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The Wild Wild West in our Oceans?

The role of start- ups in marine CDR

This paper investigates the role of start-ups in marine carbon dioxide removal (mCDR). Based on a review of literature and information available on the internet, it summarizes the development of mCDR start-ups with regards to their numbers, their locations and the economic settings including their funding. It also shows which mCDR techniques are predominantly researched or even already deployed. The paper further identifies the challenges due to the rapid development of mCDR start-ups, including risks for the marine environment, the need for reliable monitoring, reporting and verification (MRV) mechanisms as well as ethical concerns. Finally, observations regarding the legal framework mainly on international level are outlined. The conclusions evaluate the significance of mCDR start-ups in combating anthropogenic climate change and highlight the urgency of responsible national and international governance of mCDR.

1 Introduction

The following introduction informs about three framing perspectives: Firstly, the possible need for negative emission techniques due to the accelerated climate change, secondly the categories of mCDR techniques and thirdly the development of the voluntary carbon market as the economic basis for mCDR start-ups.

1.1 The accelerated climate change and the need for CDR techniques

The highest worldwide anthropogenic carbon dioxide (CO_2) emissions have been recorded in 2024 (Friedlingstein et al., 2024).

In order to reach the goal of the Paris Agreement, which states that global warming should be limited to 1.5 degrees or at least well below 2 degrees, countries would need to reduce their greenhouse gas emissions to net zero in the second half of the century (UNFCCC, 2016; Höhne et al., 2021; van Soest et al., 2021). However, the emissions of some industrial sectors, such as agricultural and cement industry, cannot be completely avoided (residual emissions) according to today’s knowledge (Rogelj et al., 2017; United Nations Environment Programme, 2022). Assuming that all emissions are reduced as ambitiously as possible, the residual emissions are estimated to remain in a range of roughly 4.8 to a maximum of 10 Gigatons annually at net zero/2025 (Smith et al., 2023; IPCC, 2023). In 2024, the annually global mean temperature has already reached +1.55°C above the preindustrial level (UBA, 2025).

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As global efforts to reduce emissions remain inadequate, many companies and governments turn their attention towards negative emission technologies that aim to actively remove and permanently sequester CO_2 from the atmosphere. These new methods are summarised under the term Carbon Dioxide Removal (CDR). There are different types of CDR, distinguishing between terrestrial and marine as well as differentiating between technical and nature-based solutions (see The State of CDR, 2023).

The ocean has already taken up roughly 25% of the total anthropogenic CO_2 emissions since the 1950s and each decade the oceanic CO_2 uptake is increasing so far by 610 million tonnes of carbon per year (Friedlingstein et al., 2021; DeVries et al., 2023). The ocean also holds approximately 20 times as much carbon as terrestrial plants and soils store globally (Carlson et al., 2001). Thus, in the last few years, a stronger focus has moved towards marine CDR techniques.

1.2 Marine Carbon Dioxide removal - Which techniques are discussed?

Marine carbon dioxide removal (hereafter mCDR) includes a variety of different biological and chemical methods. Biological methods encompass blue carbon management (BC), ocean fertilization (OF), artificial upwelling (AU), seaweed/ macroalgae cultivation and biomass sinking. The chemical options are ocean alkalinity enhancement (OAE) either through adding alkaline substances such as silicate and lime to the ocean's surface water (also termed enhanced weathering) or via electrochemical methods. OAE is also intended to provide a remedy against the advancing acidification of the oceans.

While Carbon Capture and Storage (CCS) involves the removal of atmospheric CO_2 and the subsequent injection and storage in sub-seabed geological formations in the ocean is not classified as an mCDR method per se and is therefore not further addressed here in detail. However, the transport of carbon dioxide, its injection and the potential of gas leakage from those injection site, can also have negative impacts on the marine environment (see also UBA, 2023).

