GESAMP
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

A SCIENTIFIC SUMMARY FOR POLICY-MAKERS

THE STATE OF THE SCIENCE FOR MARINE CARBON DIOXIDE REMOVAL

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A SCIENTIFIC SUMMARY FOR POLICY-MAKERS

THE STATE OF THE SCIENCE FOR MARINE CARBON DIOXIDE REMOVAL

Key messages

- Due to the insufficient rate of emission reductions, there is increasing interest in exploring the potential for carbon dioxide removal in marine environments.
- Marine carbon dioxide removal (mCDR) approaches are still in the early stages of development; many knowledge gaps and uncertainties remain.
- Each mCDR approach comes with trade-offs in terms of durability, energy demand and environmental impact, and would require large ocean areas if considered for large-scale implementation.
- A key challenge is to enhance technical and regulatory monitoring, reporting and verification (MRV) capacities for marine interventions.
- Future implementation of any and all mCDR approaches will require site-specific assessments, robust regulatory frameworks and an approach that balances ocean protection and use.

1. Introduction

Since net zero greenhouse gas emissions targets have become a keystone of climate policy, there has been increasing debate about the need to complement urgently needed emission reductions with active removal of carbon dioxide from the atmosphere (termed 'carbon dioxide removal', CDR) (IPCC, 2022). Demand for CDR in the context of net zero targets is expected to be driven by so-called 'hard-to-abate' sectors, in which the cessation of emissions is considered biologically, technically economically and/or politically challenging (Mistry et al., 2024; Schenuit et al. 2023). As the ocean already plays a key role in regulating the global climate by absorbing about a quarter of current CO_2 emissions (Friedlingstein et al., 2023), ideas have begun to emerge about how this capacity could potentially be increased further via so-called marine CDR (mCDR) approaches (GESAMP, 2019; Vivian et al., 2024).

In 2019, the GESAMP Working Group 41 published its *High Level Review of a Wide Range of Proposed Marine Geoengineering*[1] *Techniques* that included diverse mCDR approaches (GESAMP, 2019). Since then, there has been increasing interest in enhancing the biological or chemical CDR potential of the ocean. Most recent investigations are focused on ocean alkalinity enhancement, sinking biomass into the deep ocean, direct ocean removal (previously 'direct ocean

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GESAMP is The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection – an inter-agency body of the United Nations established in 1969 (www.gesamp.org).

1 Geoengineering is a term that encompasses both carbon dioxide removal (CDR) and solar radiation management (SRM).

capture'), artificial upwelling and micro-algal ocean fertilization (see **Figure 1**). This growing interest is reflected in the rapidly expanding number of scientific papers on mCDR, the growing number of and investments in start-up companies, and the increase in public and private funding for mCDR research (Smith et al., 2024; CDR.fyi – https://www.cdr.fyi/). This activity has resulted in the current consideration of potential regulation of several new mCDR techniques by the London Protocol Parties (LC/LP, 2023). Publicly funded research often initiates the generation of knowledge for new approaches on voluntary carbon markets, and private investors also play a role in funding mCDR research, innovation and development (Smith et al., 2024; CDR.fyi – https://www.cdr.fyi/), in particular through advanced purchase of carbon credits (Boyd, Bach et al., 2023). This surge of interest in mCDR poses many technical, environmental, political, social, legal and regulatory challenges (Baatz et al. 2025). All mCDR techniques are still in the early stages of development, with much still to be learned about their effects on the ocean carbon cycle and the marine environment before any decisions can be made about large-scale implementation.

This document provides a concise summary of the state of mCDR science, with a focus on those methods that are currently being most actively researched.[2] These include mCDR options that aim to enhance the biological carbon pump: microalgal ocean fertilization, biomass (macroalgae and crop-waste) sinking, artificial upwelling and mCDR options that aim at increasing the chemical carbon sink: ocean alkalinity enhancement and direct ocean removal (also termed 'direct ocean capture' and 'direct water removal').

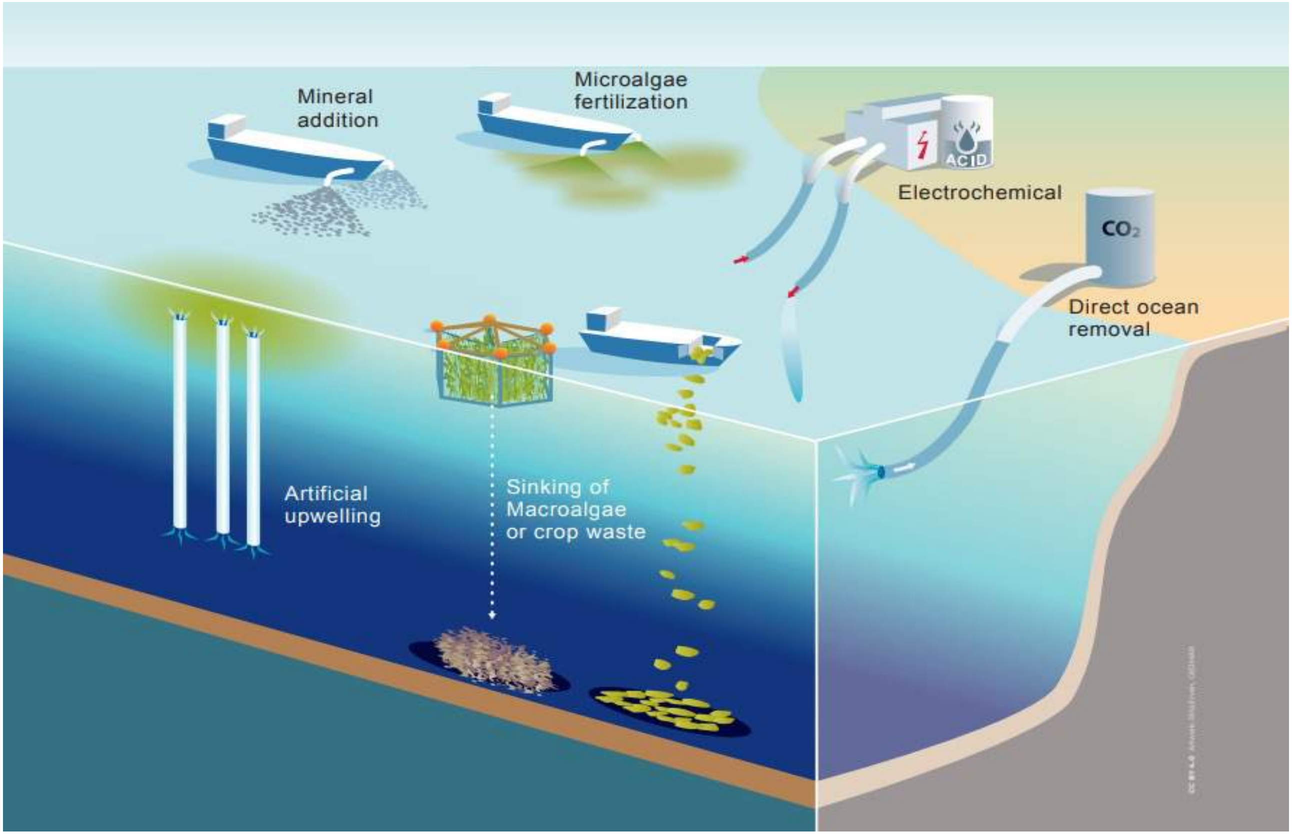

Figure 1. Overview of marine carbon dioxide removal methods covered in this report. Artwork: Rita Erven, GEOMAR // Licence: CC BY 4.0.

