO_2); High (100–500 \$t/CO_2); Very high (>500 \$t/CO_2).*

The examples and considerations provided in this table are not exhaustive and are likely to vary by implementation method, setting and scale for each approach. Similarly, the TRL, SRL, efficacy, durability, sequestration potential and estimated cost of implementation may also vary by implementation scenario.

Abbreviations: TRL: Technology Readiness Level; SRL: Scientific Readiness Level; mCDR: marine carbon dioxide removal; CO_2: carbon dioxide; MRV: monitoring, reporting and verification; Gt CO_2e/yr: gigatonnes of carbon dioxide equivalent per year; \$t/CO_2: dollars per tonne of carbon dioxide.

Sources: NASEM 2022; IPCC 2022a; Smith et al. 2024; and references therein.

1.4 Physical approaches

The use of artificial downward vertical currents, or pumps, has been proposed as a means of directly transporting carbon-rich surface waters into the deep ocean. Artificial downwelling is often coupled with artificial upwelling as a mechanism for increasing the rate of export of phytoplankton into deeper waters, limiting the potential for their degradation and degassing within the CO_2-rich surface waters. As with AU, various techniques have been proposed for conducting artificial downwelling, including wave-powered fans, pipes, pumps and salinity gradients (NASEM 2022). However, only a few localised downwelling tests have been conducted in the context of re-oxygenating deepwater environments (Stigebrandt et al. 2015) and the carbon sequestration efficiency of these approaches remains unknown.

The potential for environmental impacts beyond perturbations in seawater oxygen content is also unknown, though changes in light, salinity and temperature, driven by the displacement of water masses, are likely to impact local phytoplankton and zooplankton communities and the associated infrastructure may impact larger organisms and/or shipping. While natural downwelling ocean currents have been proposed as potential analogues for this approach, the scale, cost and logistical requirements associated with modifying their carbon export potential is unlikely to be competitive (Zhou and Flynn 2005). This anticipated high cost per tonne of CO_2 removed means that artificial downwelling is not considered a high priority for further mCDR research (NASEM 2022), and no significant field trials or in situ assessments are currently planned (Table 3).

TABLE 3. **Technology Readiness Level and Scientific Readiness Level classification scheme for physical mCDR approaches and considerations associated with their implementation potentials**

APPROACH AND EXAMPLE METHODS	SCIENTIFIC PRINCIPLES	TECHNOLOGICAL CAPABILITY	COST CHAR-ACTERISATION	ENVIRONMENTAL IMPACTS	MRV READINESS	OVERALL READINESS AND LIMITING FACTORS
Artificial downwelling Pumps and pipes Downwelling turbines	**Theoretical** Scientific assessments of this approach are very limited, with little understanding of the effectiveness of its CDR potential and/or scalability. *Efficacy:* Low *Durability:* Medium–long *Sequestration potential:* Medium	**Conceptual** Pipes, pumps and turbines have been proposed as mechanisms for driving downwelling, though only a few preliminary assessments have been conducted.	**Theoretical** Substantial material and energy requirements are likely to be associated with the marine infrastructure, resulting in high costs. *Estimated cost at scale:* High	**Conceptual** Downward transport of carbon and nutrients from surface waters is likely to kill phytoplankton and impact the wider food web, with equivalent impacts linked to their emplacement at depth. The associated marine infrastructure may impact marine biota.	**Theoretical** The processes of monitoring which carbon species are removed from surface waters and/or their fate following emplacement at depth have yet to be considered.	**Conceptual** Although conceptually possible, the infrastructure requirements, cost and potential for environmental impacts have prevented artificial downwelling from being considered a priority for mCDR research. *Limiting factors:* All aspects

Notes: We adapted this Technology Readiness Level and Scientific Readiness Level classification scheme from the United Kingdom Research and Innovation's classification (UKRI n.d.), International Energy Agency groupings (IEA 2020) and European Space Agency definitions (ESA 2015).

Conceptual/theoretical	TRL/SRL 1: basic principles conceived, observed and reported TRL/SRL 2: technological concept or application formulated
Experimental/recognised	TRL/SRL 3: analytical or experimental proof of concept TRL/SRL 4: basic validation in a laboratory environment
Prototype/established	TRL/SRL 5: basic validation in a relevant environment TRL/SRL 6: prototype evaluation in a relevant environment
Operational/demonstrated	TRL/SRL 7: prototype demonstration in an operational environment TRL/SRL 8: technology completed and qualified through test and demonstration
Mature/quantified	TRL/SRL 9: technology qualified through successful operation

Efficacy: level of confidence that the approach will remove atmospheric CO_2 and increase ocean carbon storage. *Low; Medium; High*

Durability: likely duration over which CO_2 is expected to be removed from the atmosphere and stored away from the surface ocean. *Short (years–decades); Medium (decades–centuries); Long (centuries–millennia); Permanent (>10,000 years)*

Sequestration potential: anticipated maximum extent of net annual CO_2 removal that could be achieved with the approach if conducted globally at appropriate locations in the future. *Small (<0.1 Gt CO_2e/yr); Medium (0.1–1 Gt CO_2e/yr); Large (1–5 Gt CO_2e/yr); Very large (>5 Gt CO_2e/yr)*

Estimated cost at scale: approximate cost (dollars per tonne CO_2) for deployment at scale in the future, excluding the cost of MRV and associated development. *Low (<50 \$t/CO_2); Medium (50–100 \$t/CO_2); High (100–500 \$t/CO_2); Very high (>500 \$t/CO_2).*

The examples and considerations provided in this table are not exhaustive and are likely to vary by implementation method, setting and scale for each approach. Similarly, the TRL, SRL, efficacy, durability, sequestration potential and estimated cost of implementation may also vary by implementation scenario.

Abbreviations: TRL: Technology Readiness Level; SRL: Scientific Readiness Level; mCDR: marine carbon dioxide removal; CO_2: carbon dioxide; MRV: monitoring, reporting and verification; Gt CO_2e/yr: gigatonnes of carbon dioxide equivalent per year; \$t/CO_2: dollars per tonne of carbon dioxide.

Sources: NASEM 2022; IPCC 2022a; Smith et al. 2024; and references therein.

1.5 Priorities for progressing scientific knowledge and technological capability

1.5.1 Upscaling mCDR to climatically relevant levels

Advancing our scientific understanding of the potential for mCDR approaches to operate at climatically relevant scales requires the development and implementation of a suite of tools, including laboratory-based experiments, field-scale mesocosms, numerical model simulations and the investigation of natural analogues (Bach and Boyd 2021). The initiation of small-scale, controlled, in situ field trials is particularly critical to ensuring that financial and/or political pressures to implement and upscale mCDR techniques do not get ahead of scientific awareness of their effectiveness and impacts (Ricart et al. 2022; Ocean Visions 2023; Palter et al. 2023). Testing mCDR techniques through small pilot studies enables key knowledge gaps to be addressed under real-world conditions, while minimising the potential for significant unintended negative impacts, and improves our understanding of the suitability, and requirements, of different MRV approaches. Pilot studies also improve our understanding of the energy and material requirements of different approaches, enabling full life cycle analyses to be conducted to help assess the expected costs and net efficiency of the approach if applied at greater scales. In addition to these technological benefits, small-scale trials provide vital guidance for the development of appropriate governance frameworks and help improve social awareness of the different mCDR approaches.

Despite their importance for advancing our understanding of mCDR techniques, it remains extremely challenging for both academic and commercial entities to conduct controlled field trials owing to the complexities associated with issuing permits and coordinating with regulatory bodies in the absence of clear governance mechanisms. At the time of this report, 45 operational or completed mCDR in situ trials had been openly acknowledged, with a further 9 trials within the planning, permitting or proposal stages (Ocean Visions n.d.). Chemical and biological approaches are comparably represented within these activities, though OAE is currently the most frequently tested approach. Although trials are being conducted, or proposed, globally, all are located within national waters, with most located within the United States' exclusive economic zone. It is vital that the knowledge derived from these (and future) trials, whether successful or unsuccessful, is shared openly and swiftly among all interested parties (Boettcher et al. 2023; AGU 2024) to help maximise the rate of advancement and avoid unnecessary environmental and/or financial impacts during this developmental phase. Such recommendations and requirements for enabling the responsible advancement of mCDR approaches are discussed further in section three, 'How national governments can advance responsible mCDR'.

Beyond this necessity for in situ assessments, the potential for initiating and upscaling mCDR activities would benefit from a greater understanding of the extent to which they can be safely and effectively deployed in conjunction with more established coastal or marine activities. Many of the advancements in mCDR scientific and technological understanding are currently being driven by commercial entities seeking to establish themselves as suppliers within the mCDR sector. However, the financial volatility of the voluntary carbon market (see subsection 'Establishing viable financing mechanisms' below) and restrictions within international governance frameworks (see section two, 'Governance considerations for the research or potential deployment of mCDR') mean that they are unable to rely on revenue derived from mCDR carbon credits alone to fund their activities. Accordingly, mCDR start-ups may be forced to diversify away from their 'core businesses' to remain fiscally viable, and as with any new sector, it's unlikely that all new mCDR companies will succeed and scale with the rate of implementation. Identifying opportunities for multiple mCDR approaches to be conducted simultaneously and/or implemented alongside other marine infrastructure (e.g. shipping, coastal management, cooling or wastewater discharge) may provide mechanisms for reducing MRV costs and capital expenditure and help align governance processes alongside other well-regulated activities. Characterisation of the potential for mCDR techniques to be implemented for benefits beyond CO_2 removal is also likely to increase the rate of application, as inferred for terrestrial CDR approaches such as enhanced rock weathering (Beerling et al. 2020; Skov et al. 2024) and reflected by the greater

Historically, global observing systems have been optimised to measure open-ocean carbon dynamics rather than the fine-scale, coastal and nearshore environments where many mCDR techniques are likely to be deployed, and notable gaps remain in southern hemisphere coverage.

application of approaches to restore blue carbon ecosystems despite their lower effectiveness as an mCDR strategy (Williamson and Gattuso 2022).

1.5.2 Developing MRV capabilities

The existing global ocean carbon observing infrastructure is not yet fully equipped to monitor and verify mCDR projects at scale. Historically, global observing systems have been optimised to measure open-ocean carbon dynamics rather than the fine-scale, coastal and nearshore environments where many mCDR techniques are likely to be deployed, and notable gaps remain in southern hemisphere coverage (Kelly et al. 2025). Of the comprehensive global observing systems that do exist, the Surface Ocean CO_2 Atlas (SOCAT) has seen a decline in the frequency and comprehensiveness of oceanic CO_2 measurements as a result of funding limitations and a slow recovery of operations since COVID-19 (NOAA 2023).