The term "blue carbon management" refers to elevated carbon removal rates due to the expansion or restoration of ecosystems, including mangroves, saltmarshes, kelp forests and seagrass meadows. It belongs to the scientifically more established methods with well-known and manageable impacts and is often regarded as a no-regret method that has many additional benefits beyond carbon sequestrations (Macreadi et al., 2021; Oschlies et al., 2025). The restoration and reforestation of blue carbon habitats has co-benefits for marine biodiversity or coastal protection with very low risks of negative consequences (Luisetti et al., 2020; Laffoley, 2020; Macreadi et al., 2022). In contrast, technical mCDR approaches are estimated to have a high potential for climate mitigation, while also having a risk of not being able to meet their predicted carbon sequestration capacities as well as having a high likelihood of bringing unforeseen and potentially negative consequences for marine ecosystems with their application (Johnson et al., 2024).

The addition of iron or nutrients, such as nitrogen, phosphorus or silicate to the surface waters of the ocean is termed ocean fertilization (OF). The nutrients are added with the intention to stimulate the growth of phytoplankton. Carbon is fixed through photosynthesis by phytoplankton and is supposed to be buried when dead plankton biomass sinks to the ocean floor (Aumont and Bopp, 2005; Boyd et al., 2007; GESAMP, 2025). If the biomass is sunk deep enough, the organic carbon is estimated to be trapped for centuries to millennia (Siegel et al., 2023; Oschlies et al., 2025). Studies suggest that the phytoplankton biomass needs to be exported roughly below 1,000 m to avoid remineralization in shallower depths (Siegel et al., 2021). Artificial upwelling (AU) works after the same principle - added nutrients boost the growth of phytoplankton. In contrast to OF, the nutrients are introduced by transporting nutrient-rich water from deeper layers to the surface via electrical or wave-driven pumps (Baumann et al., 2021; Ortiz et al., 2022). It has been suggested that the increased phytoplankton biomass would lead to an

elevated vertical export flux of sinking particulate organic matter that gets buried in the ocean floor.
Seaweed or macroalgal cultivation is done mostly on large rafts or ropes in the coastal areas and sometimes by installing seaweed farms in the open ocean. It is often done with the intention to sink the farmed biomass to the deep sea for permanent storage to sell carbon credits. Biomass sinking is not only done from cultivated seaweed farms, but also by using agricultural waste or by collecting and sinking the naturally occurring nuisance seaweed Sargassum.
Ocean alkalinity enhancement (OAE) is assumed to increase the ocean's capacity for atmospheric CO_2 uptake by changing seawater chemistry while presumably also counteracting ocean acidification (Rau et al., 2013). It is done by either adding alkaline material to the ocean surface or coastal environments, or by removing CO_2 via electrochemically splitting water into a base and acid stream (Eisaman et al., 2023; Eisaman, 2024). The acid and base stream are either combined before the water is returned back to the ocean or alkaline rocks can be added to the acid stream (Service, 2024). The discharged water is - depending on the method used - neutral or alkaline. In both cases CO_2 has been removed and the returning water is ready to absorb more CO_2 from the atmosphere (Service, 2024; Oschlies et al., 2025).

All technical mCDR approaches are relatively novel methods involving many uncertainties and require rigorous scientific research in terms of their scalability, durability of carbon removal and risks associated with research and their potential future deployments.