2 Some of the mCDR techniques covered in the GESAMP 2019 report do not appear to have been the subject of significant research since then and consequently the current state of the science for those techniques is still reflected in that report – as such, they are not addressed in this summary. We also do not address here restoration of coastal blue carbon habitats (salt marshes, seagrass beds and mangroves), as other organizations have covered this subject extensively, e.g. IPCC (2019) [SROCC], etc. We would address the deliberate enhancement of carbon sequestration in existing coastal blue carbon habitats, but there appears to be very little activity in this area.

2. Enhancing the biological carbon pump

Several proposed mCDR methods seek to enhance the ocean's biological carbon pump. This pump significantly influences the distribution of carbon, nutrients and oxygen in the ocean. However, although it annually removes around 10 billion tonnes (10Gt) of carbon (Siegel et al., 2021), this does not lead to net changes in ocean carbon storage in its unperturbed state, as the sinking of organic carbon, mainly as particles, is balanced by the upward movement of water that contains remineralized dissolved inorganic carbon (Frenger et al., 2024). The CDR methods detailed below aim to manipulate aspects of this pump to enhance carbon dioxide removal.

Figure 2 gives an outline of the mechanisms of biological carbon sink without anthropogenic enhancements. Carbon dioxide is taken up by the ocean through biological activity. Phytoplankton or microalgae convert dissolved inorganic carbon (i.e. the main form in which carbon dioxide is held in the ocean) into particulate organic carbon via photosynthesis in the sunlit surface waters. Particulate organic carbon then sinks out of the upper ocean or is moved to depth by ocean currents. Less than 1% of organic carbon from surface waters ends up in sediments on the ocean floor, where it is stored on geological timescales. The remainder is consumed by marine life and hence respired (termed remineralization) into dissolved inorganic carbon throughout the water column. Timescales on which this dissolved inorganic carbon will eventually return to the ocean surface depend on the location and depth of where the remineralization occurs, generally increasing with depth (DeVries et al., 2012; Siegel et al., 2021; Ricour et al., 2023).

Proposals for mCDR focus on either increasing the biological activity at the surface, e.g. micro-algal fertilization and artificial upwelling, or accelerating the sinking of particulate organic carbon while reducing its remineralization, e.g. macro-algal sinking. Such interventions will likely affect marine ecosystems (Boyd et al., 2022). In particular, they will change the local availability of nutrients and oxygen.

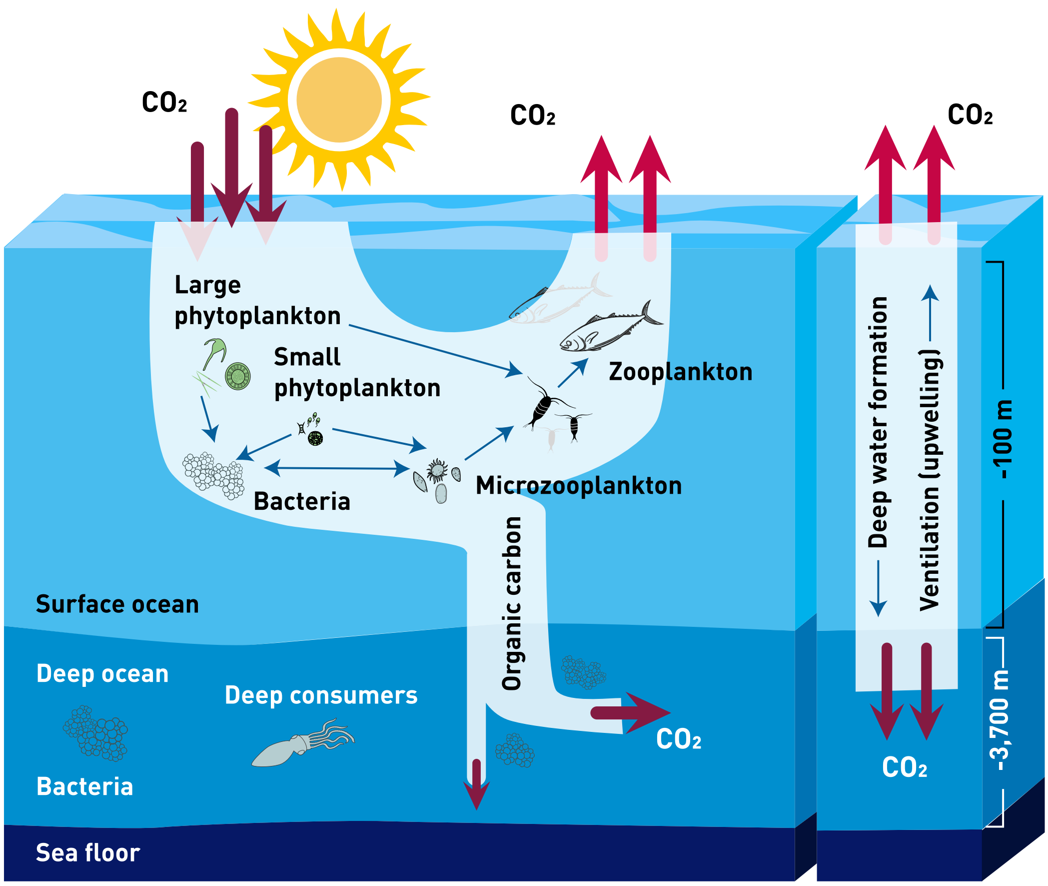

Figure 2. Illustration for the biological carbon pump (left) driven by biological activity and production at the ocean surface and the solubility pump (right) driven by chemical and physical processes. Source: GESAMP, 2019. Reprinted with permission from Nature © Chisholm, 2000.

2.1. Microalgal ocean fertilization

Approach

Ocean fertilization refers to the purposeful addition of the trace element (or micronutrient) iron, or one or more of the macronutrients nitrogen, phosphorus or silicate, to the surface waters of the ocean. This stimulates blooms in regions deficient in one or more of those nutrients, which in turn results in enhanced carbon sequestration via the biological pump and, potentially, carbon dioxide removal (GESAMP, 2019; NASEM, 2022; Jiang et al., 2024; Bach, Tamsitt et al., 2023).

Ocean iron fertilization (OIF) is the main technique considered here, as it is economically and logistically more attractive than macronutrient fertilization due to it being a trace element and thus has the potential to stimulate a disproportionately large removal of carbon dioxide (Oschlies et al., 2025). It has a long history of scientific field experiments of ~100 km^2 to 1,000 km^2 between 1993 to 2009 (de Baar et al., 2005; Boyd et al., 2007; NASEM, 2022; Wallace et al., 2010) that targeted ocean areas with high nitrate but low chlorophyll levels due to the lack of iron needed for photosynthesis. There are plans by the Exploring Ocean Iron Solutions Consortium (ExOIS) to carry out a field experiment larger than those previously conducted – in the low-iron waters of the North-East Pacific (https://oceaniron.org/our-plan/).

State of research

The NASEM (2022) report reviewed a wide range of issues, side-effects and uncertainties associated with ocean fertilization. It also suggested an extensive research agenda to resolve outstanding questions. Similarly, others have set out next steps for developing and assessing OIF for mCDR, including Buesseler et al. (2024) and Ocean Visions (2023).-

In recent years, several variants of OIF have been examined, including using iron-rich biogenic dust (Emerson, 2019), adding mineral dust to blooms to accelerate settling driven by particle scavenging (Sharma et al., 2024; Yuan and Liu, 2021), combining OIF with artificial upwelling (Jürchott et al., 2024) and a combined OIF and ocean alkalinity enhancement approach (Taqieddin et al., 2024). None of these techniques appear to have had any field testing.