Currently, sensors for mCDR rely on direct sampling, optical techniques and laboratory titrations (IEEE 2023). Observations required for facilitating accurate MRV at scale will rely on the development and integration of new generations of sensors, autonomous platform technologies such as drone arrays (S. Chen et al. 2024), and remote sensing capabilities. Long-term observation is critical to help detect the effects of any intervention over natural variability, but observations may be limited by operational constraints and costs (Ocean Visions 2023; Doney et al. 2025). Moreover, ocean turbulence makes distinguishing observed carbon sequestered through mCDR approaches from natural variability especially difficult. For example, added alkalinity in OAE will be so diluted as to be undetectable above existing variability in the time scale needed for MRV (Ho et al. 2023). Robust, fit-for-purpose models validated by observational data will likewise be needed. Model comparisons between controlled conditions and at-sea scenarios, combined with climatological baselines and natural variability, can aid in assessing efficacy and quantifying CO_2 removal. Advances in both observational technologies and modelling capabilities are currently being established across mCDR approaches, supported by programmes like the Advanced Research Projects Agency–Energy (ARPA-E 2023) and the Carbon to Sea Initiative (CtSI n.d.).

Research institutions, start-ups and others are establishing MRV strategies for field trials. The vast majority (88 percent) of field trials registered in Ocean Visions' database include MRV (Ocean Visions n.d.). Of these, nearly two-thirds (63 percent) conduct MRV themselves and only 11 trials (20 percent) involve a third party. To deploy mCDR at scale with carbon removals calculated and sold for credit, MRV must include reporting results to an accredited third party for verification and certification, which should be done transparently (Arcusa and Sprenkle-Hyppolite 2022; DOE 2023; Ho et al. 2023).

MRV considerations are likely to become increasingly complex if multiple mCDR techniques are deployed near each other. Techniques may produce overlapping or confounding effects on local carbon dynamics, and each mCDR approach may have specific spatial and temporal monitoring requirements, existing sensor capabilities, and particular baselines. Without standardised protocols and transparent sharing, data compatibility issues and potential redundancies in measurements are likely to arise. Moreover, the interconnectivity of marine ecosystems and potential interference among sensors or platforms could distort data quality and reduce the accuracy of assessments.

1.5.3 Establishing viable financing mechanisms

Facilitating the scientific and technological advances required to enable mCDR implementation will entail significant investment. Estimates show that roughly $1.5–$2.5 billion will be required to conduct the foundational and applied research needed to evaluate the viability of mCDR approaches (NASEM 2022). Given this scale, these costs will likely need to be shared globally across an array of funders and funding mechanisms.

Three financing routes are likely to be important for mCDR: carbon markets, debt financing, and international transfers or flexible mechanisms (Cooley et al. 2023a). Although debt instruments, such as green bonds, and flexible funding processes, such as the UNFCCC's Clean Development Mechanism, are already being used to support climate finance and/or governmental climate mitigation efforts (Bhandary et al. 2021), their suitability for mCDR will vary by approach and location. Debt mechanisms are more suited to technologies requiring substantial infrastructure investment (Cooley et al. 2023a).

As with other CDR techniques, carbon markets are a source of support for mCDR, especially for techniques such as OAE and DOCC with moderate up-front costs that can be conducted on a medium to large scale (Cooley et al. 2023a; Michaelowa et al. 2023). Projections that the mCDR sector may be worth half a trillion dollars per year once fully scaled (Gagern et al. 2022) have driven significant investment into mCDR companies (e.g. www.cdr.fyi). However, in 2023, the weighted average cost per carbon credit for mCDR approaches was two-to-four times greater than terrestrial CDR equivalents, and several orders of magnitude greater than conventional land use methods (Smith et al. 2024). While transitioning from funding via the voluntary carbon market to compliance market may be a way to drive long-term future demand across the CDR sector, increased public funding is needed in the near term to assess the viability of individual techniques.

All of these potential mCDR funding mechanisms are associated with a number of equity and welfare considerations that align with those identified for terrestrial CDR and climate mitigation approaches (Cooley et al. 2023a) and are further complicated by the prevailing research needs of the sector. For example, ensuring transparency during the assessment of mCDR approaches dictates that they are not influenced by economic interests (Boyd et al. 2025), yet the majority of in situ field trials and pilot studies are currently being funded by commercial entities wishing to advance the sector in line with voluntary carbon market requirements. Similarly, the necessity for funders to include adequate financial support for assessing community perspectives

(Boettcher et al. 2023) can be challenging for investors seeking viable returns on short time frames. Philanthropic and governmental funding mechanisms have the potential to help facilitate these transparent, interdisciplinary assessments of mCDR approaches, yet the majority are not currently available at the scales required to drive meaningful advancements in knowledge.

1.5.4 Aligning operational requirements with governance and social considerations

Financing is central to conducting the research needed to advance scientific knowledge of mCDR, but it is not enough to ensure that mCDR can be used to meet climate mitigation targets. The implementation potential of any mCDR approach depends on the availability of appropriate national and international governance frameworks and societal acceptance. The significance of these aspects—covered in sections two, 'Governance considerations for the research or potential deployment of mCDR', and three, 'How national governments can advance responsible mCDR'—in determining the feasibility of mCDR stems from the fact that despite the absence of people, any offshore intervention must be treated as a social context with impacts on the associated communities (Nawaz and Satterfield 2024). It is therefore critical that mCDR technologies are developed with consideration of their operational requirements and sites of implementation. For example, physical and sustainability limitations on deployment at scale, coupled with technologically demanding infrastructure, are likely to favour the advancement of mCDR approaches within developed nations that have access to the necessary expertise and capital (Craik 2025). Yet, over 45 percent of marine exclusive economic zones are in developing nations whose geographical and/or oceanographic settings may make them ideal locations for mCDR deployment. Similarly, prioritising development of mCDR approaches designed to operate primarily in areas beyond national jurisdiction may ultimately delay atmospheric CO_2 removal via marine approaches because of the complexities of international governance (Gattuso et al. 2021). Full recognition of these sociotechnical perspectives when advancing mCDR scientific and technological capabilities is vital to ensuring their ultimate success (Cooley et al. 2023a).

1.6 Summary

The natural efficiency of the ocean as a sink of atmospheric CO_2 has resulted in significant interest in artificially manipulating, or accentuating, those processes to increase the rate of CO_2 absorption into seawater. The sustainable management and restoration of coastal blue carbon ecosystems (mangroves, wetlands and seagrass meadows) is scientifically and technologically the most mature mCDR approach and is already included in IPCC greenhouse gas accounting guidelines. However, the CO_2 sequestration potential of restored blue carbon ecosystems is limited, so it may be more likely to be implemented for non-mCDR-related benefits. More novel mCDR techniques can be characterised as chemical (OAE, DOCC) or biological (phytoplankton growth, macroalgal growth) approaches, though the physical downwelling of carbon-rich surface waters has also been proposed. Carbon storage in marine environments via terrestrial biomass deposition and/or sub-surface CO_2 injection and mineralisation shares many overlapping considerations with mCDR techniques, though is not mCDR as the removal of CO_2 from the atmosphere occurs elsewhere.

Chemical approaches are technologically the most advanced and scalable mCDR techniques at present, with several companies already running small-scale OAE and DOCC pilot plants. While the global commercial seaweed (macroalgal) aquaculture sector is well established for other purposes, research efforts on macroalgal CDR seek to improve understanding of the viability of durably storing this biomass in deep-ocean settings through controlled field trials.

Despite increasing understanding of mCDR techniques in recent years, their potential for implementation at climatically and commercially relevant scales remains highly uncertain. Significant advancements in our technological capabilities and scientific knowledge of their CDR efficiency, environmental implications and monitoring requirements are urgently needed if these approaches are to meaningfully contribute to global climate change mitigation. These efforts must also be coupled with the simultaneous development of appropriate governance structures, financing mechanisms and societal engagement processes.

Governance considerations for the research or potential deployment of mCDR

There is currently no single, comprehensive international governance framework for mCDR research or deployment. However, there are several international regimes pertinent to the protection of ocean environments or the climate that have exerted, or could exert, influence over mCDR activities (Brent et al. 2019; Webb 2023). This section will scrutinise the 'sketchy international governance seascape' of mCDR activities (VanderZwaag and Mahamah 2024). Key international agreements relevant to mCDR are summarised in Table 4 and discussed in greater detail below.

TABLE 4. **Summary of key international agreements relevant to marine carbon dioxide removal**

AGREEMENT	YEAR ADOPTED/ ENTERED INTO FORCE	NUMBER OF PARTIES	GENERAL FOCUS OF THE AGREEMENT
United Nations Convention on the Law of the Sea (UNCLOS)	1982/1994	169 states and the European Union	Establishes a legal framework for management and use of the ocean, including defining maritime boundaries and establishing rules governing cooperation in transboundary waters, mineral exploitation, and scientific research and control of pollution that may negatively impact human health or marine species and ecosystems, and more broadly protection and preservation of the marine environment
Biodiversity beyond National Jurisdiction Agreement	2023 (not yet entered into force)	28 states	Provides the legal framework and process under UNCLOS to protect marine life and biodiversity in areas beyond national jurisdiction; allows for the creation of marine protected areas in international waters as well as other area-based management tools and requires environmental impact assessments for certain activities
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention, or LC)	1972/1975	87 states	Establishes a regulatory system to promote the effective control of pollution in all marine waters other than internal waters and prevent pollution of the sea by dumping of wastes and other matter; requires Parties to establish domestic laws governing dumping; Parties may permit the dumping of any substance except for 'blacklisted' substances listed in an annex
1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Protocol, or LP)	1996/2006	55 states	Aims to protect and preserve the marine environment from pollution more comprehensively than the LC (which it is intended to modernise and eventually replace); Parties must prohibit the dumping of all substances except those listed in an annex; states can be contracting Parties to the LC, the LC/LP or neither the LC/LP; if states are Parties to both, LP supersedes the LC

TABLE 4. **Summary of key international agreements relevant to marine carbon dioxide removal, continued**

AGREEMENT	YEAR ADOPTED/ ENTERED INTO FORCE	NUMBER OF PARTIES	GENERAL FOCUS OF THE AGREEMENT
Convention on Biological Diversity	1992/1993	195 states and the European Union	Focuses on the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of genetic resources; requires prior environmental review of activities that have or are likely to have significant adverse impacts on biological diversity and establishes additional requirements for activities with potential transboundary impacts
United Nations Framework Convention on Climate Change	1992/1994	197 states and the European Union	Aims to stabilise concentrations of greenhouse gases in the atmosphere at a level that will prevent 'dangerous anthropogenic interference with the climate system'[a]
Paris Agreement	2015/2016	194 states and the European Union	Aims to limit temperature increases associated with global warming through increasingly ambitious climate actions by its Parties

Note: [a] UNFCCC 1992, Art. 2.
Sources: Adapted from Lebling et al. (2022) and Lebling and Savoldelli (2025) with further additions.

2.1 UN Convention on the Law of the Sea, 1982

The UN Convention on the Law of the Sea (UNCLOS), widely referred to as the 'constitution for the ocean', prescribes the rights and obligations of states with respect to ocean management and use (UN 1982). UNCLOS has broad membership, having been ratified or otherwise adopted by 167 countries and the European Union. Fourteen other countries have signed, but not ratified or adopted, UNCLOS and thus have an obligation under international law to refrain from acts that would defeat the object and purpose of the agreement. Even countries that are not party to UNCLOS recognise some of its provisions as forming part of customary international law and thus abide by them.