1.3 The new voluntary carbon market

The adoption of the Paris Agreement in 2015 with its goal to keep the global mean temperature well below 2°C, respective 1.5 °C revitalized the voluntary carbon market (Kreibich, 2024). Even though the main focus for combatting climate change should be on reducing generated emissions, CDR is applied in all 1.5°C scenarios within the IPCC reports (IPCC, 2022, 2023) in order to be able to reach this goal (Rogelj et al., 2017; Mengis et al., 2022). Following the Paris Agreement, a wave of carbon neutrality pledges from many companies in the private sector led to an increasing demand for carbon credits (Fankhauser, 2022; Hale et al., 2022; Kreibich, 2024). Even though, big corporations are required to fundamentally change processes within their own production and supply chains, the purchase of carbon credits offers a rapid and cheap solution on their claim to being „carbon neutral" (Kreibich, 2024; Christiansen et al., 2023; Trencher et al., 2023, 2024). Big corporations usually buy carbon credits that have been created through mitigation measures conducted by another company. If these are equivalent to 100% of their remaining emissions, their net emissions reach zero (Ahonen et al., 2022; Laine et al., 2023). This growing demand for carbon credits to offset current emissions is demonstrated by the dramatic increase of the market value of the voluntary carbon market (VCM), that has almost quadrupled between 2018 and 2021, approaching 2 billion USD in transactions (Forest Trends' Ecosystem Marketplace, 2023a, 2023b). Thus, the VCM is predicted to grow even more in the near future as the demand for carbon credits will increase as well (Bloomberg, 2023; Kreibich, 2024). The key concern is that if those bought offsets are actually not representing real greenhouse gas reductions, global emissions will continue to increase because companies use the carbon credits without cutting down their own carbon- emitting activities (Kreibich, 2024; Macintosh et al., 2024; Trencher et al., 2024). Companies need to avoid any non-residual emissions first and only purchase carbon credits to offset their unavoidable, residual emissions as a last resort. However, the incentive to purchase carbon offsets lies in the outsourcing of decarbonisation efforts to external providers and thus not being faced with the difficult and potentially costly challenge of transforming and improving the internal operations and supply chains away from fossil fuels and/or resource intensive production processes (Fearnehough et al., 2023; Christiansen et al., 2023; Trencher et al., 2023). A study looking at twenty companies that purchased the most offsets from the VCM between 2020-2023 revealed that the VCM is indeed not supporting effective climate mitigation and therefore fails to contribute to an emission reduction as claimed (Trencher et al., 2024). The diverse range of companies from various sectors including energy, aviation, car manufacturing, telecommunications and fashion had all committed to net-zero strategies or claimed to provide carbon-neutral services. However, to reach their goals the companies opted mainly to purchase cheap, low quality carbon credits that would barely have any benefits for climate mitigation (Trencher et al., 2024).

These findings highlight the problem of the VCM as a voluntary industry-led market without any international oversight or regulation and thus is prone to overstating emissions reductions and over-issuing credits as well as bad behaviour (World Economic Forum, 2023; VCMI, 2023; Axelsson et al., 2024). The missing oversight makes it almost impossible to distinguish between companies that provide credible mitigation measures and the ones that only offer low quality carbon credits. In recent years, the claims to reliably offset greenhouse gas emissions via the VCM have already started to lose credibility and as a consequence some companies get accused of greenwashing (Probst et al., 2024; UN, 2022; Trouwloon et al., 2023). However, the increasing demand to achieve carbon neutrality presumably may have been one important condition for the rapid development of mCDR start-ups.

2 mCDR start-ups – development and status quo, MRV and challenges

In this study, we examined how many mCDR start-ups are currently operating and what methods they are using. For this purpose, we used online databases such as Geoengineering Monitor, Ocean Visions and X-Prize Carbon Removal to get an overview of the magnitude of currently operating mCDR start-ups and if field trials are already taking place. We do not make any claim of completeness of information and our list of investigated mCDR start-ups is not exhaustive, but present examples of data collected about mCDR Start-ups that are publicly available. All companies known to the authors are based on publicly available sources such as newspaper outlets and information found on homepages/ platforms showcasing mCDR Start-ups (e.g Ocean Visions, Geoengineering Monitor, XPrize Carbon Removal…). The ranking in the sources is alphabetical and does not constitute a rating or recommendation (Supplementary Table 1).
The number of mCDR start-ups increased rapidly over the last 10 years. In addition, many seem to operate on a pre-commercial or full commercial scale and are already selling carbon credits or pre-selling carbon credits.