While OIF increases primary productivity, the amount of carbon that is potentially sequestered in the deep ocean is variable. Uncertainties remain regarding the rate and scale of influx of CO_2 from the atmosphere – i.e. carbon dioxide removal – due to the long (months to > 1 year) equilibration times to balance the difference in CO_2 concentrations between the atmosphere and the ocean (Bach, Ho et al., 2023).

Potential environmental impacts

These include near-field effects of stimulating species of harmful algae, or production of other more potent greenhouse gases such as nitrous oxide and methane (GESAMP, 2019). There are potential far-field effects on photosynthesis driven by the depletion of nitrogen or phosphorus nutrients ('nutrient robbing'), which could also reduce the natural oceanic carbon uptake and thereby offset part of the CDR, effects on seafloor ecosystems from enhanced POC sinking flux and the acidification of deep ocean waters (NASEM, 2022; Oschlies et al., 2025; Tagliabue et al., 2023; Wallace et al., 2010).

Potential implementation zones/scales/ durations

The likely areas for OIF CDR field trials are the oceanic high-nitrate but low-chlorophyll areas, i.e. the Southern Ocean, Eastern Equatorial Pacific and the Subarctic North Pacific, where prior scientific experiments took place (NASEM, 2022). Bach, Tamsitt et al. (2023) identified the Antarctic shelves as the most efficient regions for mCDR with OIF in the Southern Ocean. However, the use of these shelves raised legal questions as they fall under three overlapping layers of international law, i.e. the 1991 Madrid Protocol to the Antarctic Treaty (covering the area south of 60° S), the London Convention/London Protocol, and the marine protected area under the Commission for the Conservation of Antarctic Marine Living Resources in the Ross Sea. However, even though OIF may locally enhance the growth of microalgae in such areas, it remains to be shown that there is a net CO_2 drawdown rather than a regional or spatial shift of algal growth that may ultimately be limited by the amount of macronutrients available in the system under consideration. Southern Ocean surface waters subduct into the ocean interior well before macronutrients are used up. Therefore, this region is, from a scientific view, the most promising one for a net drawdown of unutilized macronutrients and atmospheric CO_2 by OIF.

Oschlies et al. (2025) found that the durability of the mCDR after the implementation of ocean fertilization was difficult to estimate, which is considered one of the biggest limitations of the approach (NASEM, 2022). Among other things, the duration of mCDR from OIF depends on the depths to which it sinks. For example, less than 50% of the carbon is retained for more than 100 years in large parts of the ocean if carbon resides between 200–500 m depth, but the carbon is largely retained in most areas when it sinks below 1,000 m (Siegel et al., 2021).

2.2. Sinking of macroalgae and crop waste

Approach

Proposals to remove CO_2 via sinking biomass in the deep ocean often include growing macroalgae for this purpose but can also include gathering macroalgae floating in the ocean, e.g. *Sargassum* species, and sinking it. The carbon in the surface waters consumed by the macroalgae results in a decrease in partial pressure of CO_2 in the uppermost ocean layer, increasing the uptake of atmospheric CO_2 (Bach, Ho et al., 2023). The macroalgae to be used are likely to be fast-growing types like kelp, *Macrocystis, Laminaria* and *Saccharina* that grow predominantly in shallow coastal waters, often on rocky sea floors or on floating structures in coastal or open ocean waters (N'Yeurt et al., 2012). However, offshore areas are not suitable, as they are likely to be iron-limited for macroalgal growth (Paine et al., 2023). There are also proposals for sinking agricultural crop waste in the deep ocean (Metzger and Benford, 2001) – a sort of hybrid option, where the CO_2 is captured by terrestrial ecosystems, while the ocean serves as a carbon storage site.

CDR by biomass sinking may remove the carbon for longer periods compared to microalgal fertilization because of slower remineralization rates and hence longer turnover times of the deep ocean (DeVries et al., 2012; Siegel et al. 2021; Ricour et al., 2023). In addition, the carbon-to-nutrient ratios in macroalgae can be several times higher than in microalgae, i.e. they produce more organic carbon per nutrient unit, which may be beneficial for mCDR (Sheppard et al., 2023).

State of research/knowledge

The environmental consequences of adding large amounts of organic matter to marine sediments and its decomposition there is well understood in principle (Gray and Elliott, 2009; Bach et al., 2021; Paine et al., 2021; Hurd et al., 2022, 2024; Levin et al., 2023). An exception is crop waste, where deposition and degradation in the deep ocean has been little studied.

Current research includes determining the uncertainties, efficacy and scalability of the method (e.g. Xiong et al., 2024). While macroalgal farming may have mCDR potential (Chen et al., 2024), there are uncertainties regarding the energy demands (Thomas et al., 2024), its potential environmental impacts and challenges in monitoring and verifying CDR (Hurd et al., 2024; Chopin et al., 2024; Ricart et al., 2022).

Future research (NASEM, 2022; Ocean Visions, 2022) should include lab and field experimental observations (including mesocosms), and predictive work using numerical models based on empirical and deterministic information from those studies. There is also the need for environmental, economic and technological impact assessments, including better methods of accounting and determining life cycle costs (including transport on land and at sea, fuel use in culturing, harvesting and sinking) (Krause-Jensen et al., 2018; Ocean Visions, 2022) and the need for forensic carbon accounting (Hurd et al., 2022).

Potential environmental impacts

The introduction of large amounts of organic matter may produce adverse environmental effects. Large-scale macroalgae cultivation may perturb global oceanic nutrient cycles (Chopin et al., 2024; Levin et al., 2023). It could also reduce phytoplankton production by competition for nitrogen and phosphorus, with implications for additionality, and by reducing the penetration of sunlight into the ocean. Nutrient availability and iron requirements may hinder large-scale offshore farming (Paine et al., 2023). Some of the carbon removed by macroalgae will be offset by the growth of calcified organisms (Bach et al., 2021). Floating macroalgae can also increase the ocean albedo, leading to more reflectance of sunlight and less heat uptake of surface waters (Bach et al., 2021). There may also be adverse effects on the ozone layer, as macroalgae are known to release bromoform and other halomethanes (Carpenter et al., 2009; Leedham et al., 2013; Mehlmann et al., 2020). The magnitude of the emissions of these gases needs additional research, as their natural marine emissions are already estimated to be responsible for around 9% of stratospheric ozone loss (Tegtmeier et al., 2015) and they also contribute to global warming. The scale of this effect compared to the potential benefits of CDR needs to be researched.

Adverse effects of macroalgae cultivation and sinking can occur in each layer of the ocean (i.e. the upper, middle and lower parts of the water column) on the seabed and beneath the seabed. This includes the sinking of other organisms associated with the macroalgae and the potential smothering of the deep seabed. The fate of the biomass in any of these layers depends on the local physical and chemical conditions, especially the hydrodynamics. A large amount of organic matter in one small area will have adverse consequences, but spread over a large area it would have fewer adverse impacts per area.