In general, UNCLOS takes a largely permissive approach to maritime activities conducted under the jurisdiction or control of state Parties, provided such activities are carried out in conformity with the obligations prescribed in UNCLOS and with due regard of the rights and interests of other states and the international community (since the obligation to protect and preserve the marine environment is an obligation owed to the international community as a whole).

Marine CDR is not specifically addressed in UNCLOS, which is not surprising given that UNCLOS was negotiated in the 1970s and adopted in 1982. Nevertheless, marine CDR activities could implicate various UNCLOS provisions, including those in Part XIII on 'marine scientific research' (MSR). While UNCLOS does not define MSR, legal scholars have concluded that the term likely encompasses marine CDR research, at least in some circumstances (Brent et al. 2019; Webb 2023). For example, some scholars have argued that in-ocean field trials to assess the efficacy and impacts of mCDR techniques would qualify as MSR (Brent et al. 2019).

Under UNCLOS, 'All States have the right to conduct marine scientific research', but this is 'subject to the rights and duties of other States' (Art. 238, UNCLOS). Coastal states 'have the exclusive right to regulate, authorize and conduct [MSR] in their territorial sea' (Art. 245, UNCLOS) and exclusive economic zones (Art. 246, UNCLOS). A coastal state must, therefore, give its consent before MSR can be conducted within its territorial sea or exclusive economic zone. States have broad discretion to refuse to consent to MSR within their territorial seas. For MSR within states' exclusive economic zones, UNCLOS declares that 'Coastal States shall, in normal circumstances, grant their consent for [MSR] projects by other States or competent international organizations in their exclusive economic zone' (Art. 246, UNCLOS).

Notably, however, coastal states may withhold consent for certain MSR projects, including those that are 'of direct significance for the exploration and exploitation of natural resources', involve 'the introduction of harmful substances into the marine environment', or 'involve the construction…of [certain] artificial islands, installations and structures' (Art. 246, UNCLOS). Some marine CDR research projects could, for example, involve the introduction of harmful substances in the ocean or require the construction of structures, and thus coastal states might argue that they have the right to refuse to permit such research within their exclusive economic zones (Burns and Webb 2023).

All states have the right to conduct MSR on the high seas, subject to other provisions of the convention. In the case of marine CDR research, the most pertinent provisions would likely be found in Part XII, focused on protection and preservation of the marine environment, discussed in more detail below (Burns 2025). All MSR (whether conducted on the high seas or within a coastal state's territorial waters) must be undertaken 'exclusively for peaceful purposes', employ 'appropriate scientific methods', and 'not unjustifiably interfere with other legitimate uses of the sea' (Art. 240, UNCLOS). UNCLOS further requires that 'information on proposed major [research] programmes' and 'knowledge resulting from' MSR shall be 'made available by publication and dissemination' (Art. 244, UNCLOS). Compliance with this provision could help improve the transparency of marine CDR research.

Part XII of UNCLOS, dealing with the protection and preservation of the marine environment, is also pertinent to marine CDR activities. Under Part XII, state Parties to UNCLOS must take 'all measures… necessary to prevent, reduce and control pollution of the marine environment from any source' and 'ensure that activities under their jurisdiction or control are so conducted as not to cause damage by pollution to other States or their environment' (Art. 194, UNCLOS). Pollution is defined broadly in UNCLOS to mean 'the introduction by man, directly or indirectly, of substances or energy into the marine environment…which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities'

(Art. 1, UNCLOS). In a recent Advisory Opinion, the International Tribunal for the Law of the Sea (ITLOS) concluded that anthropogenic GHG emissions into the atmosphere fall within this definition of 'pollution' and thus 'States parties to [UNCLOS] have the specific obligation to take all necessary measures to prevent, reduce and control marine pollution from anthropogenic GHG emissions' (ITLOS 2024). Certain marine CDR activities might be used to offset emissions and thus contribute to pollution control. However, where those techniques involve the introduction of substances or energy into the ocean, they might also qualify as sources of marine pollution, thereby triggering an obligation to use due diligence to prevent and ameliorate the impacts of mCDR operations. Notably, the ITLOS Advisory Opinion indicated that Parties deploying 'marine geoengineering approaches' (which would encompass marine CDR under definitions outlined by other regimes, including the London Convention and the Convention on Biological Diversity) are not only subject to the general obligations under Part XII to address marine pollution, but also specifically Article 196, which requires Parties 'to take all measures necessary to prevent, reduce and control marine pollution resulting from the use of technologies under their jurisdiction or control'.

Moreover, Article 195 of UNCLOS requires state Parties, in taking measures to control pollution, not to 'transform one type of pollution into another'. This could be pertinent in circumstances where a Party seeks to meet its obligations to abate a marine pollutant—carbon dioxide—through research and/or deployment of marine CDR approaches that, themselves, involve the introduction of potentially deleterious substances into the ocean. The recent ITLOS Advisory Opinion on climate change noted that marine geoengineering activities that have ‘the consequence of transforming one type of pollution into another’ could violate this provision (ITLOS 2024). Whether any particular marine CDR activity runs afoul of this provision would need to be determined on a case-by-case basis, considering the specifics of the activity and appraised in light of contemporaneous developments under international law.

Under UNCLOS, the state Party with jurisdiction or control over an activity that may ‘cause substantial pollution or significant and harmful changes to the marine environment’ must conduct an environmental review before the activity is undertaken (Art. 206, UNCLOS). UNCLOS also requires ongoing monitoring and reporting of activities’ environmental impacts (Art. 204–5, UNCLOS). Article 197 of UNCLOS calls upon states to cooperate globally or regionally ‘in formulating and elaborating international rules, standards and recommended practices and procedures consistent with this Convention, for the protection and preservation of the marine environment…’. Given the nascent state of marine CDR, and its potential for impacts on the global commons or across borders, this provision may provide a salutary framework for global assessment and standard-setting for both research and potential deployment for such approaches.

Given the above, although UNCLOS does not explicitly regulate marine CDR activities, state Parties remain bound to ensure that any activities carried out under their jurisdictions or control do not contravene the provisions of UNCLOS. Failure to comply with UNCLOS can expose states to responsibility and liability under international law as well as having political repercussions and resulting in reputational harm. Similarly, states may also be held accountable under their respective domestic legal systems for failure to meet their obligations and commitments under international law, including UNCLOS.

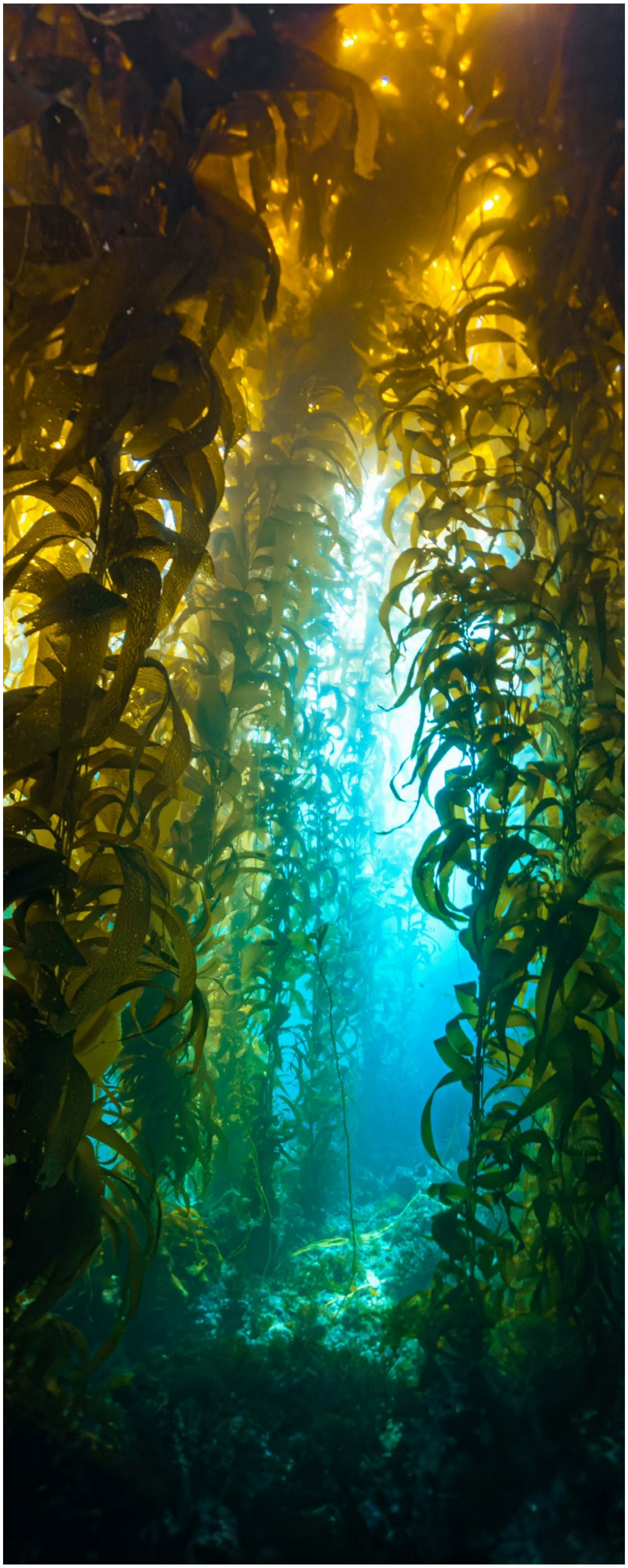
The Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement), adopted in 2023, could, if and when it enters into force, provide additional guardrails around marine CDR activities (UN 2023). The BBNJ Agreement applies to activities in, or affecting, areas beyond national jurisdiction. Although the

treaty does not explicitly regulate marine CDR, some provisions would be relevant thereto (Scott 2022). For example, the BBNJ Agreement provides for the use of area-based management tools (ABMTs) to manage 'sectors or activities...with the aim of achieving particular conservation and sustainable use objectives' (Art. 1, BBNJ Agreement). ABMTs could, at least in theory, be used to control where, when and how marine CDR activities are conducted (Webb 2024; Burns and Webb 2023). The BBNJ Agreement also includes detailed requirements for conducting environmental impact assessments (EIAs), which could help ensure more robust analysis is done on the potential impacts of marine CDR activities (Burns and Webb 2023; Webb 2024). It also provides for review of EIAs by the agreement's Scientific and Technical Body (STB), and requires the Party with jurisdiction over a proposed project to respond to comments by the STB (Art. 33, BBNJ Agreement). Moreover, the treaty includes a provision for Parties to conduct strategic environmental assessments for 'plans and programmes' in areas beyond national jurisdiction (Art. 39, BBNJ Agreement). This could provide a framework for scrutinising large-scale national or regional mCDR programmes, including the assessment of potential cumulative impacts and institutional capabilities to oversee such programmes, as well as guidelines for conducting EIAs for discrete projects (Hassanali and Mahon 2022).

The agreement has several other provisions that might be apposite to mCDR research or deployment. These include many of its general principles, including the polluter pays principle, the precautionary principle (or precautionary approach) and the right to conduct scientific research on the high seas and to encourage international cooperation for such research (Art. 7, Art. 8, BBNJ Agreement). Moreover, the BBNJ Agreement seeks to enhance cooperation and coordination with other legal instruments and bodies with the goal of promoting the protection of marine biodiversity (Art. 47, BBNJ Agreement). As such, the regime might ultimately play a role in coordinating the responses of regimes engaged in the regulation of mCDR activities.