Looking at the Map of Geoengineering Monitor, mCDR start-ups underwent a rapid development. In the year 2000, there was only one company called "Ocean Nourishment Corporation Pty Ltd (ONC)" conducting ocean fertilization (OF) trials. In 2004 it was registered as a commercial company and partnered later with the Ocean Nourishment Foundation (ONF), a not-for-profit organization. Both, ONC and ONF had the same CEO. Up until today, ONC/ONF are operating and are taking part in the WhaleX project conducting OF experiments in the open ocean (https://www.geoengineeringmonitor.org/).
The number of mCDR start-ups continued to rise steadily over the years to at least 54 start-ups actively operating in 2025 (https://map.geoengineeringmonitor.org/). From 2015 to 2020 and from 2020 to 2025 the number of start-ups roughly doubled in both timeframes (Figure 1). The number of field experiments and/ or commercial deployments or expansion of start-ups into different countries increased also drastically over the years (Figure 1). However, these are only mCDR start-ups that are listed on the database Geoengineering Monitor and did not include other ones we additionally found on Ocean Visions or under the Top 100 of the Carbon Removal X-Prize.

The focus on different mCDR techniques also shifted over the years. In the early 2000s most start-ups used methods for OF or AU, while algae cultivation projects and ocean alkalinity enhancement (OAE) methods are gaining more attention since the 2020s (Figure 1). Seaweed farming has even become the largest growing aquaculture sector worldwide (Ricart et al., 2022).

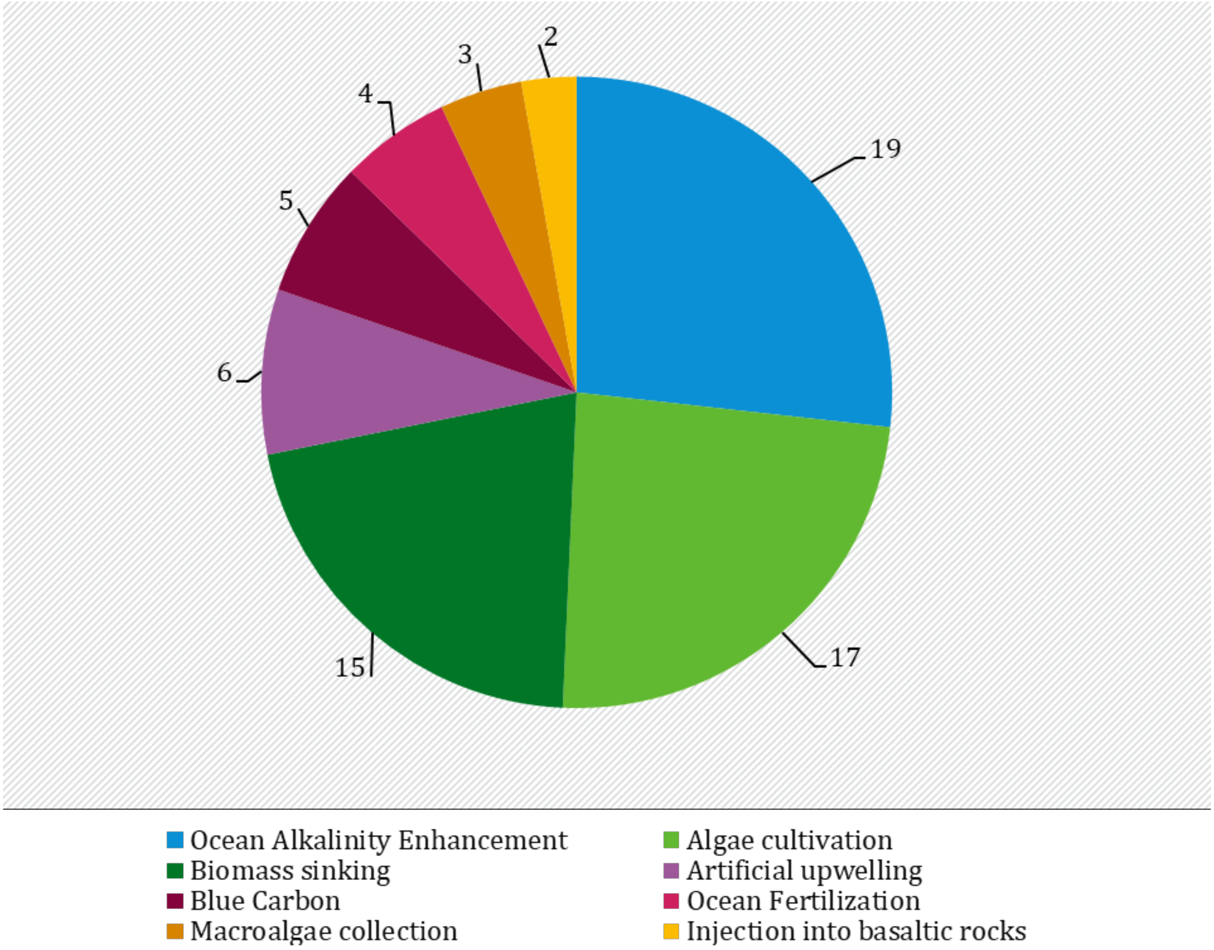
Figure 1: Development of mCDR Start-ups and their applied methods