Deposition in zones that are temporarily without oxygen, i.e. anoxia, would prolong that anoxia, while in oxygen-poor zones it may lead to anoxia. In oxygenated zones, even at low temperatures, remineralization of the organic carbon will occur. There, it leads to enhanced oxygen consumption and increased levels of nutrients, methane, hydrogen sulphide, nitrous oxide and CO_2 from the degradation of organic material. In general, decomposition of biomass in the deep ocean is slow because of the ambient conditions of low temperature and limited oxygen availability. It might create anoxic areas upon degradation, and modelling studies of large-scale deployment show the development of oxygen-depleted regions even in formerly oxygen-rich bottom waters (Wu et al., 2023). Although requiring more research, there are already studies showing that increased carbon levels in deep-ocean waters will eventually return to the surface ocean by upwelling or mixing (Siegel et al., 2021).

For crop waste, the degradation process might be even slower due to the apparent lack of a marine mechanism for the breakdown of lignocellulose material and the anaerobic conditions within the bales (Burdige, 2005; Keil et al., 2010; Strand and Benford, 2009). In 2009, researchers from the Monterey Bay Aquarium Research Institute (MBARI) sank a bale of corn stover to 3,200 m depth off the coast of California. Since then, they have visited the site every three years and have shown that, so far, the block of material has remained intact and inert (https://news.uci.edu/2022/08/03/addressing-climate-change-plants-instead-of-plants/).

Potential implementation zones/scales/durations

Proposed sources of the biomass include dedicated macroalgae cultivation inshore, gathering floating Sargassum seaweed, or using crop wastes. The logistics, costs and time effort of culturing macroalgae, the influence of bad weather on the equipment and the suitability of the equipment indicate that near-shore culturing will be favoured over offshore farming (Ocean Visions, 2022; NASEM, 2022). However, the operational scale and effectiveness of the technique has been challenged in empirical and theoretical studies, as to whether a sufficiently large-scale implementation could be achieved (Hurd et al. 2022, 2024; Troell et al., 2023).

Suitable areas for implementation are offshore areas where the biomass can be sunk to below 1,000–1,500 m depth, or areas of rapid sedimentation such as major river deltas that receive substantial sediment loads. There, the introduced organic matter would be rapidly buried and securely stored (Strand and Benford, 2009). Similarly, anoxic marine basins, e.g. the Black Sea or deep fjords, have been proposed as locations to sink biomass (Raven et al., 2024; Rewind https://www.rewind.earth/; Zimmerman and Cornelissen, 2018). Some of the deposited macroalgae and crop wastes would be incorporated into the deep sea sediments, but the remainder would ultimately be remineralized. The return times of deep ocean bottom waters to the surface may be 1,000–1,500 years, depending on the location (DeVries and Primeau, 2011; Siegel et al., 2021; Ricour et al., 2023).

2.3. Artificial upwelling

Approach

Artificial upwelling (AU) refers to the process of bringing nutrient-rich waters from below the ocean's thermocline to the surface, with the goal of stimulating biological activity, such as phytoplankton growth, to sequester atmospheric CO_2. First proposed in a short memo by Lovelock and Rapley (2007), it was initially seen as a potential method to enhance the biological carbon pump, but since deeper waters are generally colder than surface waters, artificial upwelling could also cool the ocean surface and overlying atmosphere. More recently, AU has been proposed in the context of macroalgal farming, in order to provide additional nutrients (e.g. Wu et al., 2023).

State of knowledge

Modelling studies responding to the original idea of Lovelock and Rapley (2007) showed that the net impact on CO_2 drawdown is limited, as with the upwelled nutrients, respired CO_2 is also upwelled (Yool et al., 2009; Oschlies, Pahlow et al., 2010). A more detailed analysis by Jürchott et al. (2023) suggested that the success of AU in enhancing oceanic carbon uptake depends heavily on the background climate and the emission scenario. Lower emission scenarios cause AU to be less efficient for carbon sequestration, whereas the faster atmospheric CO_2 increase in high emission scenarios leads to higher air-sea CO_2 fluxes. Technological innovation in open ocean engineering for any implementation and maintenance of upwelling pumps would be necessary before such options can be considered.

Potential environmental impacts

The environmental effect of AU options is highly uncertain and has so far mostly been assessed within modelling studies. Ocean fertilization from AU options, introducing nutrient-rich deep water to the surface, may increase primary production and shift plankton community structure (Baumann et al., 2021; Ortiz et al., 2022). An increase of primary production results in an increase of carbon export and remineralization that could reduce oxygen concentration in deeper waters and increase GHG release (e.g. methane and nitrous oxide; Williamson et al., 2012). Besides direct impacts on marine biota via the mechanical effects of pumping large volumes of water through industrial-scale structures and the mixing of different ecosystems previously residing at different depth levels, AU raises concerns about its impacts on ocean stratification, salinity and temperature. Through the redistribution of these properties, AU has the potential to disrupt ocean circulation and might even contribute to global warming (Oschlies, Pahlow et al., 2010), which in turn would disrupt atmospheric dynamics and the hydrological cycle (Kwiatkowski et al., 2015).

Potential implementation zones/scales/ durations

Potential implementation sites for AU are regions with nutrient-poor surface waters in low- to mid-latitude oceans, particularly in coastal zones or upwelling zones. A first estimate for area demand for an implementation at scale is sizable (Yao et al., 2025). The technical challenges of pumping water up from several tens to a few hundred metres depth are substantial, and the few practical field trials so far did not last longer than a few days in the energetic marine environment (e.g. White et al., 2010). New engineering efforts aim at improving efficiency and robustness of artificial upwelling devices, and test implementations continue, particularly in the context of aquafarming or ocean thermal energy conversion (OTEC) plants in coastal environments.

As long as AU is continuously applied, the duration time of additionally stored CO_2 in the ocean is expected to range from decades to millennia (Siegel et al., 2021); however, this does not consider the disruption of ocean dynamics and stratification which might act to substantially reduce CO_2 storage duration. It is, however, worth noting that AU, once implemented, would need to work continuously to further increase and keep the additionally added CO_2 stored in the ocean (Keller et al., 2014; Oschlies, Pahlow et al., 2010). If AU were abruptly discontinued, the surface ocean would immediately respond with a release of CO_2, while at the same time additionally stored heat in the ocean interior would radiate back to the atmosphere, and within years to decades, atmospheric temperatures would rise even above the reference simulation (Oschlies, Pahlow et al., 2010).