2.2 London Convention and London Protocol

The Parties to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) (UN 1972) and the 1996 Protocol to the London Convention (London Protocol)



(IMO 1996)—two international instruments regulating ocean dumping—have taken the lead in developing an international governance framework for mCDR. Early work focused on ocean fertilisation but, in recent years, the Parties have examined a broader range of mCDR techniques. Notably, however, since some mCDR approaches do not involve 'dumping' within the terms of the London Convention and Protocol, they fall outside the scope of those instruments and thus have not been addressed by the Parties. As an example, the London Convention and Protocol apply to dumping only from 'vessels, aircraft, platforms, or other manmade structures *at sea*' (emphasis added) and thus do not directly regulate marine CDR and other activities that use onshore, coastal facilities to discharge into ocean waters. This highlights the challenge of attempting to fit mCDR into existing international regimes that were designed to regulate other activities.

The London Convention was adopted in 1972 with the goal of 'prevent[ing] pollution of the sea by the dumping of waste and other matter' (Art. I, London Convention). In the 1990s, there was an effort to update and modernise the convention, leading to the adoption of the London Protocol in 1996. The London Protocol is intended to replace the convention but, for that to happen, it must first be ratified by all convention Parties. That has not yet occurred and thus the two instruments continue to operate in parallel.

Both the London Convention and Protocol require Parties to establish domestic permitting regimes to control ocean dumping (Art. IV, London Convention; Art. 4, London Protocol). The London Convention is generally more permissive, allowing Parties to issue permits for the dumping of all wastes and other matter, except those listed in its Annex I. The London Protocol takes the opposite approach, requiring Parties to prohibit the dumping of all wastes and other matter, except for those on the so-called reverse list in its Annex I. Both instruments define dumping to include the 'deliberate disposal of waste or other matter at sea from vessels, aircraft, platforms, or other man-made structures' (Art. III(1), London Convention; Art. 1(4), London Protocol). The definition notably excludes the 'placement of matter for a purpose other than mere disposal thereof, provided that such placement is not contrary to the aims of' the London Convention or Protocol (Art. III(1)(b), London Convention; Art. 1(4)(2), London Protocol). The aims of the London Convention include preventing ‘the pollution of the sea by the dumping of waste and other matter that is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea’ (Art. I, London Convention). The London Protocol establishes even more ambitious goals, declaring that Parties should ‘take effective measures…to prevent, reduce and where practicable eliminate pollution caused by dumping or incineration at sea or wastes or other matter’ (Art. 2, London Protocol).

In 2007, in response to a proposed commercial ocean fertilisation project, the scientific groups under the London Convention and Protocol issued a statement of concern noting, ‘the potential for large-scale ocean iron fertilisation to have negative impacts on the marine environment and human health’ (IMO 2007b). The statement was endorsed by the Parties to the London Convention and Protocol, which concluded that ocean fertilisation activities fell within ‘the scope of work’ of those instruments (IMO 2007a). The Parties reiterated this view in a 2008 resolution, which further declared that ‘given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed. To this end, such other activities should be considered as contrary to the aims of the Convention and Protocol and not currently qualify for any exemption from the definition of dumping’ (Resolution LC-LP.1(2008)).[2] Parties have, then, taken the view declared that ocean fertilisation projects that do not involve research should be regulated as dumping. Notably, however, classifying projects as dumping does not necessarily mean they will ‘not be allowed’ as suggested in the 2008 resolution. Parties to the London Convention could issue dumping permits for ocean fertilisation activities because those activities do not involve the discharge of any ‘blacklisted’ substance identified in Annex I to the convention. However, because of the broader prohibition on dumping in the London Protocol, Parties to that instrument likely could not permit ocean fertilisation activities (i.e. because the materials discharged in ocean fertilisation are not listed in Annex I to the Protocol) (Webb 2024).

While the 2008 resolution sought to restrict non-research activities, the Parties did express a desire ‘to provide for legitimate scientific research’ into ocean fertilisation. In 2010, the Parties adopted an assessment framework for evaluating proposed ocean fertilisation research projects, which requires a two-stage review (Resolution LC-LP.2(2010)).[3] The first stage focuses on whether the project has proper scientific attributes to qualify as ‘legitimate scientific research’, while the second involves an environmental review to evaluate its likely impacts. The 2010 assessment framework declares that projects should be allowed only if ‘conditions are in place to ensure that, as far as practicable, environmental disturbance would be minimized, and the scientific benefits maximized…If the risks and/or uncertainties are so high as to be deemed unacceptable, with respect to the protection of the marine environment, taking into account the precautionary approach, then a decision should be made to seek revision of or reject the proposal’.

It should be noted that neither the 2008 resolution nor the 2010 assessment framework are legally binding. However, in 2013, the Parties to the London Protocol adopted an amendment that effectively codifies the approach adopted in those non-binding instruments (Resolution LP.4(8)).[4]

The 2013 London Protocol amendment has yet to enter into force, but it is intended to create a framework for regulating ‘the placement of matter into the sea’ in connection with certain listed ‘marine geoengineering activities’. The amendment defines ‘marine geoengineering’ broadly 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

Given the potential for mCDR to affect both the ocean and atmosphere—two globally shared resources—development of a robust international governance framework is essential.

GESAMP has argued in favour of considering both benefits and risks, while some Parties and observers have expressed concerns about this approach. At their 2024 meeting, all parties agreed to continue 'discussions on marine geoengineering including potential risks to the marine environment and potential benefits for mitigating climate change.'

deleterious effects'. While this definition could encompass a range of mCDR techniques, by its terms, the 2013 amendment applies to only marine geoengineering activities that involve the placement of matter in the sea and that are listed under the amendment. The amendment currently lists only ocean fertilisation, but the Parties have been evaluating four other activities for potential listing. The activities under review include ocean alkalinity enhancement and biomass sinking (along with two solar radiation management techniques).

The Parties have determined that some, but not all, forms of ocean alkalinity enhancement and biomass sinking may qualify for listing under the 2013 amendment. The Parties have expressed conflicting views on whether additional activities should be listed now, before the 2013 amendment has entered into force, and some have proposed adoption of an entirely new amendment. Pending continued discussion of these and other options, the Parties issued a *Statement on Marine Geoengineering* in 2023 (IMO 2023). The statement concluded that the techniques under review present 'risks of adverse environmental impacts…with limited knowledge of their effectiveness, and as such activities other than legitimate scientific research should be deferred'. The Parties proposed using the 2010 assessment framework to evaluate proposed research projects.

One particularly contentious issue within the deliberations of the Parties to the London Convention and Protocol has been whether the evaluation of mCDR approaches should focus on the risks they may pose marine ecosystems or also account for their potential benefits. The chair of GESAMP, a group of independent scientific experts that provides advice to the convention and protocol, has argued in favour of considering both benefits and risks (IMO 2024), while some Parties and observers have expressed concerns about this approach (Webb 2024). At their 2024 meeting, the Parties agreed to continue 'discussions on marine geoengineering including potential risks to the marine environment and potential benefits for mitigating climate change' (IMO 2024).

2.3 The Convention on Biological Diversity

As was true with the London Convention and Protocol, the Parties to the Convention on Biological Diversity (CBD) initially addressed marine carbon removal in response to concerns that large-scale, commercial ocean fertilisation activities might ensue in the absence of adequate scientific scrutiny or governance (Williamson et al. 2012). At the ninth Conference of the Parties (COP) in 2008, the Parties adopted a decision strongly paralleling the scientific and legal analysis of the Parties to the London Convention and Protocol (CBD 2008). Invoking the precautionary approach, the decision requested that the Parties refrain from ocean fertilisation activities 'until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities'. However, the Parties carved out an exception for 'small scale scientific research activities within coastal waters' as long as such activities are not used for commercial purposes and are subject to impact assessment.

In the ensuing years, the CBD has remained an active player in seeking to regulate climate intervention approaches, gradually extending its purview of concern. In subsequent decisions, the Parties have moved beyond ocean fertilisation options to a focus on 'climate-related geo-engineering activities', defined as 'technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity…' with 'carbon sequestration' defined as 'the process of increasing the carbon content of a reservoir/pool other than the atmosphere' (CBD 2010). These definitions are broad enough to encompass all mCDR approaches.

Decisions over the past 15 years have called on CBD Parties to prohibit any climate-related geoengineering activities that might affect biodiversity until there is an 'adequate scientific basis' to support such activities as well as an assessment of potential biodiversity risks and socio-economic and cultural impacts (CBD 2010, 2014). However, the decisions also permit small-scale scientific research on geoengineering activities that are designed to 'gather specific data', subject to thorough prior risk assessment (CBD 2010).

It should be noted that while the first geoengineering decision passed by the Parties restricted scientific research to 'coastal waters' (CBD 2008), subsequent decisions have called for such activities to be conducted in a 'controlled setting' (CBD 2010). While the term 'controlled setting' is not defined in the decision, a decision passed at the ninth COP references Article 3 of the CBD in this context. Article 3 focuses on the impact of activities within a Party's 'jurisdiction or control', which clearly encompasses areas beyond coastal waters (CBD 1992).

The Parties have continued to adopt decisions urging caution in the face of 'significant gaps' in the understanding of the potential impact of climate-related geoengineering activities as well as requisite proof of effectiveness or affordability (CBD 2012). Moreover, the Parties have continued to note the absence of regulatory mechanisms, and have emphasised that such mechanisms might be most necessary in cases where geoengineering activities could have transboundary impacts or operate in areas beyond national jurisdiction and the atmosphere (CBD 2012). At the most recent COP, the Parties reaffirmed their previous decisions on climate geoengineering and called on Party states and non-parties to ensure implementation (CBD 2024).

The Kunming-Montreal Global Biodiversity Framework, adopted at the 15th COP of the CBD in 2022, emphasised the important role of nature-based solutions and ecosystem-based approaches in helping to ameliorate climate change in Target 8 (CBD 2022). This might provide support to mCDR approaches that could be construed as nature-based, perhaps such as seaweed farming, but might suggest that others might not be supported (VanderZwaag and Mahamah 2024).

2.4 UN Framework Convention on Climate Change and the Paris Agreement

While the Paris Agreement (UN 2015) doesn't expressly address mCDR approaches (except, perhaps, in the context of blue carbon approaches) (Webb 2024), the treaty has several provisions that are potentially pertinent. Most broadly, the treaty calls upon its Parties to 'pursue domestic mitigation measures' to achieve the climate goals of the treaty. Legal scholars have construed the term 'mitigation' to encompass both emissions reductions and carbon removal approaches (Honegger et al. 2021). Indeed, many of the nationally determined contribution pledges made by Parties to date include carbon removal pledges, albeit mostly focused on terrestrial nature-based approaches or blue carbon (Smith et al. 2023).