Quelle: https://map.geoengineeringmonitor.org/

For our own analysis, we examined 52 mCDR start-ups that were randomly selected from the above-mentioned platforms (see Supplementary Table 1). We found that most mCDR start-ups had their headquarters in the US (18 out of 52), followed by the UK (7), Israel and the Netherlands (4 each). 50 out of the 52 examined start-ups are already conducting field trials and/ or commercial deployments. Most of those take place in the US (20), followed by the Caribbean (8), Canada (6) and Australia (5). 48 of the investigated 52 start-ups operate on a commercial scale, three are mainly research-driven while one was a school project.

The most prominent mCDR approaches applied are OEA (19 start-ups; 27%), followed closely by algae cultivation (17 start-ups; 24%) and biomass sinking (21%; see Figure 2). Start-ups that conducted OEA were using mainly electrochemical approaches (10 out of 19), followed by adding an alkaline substance (8 out of 19) or a novel photochemical pigment (1 out of 19). Twelve start-ups are farming macroalgae, while five are cultivating microalgae. Biomass that is sunk by start-ups was mainly from cultivated algae (60%), followed by agricultural waste (20%), natural sinking of broken off fragments or sinking naturally occurring Sargassum seaweed. Expansion or restoration of blue carbon habitats was mainly done with macroalgae while one start-up restored oyster reefs and another one seagrass meadows and mangroves.

Figure 2: Prevalence of applied mCDR methods used by currently operating mCDR start-ups



Quelle: Supplementary Table 1

The big investors into these mCDR start-ups are carbon credit trading platforms, platforms that support early-stage mCDR start-ups, governmental innovation funds as well as philanthropists. Carbon credits, often as pre-sales (before the actual carbon has been captured) are mainly purchased by companies from the aviation, shipping and fashion sector or so called "Big Tech" companies and e-commerce. Even if the technology or mCDR method has not been fully developed, payment for pre-sales of carbon credits has been received and puts a lot of pressure on the start-ups to fulfil their paid promises. This poses an additional risk to marine ecosystems[1].

To potentially market their mCDR approaches as more nature-based solutions, some start-ups use different terminologies. Artificial upwelling (AU) is for example described as “marine permaculture”, “enhanced upwelling” or “regenerative upwelling” to possibly conceal the technical nature of the applied method. Moreover, macroalgae farms that have been installed for the purpose of selling carbon credits are sometimes referred to as ocean afforestation efforts (N’Yeurt et al., 2012). OF techniques are compared to only mimicking whale faeces.