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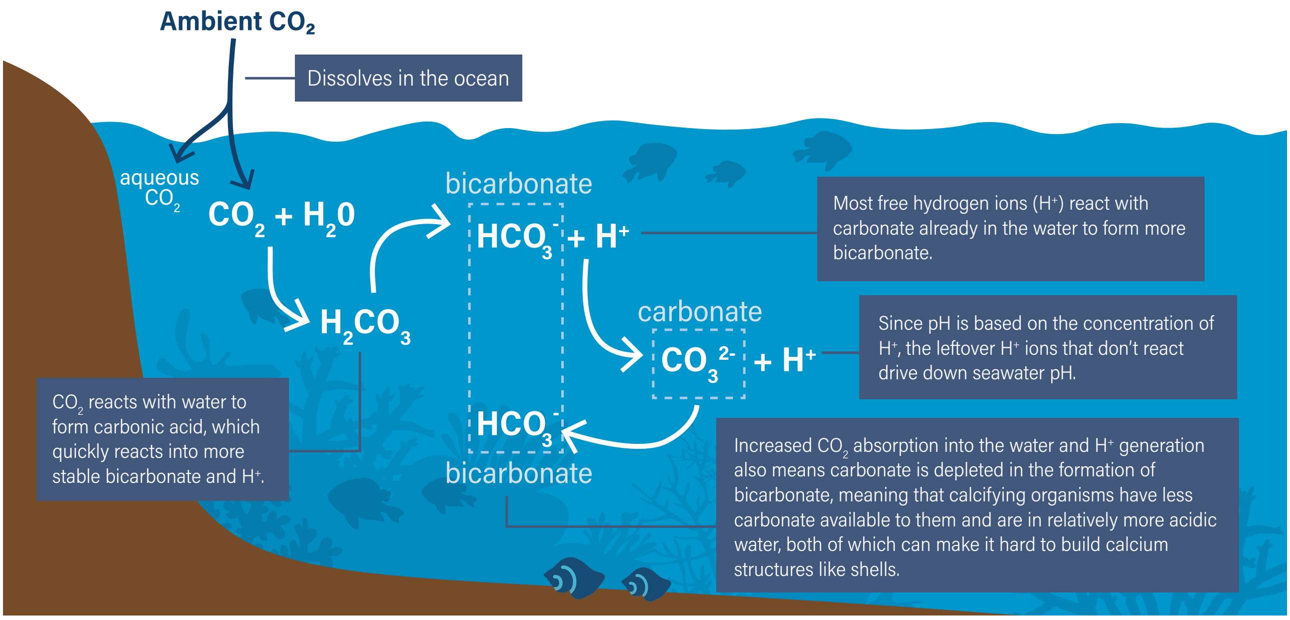
3. Enhancing the chemical carbon sink

Chemical marine CDR methods aim to increase the exchange of CO_2 between the atmosphere and the surface ocean by altering the chemistry and thereby reducing the partial pressure of CO_2 of the surface waters that are in contact with the atmosphere. This can be achieved by enhancing the surface ocean's alkalinity and thereby shifting the dissolved inorganic carbon from dissolved CO_2 towards bicarbonate and carbonate ions, or reducing the concentration of dissolved inorganic carbon in the surface waters via CO_2 extraction from the sea water, also called direct ocean removal (for more information, see **Figure 3**).



Note: CO_2 = carbon dioxide; H_2O= water; H_2CO_2 = carbonic acid; pH = potential of hydrogen; HCO_3^-= bicarbonate ion; CO_{32-} = carbonate ion; H^+ = hydrogen ion.

Figure 3. Detailed illustration of the solubility pump displaying the reactions of CO_2 when it dissolves in the surface ocean. *Source*: Lebling et al., 2022.

3.1. Ocean alkalinity enhancement (OAE)

Approach

Chemical weathering is the main control mechanism of atmospheric CO_2 and is expected to remove most of the anthropogenic CO_2 from the atmosphere on timescales in the order of 100,000 years (Archer and Brovkin, 2008). Ocean alkalinity enhancement (OAE) aims to accelerate the alkalinity production that occurs by chemical weathering of silicate or carbonate rocks. Alkalinity in this context is a metric that determines seawater's capacity to durably store CO_2 without creating acidification. The idea behind OAE is to enhance the transformation of dissolved CO_2 into bicarbonate and carbonate ions and thereby reduce the partial pressure of CO_2 in the uppermost layer of the ocean. If successful, this will result in an enhanced uptake of CO_2 by the ocean. OAE can be achieved by dissolving alkaline materials (e.g. ocean liming, or adding alkaline rock powders) or via electrochemical methods, including electrodialysis.

State of knowledge

Modelling studies have confirmed the large theoretical potential of OAE in highly idealized implementation scenarios (Keller et al., 2014; Jeltsch-Thömmes et al., 2024). Lab and mesocosm studies have begun to investigate the removal potential and the ecological impacts of using different alkaline materials and different implementation approaches. The main risk of loss of alkalinity, and accordingly the potential to sequester carbon, is spontaneous precipitation of carbonates if too much alkalinity is added too fast (Fuhr et al., 2022; Moras et al., 2022; Hartmann et al., 2023) and the reduced dissolution of already existing carbonates that lowers the natural effect of the disintegration of e.g. shells on a beach relative to a baseline without OAE (Bach, 2024).

On time and space scales that can be studied by lab and mesocosm experiments (weeks and cubic metres), ecological shifts appear largest for alkaline materials that contain 'contaminants' such as nutrients or potentially toxic substances, but these shifts may be 'tolerable', particularly when addition rates are low, and when the alkaline material is based on carbonates rather than on silicates that contain silica and iron that can act as fertilizers, as well as potentially toxic trace elements (e.g. Oschlies et al., 2025). Field trials will be required for a comprehensive assessment specifically of environmental effects. Ecological impacts of OAE are often expected to oppose those of ocean acidification, and the knowledge gained over decades of ocean acidification research may offer some guidance for addressing questions about possible side effects of OAE.

Potential environmental impacts

The possible impacts of OAE on the wider marine ecosystem on short- to long-term scales require more research (Albright et al., 2016; Bach et al., 2019; Cripps et al., 2013; Ferderer et al., 2022; Gately et al., 2023; NASEM, 2022). The introduction of alkaline substances into seawater could allow for additional CO_2 uptake while stabilizing the pH, although this does not reverse previous acidification (Hinrichs et al., 2023; Hutchins et al., 2023). The addition of alkalinity is reported to have a positive effect on ecosystems that are sensitive to ocean acidification (Albright et al., 2016; Weatherley, 1988); however, it is also shown that less dissolved CO_2 may reduce growth rates of calcifying organisms (Langer et al., 2006). At the point of alkalinity injection, OAE might cause localized temporary pH and alkalinity spikes, which might be ecotoxic and detrimental for the affected ecosystems (Locke et al., 2009). On a longer timescale, such an intervention could impact the physiology of marine organisms and the ecosystem structure (Roberts et al., 2010). If OAE options introduced silicate minerals or their solution into the ecosystem, this would likely have a fertilization effect (Hauck et al., 2016; Köhler et al., 2013). OAE with materials containing nutritive elements could therefore, similar to fertilization experiments, increase the primary productivity on site, but decrease oxygen level and increase acidification in the water column downstream (Oschlies, Koeve et al., 2010). Depending on the geochemical composition of the used minerals, potentially toxic heavy metals could also get into the water through mineral dissolution or electrolysis and desalination processes (Arribére et al., 2003; Lattemann and Höpner, 2008), which needs to be regulated. Furthermore, indirect effects from OAE options due to mining activities would likely negatively impact soil, air and water quality on land, and introduce noise pollution to the environment on and off site (Sengupta, 2021). Also, there are concerns about health risks associated with finely crushed (1–10 µm) material containing fibrous serpentine minerals like asbestos, as well as potential problems with windborne transport of fine-ground olivine (Hangx and Spiers, 2009). A comprehensive assessment will also need to consider the full life cycle that includes the sourcing of alkaline materials or the fate of reaction products in the case of electrochemical approaches – these impacts would often occur on land rather than in the ocean.

Potential implementation

Initial modelling studies assumed implementation of dissolved or very finely grained alkaline minerals from a large fleet of ships over the entire ocean surface. Economic analysis indicates that this may only be competitive compared to other costly CDR methods such as direct air capture (Kowalczyk et al., 2024). Governance and accounting aspects for open-ocean implementations are currently unclear, and may be easier to resolve for coastal implementation within exclusive economic zones (EEZs). Coastal regions offer further implementation approaches such as mineral deposition on beaches or on sediments in shallow regions, as well as the addition of dissolved alkalinity via pipelines or rivers. The durability of OAE-induced carbon storage is considered high (i.e. centuries to millennia), but the monitoring and verification of such storage would be difficult. However, there have been some recent promising developments in sensor technology (Alkalinity Sensor Specs – Aquatic Labs and Subtidal). The theoretical CDR capacity of OAE is large, but the bottleneck is how to accelerate alkalinity input and storage of additional carbon in the ocean in a safe, verifiable and efficient way (Renforth and Hendersen, 2017).