Also, under Article 4(1), the Parties undertake to achieve 'a balance between anthropogenic emissions by sources and removal by sinks' in the second half of this century. The term 'sink' is defined broadly to mean 'any process, activity or mechanism which removes a greenhouse gas … from the atmosphere' and this has been interpreted as encompassing both naturally occurring removals and those resulting from human interventions (Honegger et al. 2021). Thus, the Paris Agreement clearly contemplates a role for carbon removal approaches in meeting treaty objectives (Honegger et al. 2021). Carbon removal approaches may also play a role in the newly operationalised emissions trading provisions in Article 6 of the treaty (Burns 2025). The Parties adopted a standard to guide potential emissions trading of carbon removal credits under Articles 6.2 and 6.4 at the 29th COP to the UNFCCC (UNFCCC 2024). In the context of marine carbon removal, the Parties to the climate regimes have recently emphasised the importance of protecting and enhancing marine carbon sinks and accelerating carbon removal (UNFCCC 2023a, para. 46; UNFCCC 2023b, para. 35).

The preamble to the Paris Agreement also calls upon the Parties, when enacting climate response measures, to, inter alia, consider their obligations regarding human rights, Indigenous Peoples and the right to development. While the preambular language

of the treaty is not legally binding on its Parties, it might exert some moral suasion on them to ensure the carbon removal response measures, including marine-based options, are deployed in ways that further these interests.

There is also a potential role for the agreement's forum on the impact of the implementation of response measures, which convenes under the auspices of the Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation and is directed by the Katowice Committee of Experts on the Impacts of the Implementation of Response Measures (Craik and Burns 2016). The forum's workplan and at least one technical report in the past few years indicate that it might focus on carbon removal approaches in the future, including mCDR options (VanderZwaag and Mahamah 2024).

2.5 Other potentially pertinent international regimes

Various other international and regional ocean-based treaty regimes may also have implications for mCDR activities. These could include international treaties such as the International Convention for the Regulation of Whaling, the World Heritage Convention and the UN Fish Stocks Agreement as well as regional pollution and conservation regimes such as the Convention on the Conservation of Antarctic Marine Living Resources and the Convention on the Protection of the Black Sea Against Pollution.

2.6 Customary international law and guiding principles

Customary international law, along with the general guiding principles of international law, could also be pertinent to governing mCDR research and deployment. One key principle is the precautionary approach, which is reflected in several international environmental agreements. For example, the UNFCCC directs Parties to 'take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effect' and declares that '[w]here there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures' (UNFCCC 1992, Art. 3(3)). Additionally, under the London Protocol, Parties are required to 'apply a precautionary approach' and take 'appropriate preventative measures...when there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm even when there is no conclusive evidence to prove a causal relation between inputs and their effects' (Art. 3(1), London Protocol). Parties to the protocol have invoked the precautionary principle in resolutions and decisions on marine geoengineering. The precautionary principle could counsel in favour of incremental approaches in the early stages of development of emerging mCDR approaches, such as small-scale field trials, with expansion subject to stage-gated criteria (WOR 2024). It also argues for an emphasis on transparent information-sharing and rigorous monitoring, reporting and verification protocols (Cooley et al. 2023b).

Also important for marine CDR is the no-harm rule, which imposes a due diligence–based obligation upon states to prevent activities within their jurisdictions from causing extra-territorial environmental harm, and is a well-recognised principle of customary international law (Maljean-Dubois 2021). As set forth in the International Court of Justice's *Pulp Mills* decision, a state is obliged to use all the means at its disposal to avoid activities which take place in its territory, or in any area under its jurisdiction, causing significant damage to the environment of another state (ICJ n.d.). While the rule does not impose an absolute obligation to prevent harm associated with activities conducted under a state's jurisdiction, it does require states to formulate policies and enforcement measures to prevent and minimise the risk of harm from such activities (Jervan 2014). States must, among other things, undertake EIAs for projects that may cause 'significant' transboundary harm. However, as the International Court of Justice has observed, international law does not specify 'the scope and content' of EIAs and thus 'it is for each State to determine in its domestic legislation or in the authorization for the project, the specific content required...in each case' (ICJ n.d.).

Violation of these duties can give rise to state responsibility and an obligation to redress, including reparation, compensation, cessation of harmful activities or preventive measures to avoid future harms, or measures to reduce and abate the harms already caused (Sucharitkul 1996). In the context of mCDR activities, the no-harm rule could impose an obligation on states to conduct EIAs and otherwise monitor mCDR activities under their jurisdictions, with a view to minimising potential harms, as well as requiring that states adopt and enforce regulations to minimise the risks associated with such activities.

2.7 Application of international law to mCDR activities

International law is generally binding only on nation states, though may indirectly bind individuals or companies within those states through national laws adopted to implement international law domestically. While some principles of international law (known as customary rules) have near universal applicability to all states, international agreements bind only those states that have specifically consented to them (e.g. by signing and ratifying the agreement). Some of the international agreements relevant to mCDR—most notably the London Convention and Protocol—have fairly limited memberships. This may affect the ability of those agreements to establish a truly 'global' governance regime for mCDR.

Although not directly binding on private actors, international law significantly influences the domestic regulation of those actors' conduct. Few countries have domestic laws specifically addressing mCDR activities. Instead, most countries regulate those activities under general environmental laws, including laws enacted to implement the international agreements discussed above. For example, several countries have domestic laws requiring ex ante environmental review of certain projects, mirroring requirements under UNCLOS and the Convention on Biological Diversity. Additionally, countries that are Party to the London Convention and Protocol are required to enact domestic laws to permit ocean dumping, and some have applied those laws to mCDR activities. In the United States, for example, the Environmental Protection Agency has determined that many mCDR projects will require permits under the federal Marine Protection, Research, and Sanctuaries Act—the domestic law implementing the London Convention.

A small number of states have enacted, or are in the process of enacting, domestic laws that specifically address mCDR techniques or a subset of them. Most focus on ocean fertilisation, likely because that technique has received the most attention in international discussions. For example, Denmark recently announced that it was preparing an amendment to its domestic ocean dumping law to implement the 2013 London Protocol amendment restricting ocean fertilisation. Australia has already revised its domestic laws to align with the 2013 London Protocol amendment, but the revisions will not take effect until the amendment enters into force. Germany has gone beyond the requirements of the 2013 amendment, prohibiting any addition of substances into certain ocean areas in connection with marine geoengineering, with only a limited exception for ocean fertilisation research activities. German law thus prohibits both research into, and deployment of, various mCDR approaches involving the addition of substances into the ocean (Proelss and Steenkamp 2023).

Given the potential for mCDR to affect both the ocean and atmosphere—two globally shared resources—development of a robust international governance framework is essential. Over the last two decades, the international community has taken some important steps towards developing such a framework, but progress has been slow, and interest in mCDR has only increased in the interim. There is thus an urgent need to accelerate work on mCDR governance. In the near term, it is expected that such work will continue under several international treaty regimes (e.g. London Protocol), creating the potential for inconsistent or even conflicting outcomes. Enhanced coordination and cooperation among states and frameworks will be essential to avoid further fragmentation and ensure legal clarity and robust outcomes. In addition to this work at the international level, all governments should evaluate whether their existing domestic laws provide an effective governance framework for mCDR in the national context and implement legal reforms where necessary to enable safe and responsible marine CDR research, in accordance with the requirements of international law.

How national governments can advance responsible mCDR

As mCDR has gained interest and traction in recent years, scholars have begun to work towards a consensus on what is required for its 'responsible' development. National government leadership should play a key, yet currently underdiscussed, role in supporting, guiding and regulating responsible research and public engagement regarding the future deployment of mCDR.

3.1 What is the current state of knowledge on 'responsible' research and deployment of mCDR?

As outlined in the preceding sections, mCDR is still in its early stages. As research and development progresses, many actors are focused on doing this in ethical and responsible ways. However, what 'responsible' means is not immediately obvious. Several codes of conduct and best practice guides have sought to define this term by establishing high-quality principles for early research and, thereafter, deployment of mCDR. These materials draw on diverse sources ranging from approaches to 'responsible research and innovation' to environmental justice frameworks to legal principles enshrined in risk-based regulation. To date, however, none of these has explicitly focused on the lessons that national governments might apply to ensure that mCDR research and/or deployment is conducted wisely and in ways that proactively avoid the errors of rushed development.

The Oxford Principles, which outline guidance for the governance of solar radiation modification (SRM) and CDR, are highly relevant (Rayner et al. 2013; Parson et al. 2024). First and foremost, they emphasise that these techniques should be regulated as a public good, undertaken by state and international bodies with public interest in mind. Alongside this is a strong emphasis on the need for public participation in decision-making, disclosure of research practices, open publication of results, independent assessment of impacts and governance *in advance* of deployment. The academic literature on the responsible governance of CDR also highlights the importance of simultaneous emission reductions as part of any policy involving CDR (Morrow et al. 2020) and the need to anticipate unexpected outcomes. Honegger et al. (2022) stress governance principles for CDR that include attention to climate justice, emphasising the need for international cooperation to support fair distribution of (m)CDR internationally. They argue that CDR governance should respect common-but-differentiated responsibilities and respective capacities (considering national circumstances), acknowledging that not all countries have the capacity to implement CDR. They also highlight a

As research and development progresses, many actors are focused on doing this in ethical and responsible ways. However, what 'responsible' means is not immediately obvious.

potentially important role for technology transfer, international cooperation and climate finance to help advance mCDR in Global South countries should there be a desire for it.

Other more recent research strategies and codes of conduct have focused specifically on mCDR. The National Academies of Sciences, Engineering, and Medicine's research strategy (NASEM 2022) identifies public engagement, as well as research on social and environmental impacts, as central components of responsible research on mCDR. The Aspen Institute's *A Code of Conduct for Marine Carbon Dioxide Removal Research* (Boettcher et al. 2023) establishes a set of overarching principles to guide the planning, execution and conclusion of mCDR research. These principles include acknowledgement and awareness of power imbalances, inclusiveness, respect for consent, reciprocity, responsiveness, accountability, and anticipation and precaution. Like the Oxford Principles, the Aspen Institute Code of Conduct emphasises the importance of co-designing and co-developing all research activities with impacted stakeholders, rights holders and communities. It also highlights the significance of transparency in research processes; robust monitoring and evaluation; and sharing data, knowledge and information related to research activities. Establishing collaborative partnerships between mCDR project leaders from the Global North and those in the Global South is also emphasised.

BOX 3. **The following describes the characteristics of 'responsible' mCDR research and deployment as recommended by non-governmental organisations and governments to date:**

- Regulation of mCDR as a public good
- Thorough research to understand the efficacy and safety of mCDR approaches to reduce uncertainties and inform decisions on deployment
- Public participation in decision-making and co-design and co-development of all research activities with impacted stakeholders, rights holders and communities
- Development of international decision processes to agree on what constitutes social consent across national borders
- Robust monitoring and evaluation
- Transparency and open sharing of information, data, knowledge and results throughout life span of activities
- Independent assessment of impacts
- Robust national and international governance frameworks developed in advance of deployment
- Pursuit of a fair distribution of mCDR globally, with common-but-differentiated responsibilities
- Step-by-step approach to scaling field trials

Sources: Rayner et al. 2013; Morrow et al. 2020; Honegger et al. 2022; Boettcher et al. 2023; Brent et al. 2024; AGU 2024; NSTC 2024.