3.2. Direct ocean removal

Direct ocean removal (DOR) is a method designed to extract CO_2 from seawater in a usually shore-based facility, using either chemical acidification or electrochemical processes powered ideally by renewable energy. Electrochemical DOR typically uses electrochemical processes, where acidification of seawater converts bicarbonates into CO_2, which is then extracted.

In some cases, solar energy is utilized instead of electrochemical methods, using photoacids to trigger CO_2 extraction (Saha et al., 2024). The extracted CO_2 is either stored in underground geological reservoirs or utilized in durable products. After extraction, the CO_2-depleted seawater is returned to the surface ocean, where through the air-sea gas exchange CO_2 is absorbed from the atmosphere (Bach et al. 2021). While DOR's CO_2 storage at the facility is highly quantifiable, the actual carbon removal drawing down atmospheric CO_2 levels is similar in complexity as for open ocean OAE, OIF, macroalgae farming or any other mCDR method implemented in the open ocean space (Mengis et al. 2023). If, due to ocean mixing and circulation, the interaction between the CO_2-depleted water and the atmosphere is limited, DOR will not reach its full potential, since the water will not have fully been equilibrated with the atmosphere. If the CO_2 extracted is used for short-lived products, such as synthetic fuels, the net result could increase atmospheric CO_2, reducing the ocean's carbon storage capacity. Ensuring that the process does not reduce the ocean's natural CO_2 storage capacity is crucial.

In terms of environmental effects, DOR reduces the CO_2 content in seawater, potentially reversing ocean acidification, but impacts could arise from pumping large volumes of water and fluctuations in acidity. Facilities on the coast may also have effects on terrestrial ecosystems due to their footprint and energy needs. With an extraction potential of a few grams of CO_2 per cubic metre of seawater, huge volumes of seawater need to be processed for climatically relevant CDR, and all organisms in that water need to be safely removed before entering the facilities. This will likely pose substantial technical and energetical constraints, and safe operating conditions will be required to minimize the impacts on marine ecosystems (Oschlies et al., 2025).

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4. The state of monitoring, reporting and verification

To ensure the effectiveness, transparency and reproducibility of mCDR, a globally standardized, accurate and reliable monitoring, reporting and verification (MRV) framework would be needed (Boyd, Claustre et al., 2023). Such a framework would provide standards for monitoring, measuring or quantifying the amount of greenhouse gas (GHG) removed by a mCDR activity, and comprehensively reporting on those removals results to enable verification by an independent third party (Ho et al., 2023; EMB, forthcoming). The monitoring should provide estimates of the net removal or drawdown of CO_2 and other GHGs from the atmosphere, including associated uncertainties, and assess the durability of these removals. The concept of net removal is linked to additionality (from the Kyoto protocol – see Boyd and Bressac, 2016), which determines the amount of CO_2 removed relative to a hypothetical baseline without perturbation – one that may itself be influenced by mCDR activities, such as their effects on ecosystems (Bach, 2024). Therefore, monitoring needs to integrate both observational and modelling approaches to account for the broad spatial and temporal scales over which removal occurs. In addition, MRV methodologies should assess the environmental and ecological impacts of mCDR activities, a component referred to as environmental MRV or eMRV (Eisaman et al., 2023). However, the implementation of MRV for mCDR poses significant challenges due to the dynamic and heterogeneous nature of the ocean (Mengis et al. 2023).

The current MRV landscape remains fragmented, with different and overlapping protocols applied to different mCDR approaches at different stages of development in different jurisdictions. This fragmentation makes meaningful comparisons between approaches difficult (Boyd, Bach et al., 2023; EMB, forthcoming). It also complicates the consistent reporting of carbon fluxes in marine environments that would be needed to verify removals via mCDR (Mengis et al. 2023; Berger et al., 2024). A key prerequisite for the robust and credible integration of mCDR into reporting and accounting mechanisms is the development of reliable, internationally standardized MRV protocols which include baseline assessment and additionality criteria (Boettcher et al., forthcoming).

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5. The state of governance

The governance of mCDR is highly fragmented across international and national fora, and additionally spans a range of bottom-up, science-led self-governance initiatives, with varying degrees of participation from governments and stakeholders. This governance requires vertical integration from local to global instruments and initiatives, and horizontal integration to mitigate ocean-use conflicts across the marine sectors (marine protection, offshore wind, shipping, navigation, fishing, aquaculture, etc.) potentially affected by mCDR activities. At the international level, the London Convention and the London Protocol (LC/LP) provide the only explicit governance of mCDR carried out at sea by ships, aircraft etc. (LC/LP, 2008; 2010). Discharges of material for mCDR done through pipes from land are outside the remit of the LC/LP. In 2013, the Parties passed resolution LP.4(8) (LC/LP, 2013) that amends the LP and prohibits all "marine geoengineering" activities, with the exception of those listed in Annex 4 and deemed "legitimate scientific research" according to an assessment framework put forward in Annex 5. However, these provisions are not yet in force and, although the Parties are currently considering adding several other mCDR approaches to Annex 4, it is expected to take some time before these amendments are ratified (LP/LC, 2023). A broader set of implicit and indirect governance mechanisms exist at the international level, but whether and how they may be applied to mCDR activities remains to be clarified.

Ongoing international developments may further shape mCDR governance, including new interpretations of State obligations to protect the marine environment from the impacts of climate change under the United Nations Convention on the Law of the Sea (UNCLOS) as a result of the ITLOS Advisory Opinion 31 (ITLOS, 2024; Lancaster, 2024; Boettcher and Kim, forthcoming) and the entry into force of the new United Nations Agreement on Biodiversity Beyond National Jurisdiction (BBNJ Agreement) (Boettcher and Brent, 2024). Further, obligations in the ocean will need to be read in light of the increasing links between international human rights law and rights of the marine environment (Bennett et al., 2024; Bennett et. al., 2023; UN Human Rights Council, 2024).

At the national level, regulatory approaches to mCDR vary significantly, as can be seen in the contrasting cases of the United States and Germany. While the United States established The Marine Carbon Dioxide Removal Fast Track Action Committee (MCDR-FTAC) in 2023 to "facilitate and accelerate relevant policy and research on marine carbon dioxide removal (CDR) and storage" in the US (National Science and Technology Council, 2023), Germany codified a very restrictive interpretation of the LP amendment on geoengineering into its national anti-dumping law in 2018, prohibiting almost all mCDR research in German waters, and by German flagged ships in international waters and other states' EEZs (HSEG, 2018). This internationally inconsistent regulatory landscape may – and in some cases already has – led to mCDR activities being carried out in jurisdictions with less strict regulations and oversight.

The lack of clear regulatory guidance on mCDR has led to a recent wave of bottom-up attempts at scientific and sectoral self-regulation in the forms of voluntary best practice guides and codes of conduct. These build on earlier, more general ethical principles for 'geoengineering' research (e.g. The Oxford Principles; the AGU Ethical Principles for Climate Intervention Research, the Aspen Code of Conduct for mCDR; the Best Practices Guide for OAE; Hubert, 2020).

Despite ongoing discussions, many gaps remain. A core challenge relates to creating shared regulatory standards for monitoring, reporting and verification (MRV), including attributing removals to specific mCDR activities and the establishment of baselines. The evolving Article 6.4 mechanism under the UN Framework Convention on Climate Change Paris Agreement may create pathways for countries with limited or no marine territory to finance mCDR projects in other nations' EEZs in exchange for carbon credits. However, such arrangements risk exacerbating climate injustice, increasing the potential for 'ocean grabbing', necessitating the corresponding development of governance mechanisms.

Governance for responsible mCDR research and potential implementation must ensure a balance between the protection and use paradigms in ocean governance (Boettcher et al., 2021, 2023). Key priorities include the development of standardized environmental impact assessments (EIAs), MRV protocols and internationally agreed upon additionality criteria. Transparency, open science, capacity-building and data-sharing must be prioritized to enhance legitimacy and inclusivity of mCDR research. Addressing distributive and procedural justice will be critical to ensuring that mCDR contributes equitably to climate mitigation without reinforcing historical inequities in ocean governance.


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6. Comparison of methods

mCDR methods are generally thought to have longer-scale carbon storage abilities than land-based CDR approaches (IPCC, 2022), which seemingly makes them attractive options to consider. Yet, durability of carbon storage varies significantly across mCDR approaches. The most long-lasting methods are those that store carbon for centuries to millennia through enhanced chemical carbon uptake. In contrast, approaches like ocean fertilization (OF) and artificial upwelling (AU) rely on the biological carbon pump, where organic material must sink below 1,000 m to avoid the remineralization of the organic carbon in shallower waters. Once sunk below 1,000 m, the organic carbon is expected to achieve mCDR timescales of centuries to millennia.

The current state of knowledge of the proposed approaches ranges from low to medium at best, where the more novel proposals like electrochemical OAE and DOR have the lowest state of knowledge (**Figure 4**). A similar picture can be found for the technological readiness for an implementation at scale for these mCDR methods (Boyd, Bach et al., 2023). Low maturity levels, as well as high energy demands with a strong preference for renewable sources to decarbonize the process change, can certainly be considered bottlenecks for some of the proposed chemical mCDR methods. For rock-based OAE methods, crop waste sinking options or artificial upwelling, where large amounts of material or equipment have to be produced and transported, the implementation infrastructure and access to considerable areas pose considerable challenges for scale-up of these approaches (Yao et al., 2025).

Large-scale implementation of mCDR methods would raise concerns about competition for ocean space. Coastal and offshore space may become contested among industries such as fisheries, shipping, marine conservation and tourism, particularly for methods like DOR, OAE and macroalgae cultivation, which require extensive infrastructure. Large-scale implementation could disrupt existing marine economies and livelihoods, necessitating careful planning and regulatory oversight.

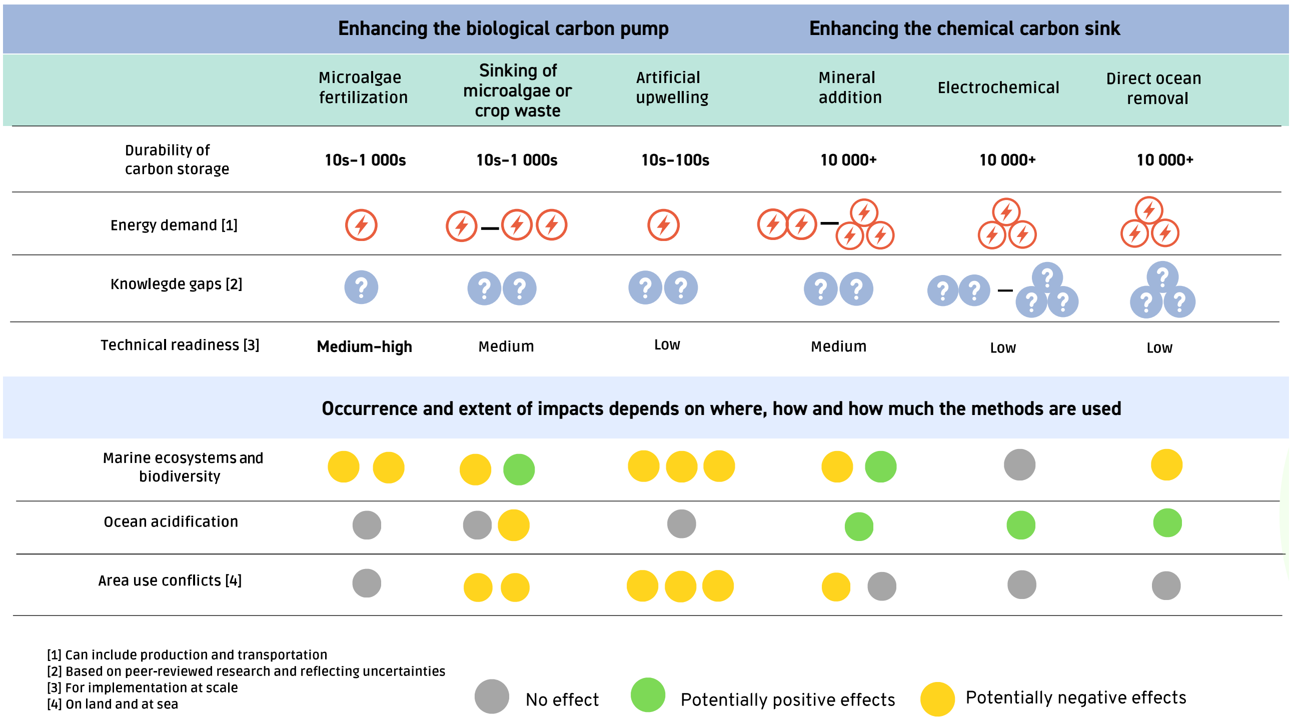

Figure 4. Table summarizing key metrics for the mCDR methods that were subject of recent peer-reviewed literature (incl. Oschlies et al., 2025; Yao et al., 2025) and expert assessments. For more details and explanations, please see the respective sections of the report. *Source*: Own compilation.

Governance complexity is particularly pronounced for those approaches which operate in the open ocean and therefore require international coordination and compliance with marine treaties. In contrast, coastal approaches may be more manageable within EEZs, where national governments can regulate their deployment. However, these approaches also introduce potential trade-offs, including social and environmental concerns related to mining, facility construction and the alteration of marine ecosystems. Public opposition could arise in response to the environmental footprint of large-scale interventions, highlighting the need for transparent stakeholder engagement and rigorous environmental assessments and eMRV.

Finally, mCDR approaches aim to alter biological, chemical or geological processes with the goal of increasing carbon uptake, yet alongside this desired effect are likely to come a variety of unintended environmental effects. The occurrence and impacts are dependent on where and how the methods are implemented, and the extent of the possible environmental effects at a specific scale at a specific site is difficult to quantify without dedicated studies (e.g. model studies with site-specific boundary conditions) and will have to be subject to further investigation.