Although the Aspen Institute's and related codes of conduct were written with research activities in mind, many guidelines apply to the potential future deployment of mCDR (Box 3). The AGU's *Ethical Framework Principles for Climate Intervention Research* (2024) shares much of this orientation, stressing the need for a 'step-by-step' approach to outdoor experiments (which may include mCDR field trials), post-project monitoring and information- sharing, and public participation in decision-making. The US federal Fast Track Action Committee on mCDR released a *National Marine Carbon Dioxide Removal Research Strategy* (NSTC 2024), which outlines several priorities for responsible research. The strategy emphasises active community involvement and the importance of minimising environmental risks, particularly in protecting all communities from hazards and ensuring their engagement in decisions that impact them throughout the project life cycle. It also underscores the necessity of partnering with Indigenous Peoples on mCDR research and ensuring public data accessibility and transparency.

In the following section, we describe how government action on mCDR might support these principles and, indeed, how such action might be essential for advancing responsible research and deployment.

3.2 Current state of knowledge on public acceptance and support of mCDR

Ensuring that publics have the opportunity to deliberate deeply about mCDR and participate in mCDR decision-making is, as discussed above, a central feature of responsible research and deployment. To date, a small body of social science research has investigated the acceptability of mCDR technologies among public groups. Marine CDR technologies studied include iron and/or nutrient fertilisation, in particular, but also other approaches like ocean alkalinity enhancement and marine biomass sinking. Studies have been conducted almost exclusively in the Global North, particularly Europe, the United States and Canada. No studies that we know of have robustly addressed what systems may look like under full-scale operations (e.g. 1–2 million tonnes of removal per year) in a particular region or site. At present, overall awareness across public groups is low: Roughly 10 percent or fewer of Canadian, US, European and British citizens are aware of or know what carbon dioxide removal means, and many associate the term with point-source carbon capture and storage (Braun 2017; Shrum et al. 2020). A 2025 study found that only 7 percent of US voters know 'a lot' about what CDR is (Fraser and Adcox 2025).

These limited studies provide an initial understanding of the types of mCDR that may be publicly desirable and supported. Early results indicate that systems that seem more natural are preferred (Bellamy 2022), while those involving bounded interventions such as direct air capture may be somewhat to moderately acceptable and interventions involving more uncontained or broadcast injections of material (such as nutrient fertilisation or alkalinity enhancement) are considered the least acceptable (Nawaz et al. 2023). A recent global comparison of public positions across 22 countries found high perceived benefit for more nature-based CDR approaches versus more engineered ones (Baum et al. 2024), although this study focused solely on blue carbon and did not address engineered mCDR approaches. Long-standing public concerns about 'messing with nature' persist (Corner et al. 2013), yet efforts to advocate for systems as more natural may backfire when large-scale developments are robustly considered. In other words, technologies initially perceived as 'natural' at small scale may be viewed much more negatively at larger scales, possibly because environmental and other ancillary impacts from biological-based mCDR approaches are harder to anticipate and understand.

Because all mCDR options are still emerging and very few field trials are underway, detailed information on trial outcomes that study participants might expect is not yet available. In this innovation context, we can consider knowledge of the technology's likely public perception only as uncertain or nascent. Social scientists are closely examining how the social and political configurations of mCDR influence support (or lack thereof). To accurately anticipate public views on mCDR, it may be equally or more important to understand people's preferred governing and financing conditions that might accompany the ongoing technological developments (Cox et al. 2024). Preliminary findings addressing this research trajectory suggest a rejection of 'status quo' private sector–led technology innovation and top-down governance regimes, while emphasising a more positive perception of deployment scenarios involving sociotechnical systems that are small scale; decentralised; modular; and owned, financed and operated by cooperatives or local communities (Cox et al. 2024). These more desirable conditions may significantly enhance perceptions of OAE among certain public groups—for example, where OAE under status quo conditions was rejected outright.

More broadly, the operation of any of these mCDR approaches at a scale of a million or billion tonnes per year will likely challenge public acceptance. To date, even relatively simple efforts to encourage study participants to consider scale have raised immediate concerns about ethical, ecological and justice-related impacts (Cox et al. 2022). Prompting public consideration of processes such as adding alkaline material to the ocean to enhance its capacity to uptake and store CO_2 is quite different from asking people to grapple with the implications of at-scale OAE with many dispersal sites, substantial volumes of mined or post-industrial alkaline material, and the energy requirements for extraction and transport. Similarly, for biomass sinking, the vast ocean surface area needed, along with the ships required for bundling and sinking material, could influence how these technologies are viewed, including whether any positive perception due to their naturalness persists. Ultimately, all mCDR technologies will be deployed in specific locations (Lezaun 2021) with unique social histories and contexts that will inform perceptions—whether those contexts are industrialised, beloved by residents, comparatively pristine or—perhaps—designated for marine protection. This is especially relevant for mCDR research and deployments in territorial waters, making it critical for national governments to bear this in mind.

Together, these challenges of judgment and perception place a profound deliberation and decision-making burden on any one person or community regarding various options. However, without introducing conversations of this 'scaled-up' kind, the potential implications that might arise when evaluating the viability of one intervention against another, or comparing the life cycles of different operations, or assessing various coastal or offshore sites, remain unnecessarily obscured.

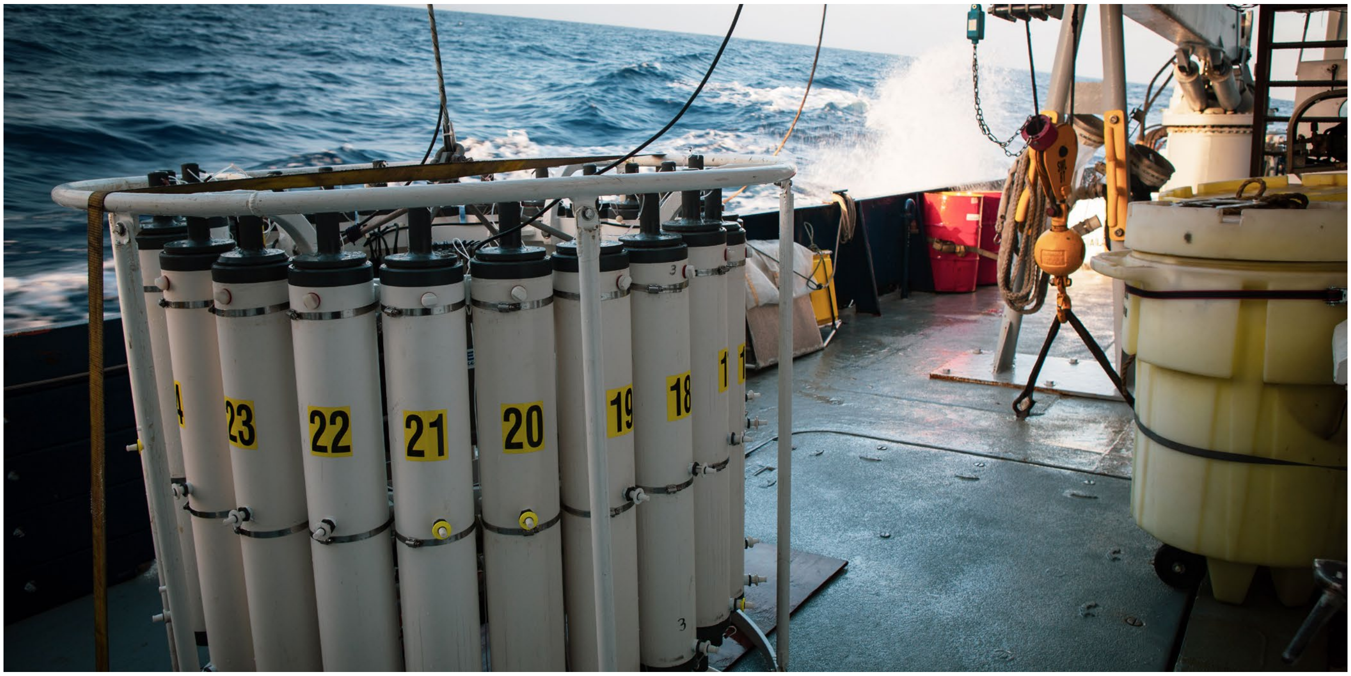
To advance responsible innovation in mCDR, participatory social science will be needed to ensure that research expands beyond public perception surveys or workshops to those that develop long-term decision-making authority involving scientists, and public groups, including Indigenous Peoples. Effective models of civic engagement incorporate diverse insights, including through citizen juries, advisory boards, deliberative polling, participatory foresight policy analysis and structured decision-making (Burns and Flegal 2015; Satterfield et al. 2023). These structured approaches are necessary to ensure that public and community knowledge about the perceptions of mCDR informs research and deployment decisions for these technologies, which are central to the 'responsibility' principles discussed above. National government implementation of these approaches can help promote transparent and inclusive decision-making as the mCDR sector develops.

3.3 Why and how governments should be central players in mCDR innovation and policy

Marine CDR provides an important global public good of atmospheric cleanup—essential for maintaining a habitable climate to benefit society yet often underfunded by individual actors such as governments and the private sector (Maher and Symons 2022). As a public good, and with a suite of innovations in the early stages of development, mCDR faces significant funding challenges because no actor feels a direct need to invest in CDR, unlike other clean technologies that deliver goods or services alongside climate mitigation benefits. As such, the government has a critical role to play in providing early-stage R&D support, which is critical to assessing whether mCDR approaches are safe and effective.

The first challenge is funding: Significantly more research and development funding is needed for policymakers to understand to what extent mCDR will be able to meaningfully contribute to climate mitigation. At present, investment in mCDR research is low compared with the outlined need: *The State of Carbon Dioxide Removal 2024* report (Smith et al. 2024) identified annual global investment of $190 million in all CDR-related research in 2022, with the vast majority directed towards non-marine approaches. Yet the National Academies of Sciences, Engineering, and Medicine's report on mCDR estimated that just under $1.5 billion for priority research areas and around $2.5 billion for all mCDR research areas will be needed over 10 years (NASEM 2022). These totals include funding to address foundational research priorities that span mCDR approaches.

If mCDR approaches are found to be safe and effective and progress beyond research and development, the cost of deployment, as well as policies or other mechanisms to create demand, must also be considered. A recent estimate found that achieving a billion tonnes of CDR annually (assuming largely terrestrial approaches but including mCDR) would require capital expenditures of $32 billion to $1.1 trillion (Sartor et al. 2024). While some have assumed that the voluntary market—that is, voluntary purchases of carbon credit offsets—will be sufficient to economically support the growing



CDR sector (Michaelowa et al. 2023), there is increasing scepticism that it will enable the level of scaling needed, so interest is growing in compliance markets such as the European Union's and California's emissions trading schemes (Burke and Schenuit 2024). There is also growing consensus that reaching the volumes of investment needed to get to billion- or trillion-dollar scales will require dedicated, non-voluntary market funding due to the lack of natural markets for mCDR without government mandates (Smith et al. 2024).

Governments can enact policies to support demonstration and deployment projects that include high standards for quality to create sufficient supply, and can also create demand through policies such as government procurement.