Some methods, such as ocean fertilization, artificial upwelling and macroalgae sinking, have the potential to trigger widespread ecosystem changes. These interventions can alter oxygen levels, nutrient cycling and marine biodiversity, with risks that include harmful algal blooms, deep-ocean anoxia and secondary greenhouse gas emissions such as methane or nitrous oxide. Other methods, like OAE and DOR, have more localized but still significant environmental effects. While these approaches may mitigate ocean acidification in targeted areas, they also risk disrupting marine chemistry. OAE, for example, could introduce heavy metals if alkaline materials are not properly sourced, while DOR could cause localized fluctuations in pH and salinity due to large-scale water extraction and processing. Additionally, both approaches may have land-based environmental consequences, as the sourcing, mining and transportation of alkaline materials for OAE or the infrastructure needed for DOR could contribute to soil degradation, water pollution and increased energy demand. It is noteworthy that in contrast to land-based CDR options, the environmental impacts of mCDR options are even less constrained by the implementation site due to the continuous ocean medium, and could cause changes downstream as the water masses move (e.g. Berger et al., 2023; Wu et al., 2023), creating challenges for the long-term monitoring and verification of carbon storage (Mengis et al., 2023).

7. Conclusions

- mCDR approaches should only be considered in conjunction with far-reaching emissions reductions. No single mCDR approach offers a comprehensive solution, as each comes with trade-offs in terms of durability, energy demand, environmental impact and area use competition.

- While some approaches may have the potential to provide durable carbon removal, they require high energy inputs, large ocean areas and significant infrastructure, may be difficult to verify, and could potentially conflict with other ocean uses. Others leverage biological processes and introduce ecological uncertainties.

- Future implementation of any and all approaches will require site-specific assessments, robust regulatory frameworks and a balanced approach that integrates multiple strategies for effective and responsible climate mitigation.

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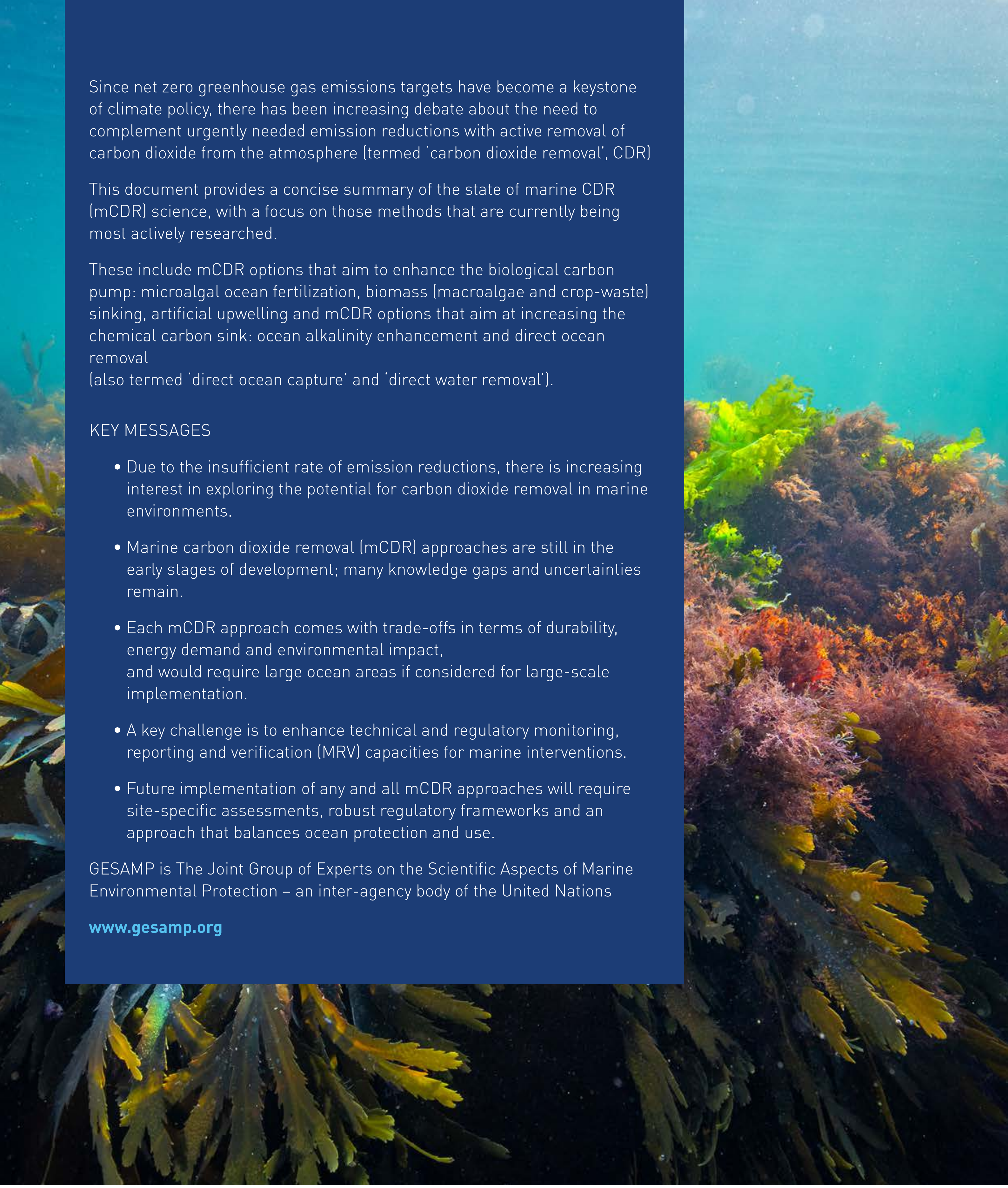
List of abbreviations

AU	Artificial upwelling
BBNJ	Biodiversity beyond national jurisdiction
CDR	Carbon dioxide removal
DOR	Direct ocean removal
EEZ	Exclusive economic zones
EIA	Environmental impact assessments
eMRV	Environmental monitoring, reporting and verification
ExOIS	Exploring ocean iron solutions consortium
GHG	Greenhouse gas
LC	London Convention
LP	London Protocol
MBARI	Monterey Bay Aquarium Research Institute
mCDR	Marine carbon dioxide removal
MCDR-FTAC	Marine Carbon Dioxide Removal Fast Track Action Committee
MRV	Monitoring, reporting and verification
OAE	Ocean alkalinity enhancement
OF	Ocean fertilization
OIF	Ocean iron fertilization
UNCLOS	United Nations Convention on the Law of the Sea
OTEC	Ocean thermal energy conversion



Since net zero greenhouse gas emissions targets have become a keystone of climate policy, there has been increasing debate about the need to complement urgently needed emission reductions with active removal of carbon dioxide from the atmosphere (termed 'carbon dioxide removal', CDR)

This document provides a concise summary of the state of marine CDR (mCDR) science, with a focus on those methods that are currently being most actively researched.

These include mCDR options that aim to enhance the biological carbon pump: microalgal ocean fertilization, biomass (macroalgae and crop-waste) sinking, artificial upwelling and mCDR options that aim at increasing the chemical carbon sink: ocean alkalinity enhancement and direct ocean removal
(also termed 'direct ocean capture' and 'direct water removal').

KEY MESSAGES

- Due to the insufficient rate of emission reductions, there is increasing interest in exploring the potential for carbon dioxide removal in marine environments.
- Marine carbon dioxide removal (mCDR) approaches are still in the early stages of development; many knowledge gaps and uncertainties remain.
- Each mCDR approach comes with trade-offs in terms of durability, energy demand and environmental impact,
and would require large ocean areas if considered for large-scale implementation.
- A key challenge is to enhance technical and regulatory monitoring, reporting and verification (MRV) capacities for marine interventions.
- Future implementation of any and all mCDR approaches will require site-specific assessments, robust regulatory frameworks and an approach that balances ocean protection and use.

GESAMP is The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection – an inter-agency body of the United Nations

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unesco Intergovernmental Oceanographic Commission
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1950-2025 SCIENCE for ACTION