Without sufficient public sector support for R&D, there is a risk that the private sector may proceed with demonstration and deployment without a sufficient knowledge base about the efficacy and impacts of mCDR approaches, which could endanger the sector as a whole if mCDR credits produced from these activities turn out to be low quality. If private sector innovation fails to de-risk the technology and ensure quality, the sale of credits could proceed in detrimental ways, not fully considering environmental and social impacts or failing to adequately verify efficacy and permanence. Publicly funded research should focus on understanding both the effectiveness of mCDR approaches in removing carbon and their environmental impacts, particularly if these approaches are scaled up.

An associated concern is that mCDR might be deployed in ways that generate negative environmental and social impacts or lead to unjust implementation in the Global South. Currently, research and development for mCDR methods is mainly carried out by start-up companies, although many of the underlying ideas are borne of academic research. These companies are mainly funded by private entities: venture capital, corporations or philanthropies. Growth in this area to date has been both organic and extremely rapid. However, some of the incentives that have structured this early work are unlikely to produce equitable and effective long-term outcomes. For-profit models may incentivise field trials without proper environmental monitoring, and deployment in places where it is most economically profitable, rather than where it is most effective, locally beneficial, supported or best governed (Carton et al. 2020; Grubert and Talati 2023).

Another risk of overreliance on private sector funding for mCDR research involves intellectual property (IP). The IP implications in private sector contexts may also raise issues for the provision of mCDR if they prevent lower-income countries and regions from participating in mCDR development and deployment. In the short and medium terms, the priority for any small-scale profit-based company is to demonstrate results quickly and develop IP to stay in business. Considering how IP is handled for mCDR techniques is worthwhile in that rendering any good option inaccessible to the public could be counter-productive to larger climate goals. This is less of a worry if independent mCDR research and development is publicly funded and supported. Another option is to ensure that any research organisation that develops the techniques retains the IP, but the government could concurrently retain a non-exclusive, royalty-free license to use that IP or grant licenses to other parties if the IP is not used in a reasonable time.

A final issue related to responsible deployment is the risk that perceptions of co-optation by the fossil industry will harm social acceptance. The long-term survival of early mCDR companies is not guaranteed, and most of these companies may never remove CO_2 at a scale that matters for climate. A logical exit for these start-ups may be to sell themselves to larger companies, including fossil fuel companies, which, because of their industrial expertise, would in the long term become carbon management companies. Yet, scholarship suggests that perceptions of the oil and gas industry negatively affect judgments of offshore carbon capture and storage, indicating that a public sector or independent mCDR approach may be prudent (Gonzalez et al. 2021; Evanson 2023). Without sufficient public sector support for R&D, and government-mediated demand creation, early mCDR companies may be more likely to be acquired by fossil fuel companies and so less trusted as they develop.

3.4 Research and development network approaches

There are several ways that mCDR would benefit from coordinated innovation and research support in targeted locations in national contexts. Here, we discuss three central concepts that could be implemented as part of mCDR R&D networks: ‘test-bed’ sites in national waters for streamlined trials of specific mCDR pathways; a national lab

approach where governments actively support mCDR research and innovation; and public engagement hubs where diverse actors coordinate research and engagement to understand public priorities and conditions for supporting mCDR. Implementing any of these approaches would be beneficial, but doing so in tandem could foster a comprehensive and multi-dimensional assessment of mCDR's viability and feasibility in specific national contexts, covering technical, environmental and social considerations. This information would support national governments in determining if, and how, to responsibly transition from research to scaling of mCDR.

The first approach is the establishment of test-bed sites by national governments in their territorial waters, where specific locations are selected for the coordinated trial of different mCDR approaches. Governments are uniquely positioned to support the development of such coordinated locations for in situ field testing of mCDR techniques through pilot studies, which (as discussed in section 'State of knowledge and technology') are essential for complementing modelling and lab- and mesocosm-based research. As also noted in that section, mCDR field trials currently lack the kind of independent oversight needed to build confidence and trust. These sites would involve coordinated regulatory approaches, infrastructure for MRV and data-sharing, among other aspects.

A test-bed model could expedite research for mCDR techniques by allowing sites to be pre-permitted for field trials, which can involve obtaining multiple permits across regulatory agencies and/or navigating competing mandates and regulations. Governments could further support the development of infrastructure (both physical and institutional) needed to enhance transparency in MRV, and facilitate the rapid sharing of information and data with interested sectors and actors associated with these test-bed field-trial sites. Of particular interest is the safety of any mCDR technology as assessed by marine biologists and toxicologists concerning marine species; test-bed sites could aid in developing the capacity for monitoring carbon fates and environmental responses. Given that mCDR will need to be researched—and deployed—in the context of complex marine environments and economies, coordination across sectors is a critical opportunity for government strategy and collaboration. Attention should be paid to the careful selection of these test beds, as specific marine conditions may be required for different mCDR pathways. Additionally, it is crucial to ensure that such sites are not located in areas where they may negatively impact less powerful or marginalised communities and/or rights holders for whom marine space is vital to their Indigenous territorial homes.

In addition to establishing specific locations for coordinated testing of mCDR, governments might also adopt a national-lab approach to support mCDR research and innovation. This approach would involve funding research and innovation to develop scientific knowledge about efficacy and feasibility. Such entities could explore not only technical innovation but also relative viability, along with various life cycle–related uncertainties and trade-offs involved across relevant systems and co-industries (e.g. energy demand and its competition with other decarbonising sectors, life cycle material requirements or cost per unit of CO_2 removed and stored). Engaging engineering, energy and material scientists would be crucial as they can address challenges presented by scaling up different options, particularly concerning the social impact and acceptability of various siting and deployment options. These centres could also foster greater collaboration among transdisciplinary actors, including business development talent, grant-based non-governmental organisation researchers, national colleges or extension services such as Sea Grant (NOAA n.d.), as well as centres with extensive networks and outreach capabilities regarding local communities, industry and the private sector. All this insight will be essential for evaluating the feasibility of scaling mCDR in specific (national) contexts. If implemented alongside the previously noted test-bed approach, this could develop a practical understanding of the broader impacts and co-benefits of different mCDR pathways.

Countries and allied groups with significant economic resources have long provided large-scale public funding for scientific and technological innovation. This involves deploying substantial resources to target a needed—and often potentially disruptive—set of innovations. For example, the United States' Inflation Reduction Act is a multi-hundred-billion-dollar investment in clean energy and climate solutions, while the US National Nanotechnology Initiative is a $45 billion effort to understand the behaviour of living and non-living materials at the nanoscale and engineer applications where possible. In this latter case, dozens of university-based centres received funding to develop applications across sectors such as energy, medicine, food and the built environment. Hundreds of patents and novel R&D partnerships emerged, resulting in both public and private sector benefits, though the latter have been controversial in some regards. Strong models are also provided by Japan's Moonshot programme and Australia's Great Barrier Reef initiative. Both aim to provide technologies for the public good, particularly in relation to Moonshot Goal 4's CDR component. Embedded in this programme (as with goal 8) are efforts to identify principles for responsible research and development and explore how to apply them in practice. Both programmes integrate social science and governance expertise, exemplifying many of the recommendations we endorse here.

Many such hubs have been hosted at universities, optimising flexibility while inviting healthy review engagement and criticism, which ensures independent and flexible research design. Other successful models also exist, such as the Electric Power Research Institute (EPRI n.d.), which aims to develop knowledge about all aspects of electricity production, delivery and regulation. It is funded through a tax on utilities but could also receive funding from incentive programmes like Canada's Scientific Research and Experimental Development tax, engaging interested companies among other goals (GoC 2025). Ultimately, substantial infrastructure will be needed to incubate ideas, for data collection and for platforms for evaluation (MRV), with open-data protocols being essential for mCDR and the broader public benefits that could follow.

Both the test-bed and national lab approaches could also be implemented in conjunction with a third related concept to facilitate coordinated learning on mCDR: public engagement hubs. Led by national governments, public engagement hubs could use the public participation approaches described earlier to increase understanding of social support and the development of governance and decision-making frameworks. We reiterate (as stated earlier in subsection 'Aligning operational requirements with governance and social considerations') that large-scale development of technologies will not succeed without significant public engagement. In the UK, for example, the express intention to transform the country's energy system was fostered by a nationally funded citizen engagement process emphasising both outcome and methodological innovation. The purpose was to ensure that many possible energy scenarios were investigated to characterise the representative combinations of energy futures that had widespread citizen support, and how energy services might be developed and operated at the household and community levels. Energy emerged as both a need and a right across public discourse (Demski et al. 2019). The publicly supported rollout of wind energy has subsequently proved particularly successful in the UK, resulting in a doubling of wind energy and a higher proportion of new renewables than in any other country. As of 2023, 25 percent of the country's energy production stemmed from wind, competing only with Denmark; the countries with the next-highest proportion of energy production coming from wind were Austria and then the United States, with roughly 10 percent. Similar proactive approaches to public engagement at the national level—where governments fund and/or support engagement efforts—have the potential to ensure successful mCDR.

There are many other pragmatic reasons to consider the UK model for citizen engagement. The first is that leaving engagement to project developers requires skills that are not commonly found. This leads to inadequate and under-trusted results, partly because the source of the information often matters (Pidgeon et al. 2014; Nawaz et al. 2024). Another key

Led by national governments, public engagement hubs could use the public participation approaches…to increase understanding of social support and the development of governance and decision-making frameworks…large-scale development of technologies will not succeed without significant public engagement.

consideration is that communities are typically not involved in the early stages of research to shape that development, resulting in plans that overlook important local benefits or more socially desirable project arrangements like siting. Social backlash can and has halted projects, particularly with new technologies. Additionally, lessons learnt from one location can often provide useful insights applicable in another context—but without a coordinating body that considers different contexts, groups and deployment locations, this knowledge can be easily lost. Engagement hubs linked to broader national lab research programmes to foster technical innovation could take many forms. Precedents include Danish consensus conferences, Swiss referenda, the UK Sciencewise Expert Resource Centre programme, public debate commissions in France and Quebec, and German workforce engagement commissions. The common feature across these examples is the presence of an independent body, with no stake in any single outcome, which then facilitates the social lessons and conditions essential for decision-making. Governments are also uniquely positioned to determine whether mCDR techniques are, in fact, the best (or least-worst) alternatives on a global scale. Ultimately, only collaborating governments can evaluate that choice in the most holistic way.

As governments provide public funding for at-sea testing and innovation and research, they have the opportunity to develop requirements that recipients of funding must adhere to. Similar to the research codes of conduct discussed earlier, this could include requirements for robust monitoring, reporting and verification; requirements for meaningful community engagement, respect for Indigenous sovereignty and transparency regarding expected environmental and social impacts; and provisions to ensure the sharing of data and lessons learnt to the extent practicable, among others. Such requirements can be designed to reflect the scale and duration of the project and can help establish a standard for the sector as a whole regarding what constitutes 'responsible' or 'high-quality' activity.

More broadly, a responsible approach to mCDR requires that national governments do not outsource mCDR to the Global South, particularly to small island developing states. Instead, efforts should focus on sharing and building capacity through two-way exchanges and knowledge transfers to cultivate home-grown mCDR research across the Global South. Nearly three decades of technology transfer experience in the low-carbon energy sector provide valuable insights for mCDR initiatives that may interest the Global South. Research on successful relationship-building and adaptation indicates that access to IP rights–sharing platforms will be key, as will sustained non-market trade and finance schemes (Weko and Goldthau 2022). To date, only about a third of such initiatives have succeeded (Kirchherr and Urban 2018); and South-South technology transfer is likely to flourish, with China being a central player in that effort (Z.M. Chen et al. 2018; Urban 2018).

3.5 Summary

In summary, governments have an essential role to play in supporting the early research and assessment activities necessary to determine the environmental safety, social acceptance and technological effectiveness of any mCDR technologies prior to moving to deployment. Governments are uniquely positioned to contribute to the research and development required to advance understanding of the potential for effective and safe mCDR at scale. They can create and improve regulations governing mCDR research, establishing high standards and criteria for the projects they fund. Governments can help close the funding gap necessary to support both research and larger-scale testing of mCDR. Additionally, they can promote the development of independent, unbiased research and MRV to ensure that techniques are implemented safely. Governments can also guard against the co-optation of mCDR by legacy interests seeking to use it for greenwashing purposes. They can facilitate robust deliberations to ensure that mCDR projects are located where and when they are desired by citizens. In the Global South, governments can engage in the co-design of mCDR activities in their waters, and proactively seek out mCDR in ways that support the development of co-benefits, such as upscaling innovation capacity and workforce development.

Despite the many advantages of governments, and their necessary roles, a significant risk of government leadership is that it can make mCDR policy vulnerable to electoral politics. Care and attention are needed to ensure that policies are established to withstand the pressures of shifting government leadership priorities.

Conclusions

As urgency increases for governments to address the growing impacts of climate change, attention is turning to the ocean as a potential option to accelerate removal of CO_2 from the atmosphere, which is needed alongside deep emissions reductions. Since carbon removal, including mCDR, is largely a public good and in the early stages of research and development, governments have a key role to play in supporting the basic and applied research needed to understand if mCDR approaches are safe for ocean ecosystems and effective at removing carbon (and over what time scales) and what impacts their application will have on the environment and people. These advancements in our technological capabilities and scientific knowledge are urgently needed if mCDR approaches are to meaningfully contribute to global climate change mitigation. If mCDR techniques are found to be safe and effective, government support will likely be needed to advance demonstration and deployment and create demand. These efforts must also be coupled with the simultaneous development of appropriate governance structures, financing mechanisms and societal acceptance. Critically, governments can help set the standards for what high-quality, responsible mCDR looks like.

Governments interested in exploring or advancing knowledge on mCDR through R&D should consider the following:

- Funding basic and applied research, including at-sea tests, for mCDR approaches to better understand the efficacy and environmental safety of mCDR techniques; this basic and applied research will help ensure that pressures to implement mCDR techniques do not get ahead of scientific understanding
- Funding efforts to improve monitoring and verification technologies and modelling capabilities
- Setting standards to ensure that government funding for mCDR research and development is done responsibly—including requirements for basic research; prior environmental impact assessments; robust monitoring, reporting and verification; transparency; minimisation of harm and maximisation of benefits; community engagement; and transparency—and works towards the development of environmental standards, criteria and precautionary thresholds

- Clarifying and streamlining permitting regimes to enable small-scale, rigorously monitored at-sea research tests
- Identifying opportunities for mCDR testing to be conducted in conjunction with existing coastal or marine activities to reduce permitting and financing burdens
- Developing data-sharing agreements that enable the sharing of knowledge gained from laboratory and at-sea tests to facilitate the advancement of the field and avoid duplication of efforts
- Pursuing mCDR R&D networks to advance research through field test-bed sites, a national lab approach and public engagement hubs
- Reviewing existing domestic laws to evaluate whether they provide an effective governance framework for mCDR activities; in instances where this is not the case, improving national governance to ensure safe and responsible mCDR activity including adherence to international law
- Advocating for enhanced communication and coordination across international legal frameworks that are addressing mCDR activities to ensure that conflict among frameworks is reduced and that there are no regulatory gaps; initiating discussions in pertinent international fora, from the United Nations Ocean Conference to the UN General Assembly, would be salutary
- Encouraging states to ratify the London Protocol, including countries actively engaged in mCDR activities, such as the United States; Parties to the London Protocol are encouraged to engage with discussions concerning the marine geoengineering amendment to the agreement
- Seeking opportunities for coordination and collaboration to avoid duplication of efforts, share learnings to accelerate progress and increase capacity-building across borders

Government support is critical for advancing knowledge on mCDR to better inform deployment decisions, create appropriate governance and regulatory frameworks for mCDR and create a responsible mCDR research-and-development framework that addresses public engagement and transparency, MRV, and safety and equity. Without adequate government investment in mCDR, the sector may move ahead with insufficient scientific understanding of the environmental impacts, climate feedbacks and efficacy and/or incomplete governance, risking its ability to meaningfully contribute to mitigating climate change and its impacts.

Abbreviations

AU	artificial upwelling
CCS	carbon capture and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
DIC	dissolved inorganic carbon
DOCC	direct ocean carbon capture
EU	European Union
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
mCDR	marine carbon dioxide removal
MRV	monitoring, reporting and verification
OAE	ocean alkalinity enhancement
R&D	research and development
SRL	Scientific Readiness Level
TRL	Technical Readiness Level
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

alkalinity The ability of ocean water to neutralise acids. More alkalinity means the ocean can absorb and store more CO_2.

artificial downwelling A method that pumps surface water down to deep waters to facilitate, or speed up, the transport of surface carbon to be stored in the deep ocean.

artificial upwelling A method that pumps deep, nutrient-rich and CO_2-rich water to the surface to stimulate the growth of tiny marine plants (phytoplankton) that absorb CO_2 from the atmosphere via photosynthesis.

biological carbon pump A general term used to define the natural processes through which marine organisms use photosynthesis to integrate CO_2 into organic matter, of which some sinks or is transported by fauna into deep marine environments where it can be stored for a long time.

blue carbon Biologically driven carbon fluxes and carbon storage in coastal marine systems that are amenable to management. Actionable blue carbon ecosystems in climate mitigation policy include mangroves, seagrass beds and tidal marshes, whereas seaweed forests are considered emerging blue carbon ecosystems.

carbon capture and storage A process whereby CO_2 is collected and stored in permanent (normally geological) reservoirs instead of being released into the atmosphere.

carbon sequestration Storage of CO_2 derived from carbon capture or carbon removal processes so that it isn't released back into the atmosphere.

carbonate chemistry When CO_2 dissolves into seawater it can form different inorganic chemical species. The chemical balance among these types of dissolved inorganic carbon depends on seawater chemistry (pH and alkalinity) and physical properties (temperature and salinity) and affects how much CO_2 the ocean can absorb.

direct air capture A technology that removes CO_2 directly from the air using special filters or chemical reactions. The captured CO_2 must then be stored in permanent (geological) reservoirs to prevent its release back into the atmosphere.

direct ocean carbon capture A process that removes CO_2 directly from seawater, helping the ocean take in more CO_2 from the atmosphere. The captured CO_2 must then be stored in permanent (geological) reservoirs to prevent its release back into the atmosphere.

dissolved inorganic carbon A collective term that encompasses dissolved CO_2 gas, carbonic acid (H_2CO_3), bicarbonate ion (HCO_3^-) and carbonate ion (CO_3^{2-}), the chemical species of the seawater carbonate system that naturally store inorganic carbon in seawater.

eutrophication A situation where too many nutrients in the water cause excessive growth of algae which, upon decay, can lead to low oxygen levels and harm marine life.

geological sequestration Storing CO_2 underground in sediment or rock formations so it doesn't return to the atmosphere.

gigatonne A unit of mass equivalent to one billion tonnes.

hypoxia A condition where there is too little oxygen in the water, so the health of marine organisms is negatively affected and sensitive species may escape or die.

macroalgae Large algae in the ocean, like kelp or seaweed, that absorb CO_2 as they grow. Some approaches to CO_2 removal involve sinking macroalgae to deep waters to store carbon for a long time.

marine carbon dioxide removal A general term for all ocean-based methods that remove CO_2 from the atmosphere via increasing the capacity of seawater to absorb more CO_2.

monitoring, reporting and verification (MRV) The process of tracking how much CO_2 is removed and making sure it stays stored as planned. Specific MRV may also be required for tracking environmental and ecological side effects.

ocean acidification	The dissolution of CO_2 into seawater changes carbonate chemistry and makes the water more acidic (lower pH). Increasing ocean acidity beyond natural tolerances may harm marine life, especially shellfish and corals.
ocean alkalinity enhancement	A method that increases the ocean's ability to absorb CO_2 by adding minerals or using electrochemical processes to make seawater more alkaline.
ocean fertilization	The addition of limiting nutrients (often iron) to stimulate the growth of phytoplankton, which remove CO_2 from the water through photosynthesis. The sequestration of carbon occurs through subsequent sinking of organic matter into deep water.
photosynthesis	The process where organisms, including tiny ocean algae (phytoplankton) and seaweed, use sunlight to take in CO_2, grow and produce oxygen.
phytoplankton bloom	A rapid increase in tiny marine algae, often stimulated by an increase in the availability of nutrients. These blooms absorb CO_2 but can also lower subsurface oxygen levels if sinking organic matter decays too quickly.
remineralisation	When dead phytoplankton, macroalgae, animals and organic detritus decay, or break down, in the ocean they release dissolved inorganic carbon and nutrients back into the seawater. The deeper that this process happens within the ocean, the longer the carbon is likely to stay out of the atmosphere.
respiration	The process by which organisms use oxygen and organic matter to produce energy and CO_2. This process transforms organic carbon to inorganic carbon and leads to the accumulation of dissolved inorganic carbon in the ocean interior.
sequestration durability	How long the stored CO_2 stays out of the atmosphere. Some methods store carbon for only a few years or decades, while others may keep it locked away for thousands of years.
upwelling	A natural process where deep, nutrient-rich and CO_2-rich water rises to the surface, boosting marine life. Artificial upwelling tries to replicate this process to increase CO_2 absorption via stimulating biological productivity.

Endnotes

1. Regulation (EU) 2018/841 of the European Parliament and of the Council allows the EU Commission to delay this mandatory reporting by five years if member states have not yet gained experience with the use of the methodologies to estimate emissions from wetlands provided by the IPCC Wetlands Supplement (IPCC 2013).

2. International Maritime Organization, *Resolution LC-LP.1 (2008) on the Regulation of Ocean Fertilization*, adopted October 31, 2008, https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LC-LP.1%20%282008%29.pdf

3. International Maritime Organization, *Resolution LC-LP.2 (2010) on the Assessment Framework for Scientific Research Involving Ocean Fertilization*, adopted October 14, 2010, https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LC-LP.2%282010%29.pdf.

4. International Maritime Organization, *Resolution LP.4(8) (2013) on the Amendment to the London Protocol to Regulate the Placement of Matter for Ocean Fertilization and Other Marine Geoengineering Activities*, adopted October 18, 2013, https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LP.4%288%29.pdf.

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