Our investigations showed that mCDR start-ups operate in a highly dynamic environment. New start-ups are emerging in large numbers, some of them are going out of business fast or disappear over time – most likely because the mCDR technology was not fully developed yet. There is a lack of transparency with no apparent transfer of knowledge or potential problems encountered and recommendations for improving methodological approaches. For several of the start-ups, it is not clear if they are still operating. If they go out of business, there is barely any

[1] see this example: https://www.canarymedia.com/articles/carbon-removal/under-the-sea-running-tides-ill-fated-adventure-in-ocean-carbon-removal

information available that it happened and the reasons for it. However, due to these untransparent processes, valuable lessons learnt and information for further research is lost.
Our investigations further revealed that some start-ups changed their names over time possibly motivated by economic reasons, such as a strategic shift of focus from selling carbon credits to a more economically sustainable business (e.g. macroalgae cultivation). Former employees of some start-ups founded also a new start-up or an "independently" operating not-for-profit organization that should verify the credibility of carbon removal from their former employer. An OF start-up had to cease its OF plans after public backlash and due to interventions by government authorities. Shortly thereafter, a similar entrepreneurial team founded another start-up which conducted a highly controversial OF experiment without the knowledge of national or international authorities (Tollefson, 2012). Afterwards, a third OF start-up got founded by the almost exact project management team as the previous one. Another example is a wave-pump manufacturing start-up that provided their wave pumps for the German Alliance of Research (DAM) Test-ArtUp field experiment (2022). The wave pumps stopped working after several hours due to detachment of the bottom weight from the pump. Since 2025 the start-up is known under another name.

Our investigations demonstrated that mCDR start-ups are a rapidly expanding business that is characterised by its highly dynamic environment (e.g. start-ups coming and going out of business). Experiments and deployments are often indistinguishable. Moreover, through our research we found that the applied methods are not well described and it is not transparent what is done exactly and what materials or compositions of chemicals are used. Further, those projects seem to be uncoordinated and unsupervised and there is no evidence that existing international assessment frameworks e.g. the Annex 5 of the 2013 amendment on marine geo-engineering to the London Protocol are applied. While small-scale field trials in a controlled setting are useful to test applied hardware and the methodological approach, experiments with longer time frames are needed to provide valuable knowledge about the potential effects on marine ecosystems and the long-time fate of the captured carbon. Based on the data collected, the scale on which most start-ups are operating is not mainly done for scientific purposes, but with a clear intention to operate on a pre-commercial or commercial scale. Moreover, most field trials/deployments are not conducted in a controlled setting. This is actually of great concern as the scientific community agreed that mCDR techniques would need more research to investigate the potential impact of large-scale mCDR deployments (Buesseler and Boyd, 2023; Levin et al., 2023; Oschlies et al., 2025; GESAMP, 2025). As detailed below, the potential negative effects of the various mCDR techniques could have unforeseen or unwanted consequences for marine ecosystems and alter nutrient cycling, fisheries production and impact threatened or endangered species.

3 The challenges, environmental risks and ethical concerns

Several challenges have to be considered and managed concerning mCDR projects undertaken by start-ups, including risks for the environment, the availability of robust MRV mechanisms as well as ethical concerns. The three challenges are not meant to be exhaustive, however, they are certainly the most relevant ones. These challenges do not necessarily differ for start-ups or larger research institutes. However, also start-ups have to cope with the necessary provisions and measures.

3.1 Serious environmental risks of mCDR

Research in mCDR techniques is still in its infancy. Some methods are well established, such as restoration of ecosystems (BC), while others such as open ocean seaweed farming with biomass sinking or ocean alkalinity enhancement (OAE) are less researched, but have gained more attention in recent years (Wu et al., 2023; Bach et al., 2024; Oschlies et al., 2025). However, especially the technical and manipulative methods represent a massive intervention into marine ecosystems with so far unknown consequences and have "the potential for deleterious effects that are widespread, long-lasting or severe" (London Protocol Statement on Marine Geoengineering 2023).

Each mCDR approach could have unforeseen and long-lasting impacts on marine ecosystems that might not be reversible: Cultivating macroalgae in the open ocean could deplete the scarcely available nutrients and thus limit phytoplankton growth (Campbell et al., 2019; Ricart et al., 2022). Moreover, shading caused by large-scale macroalgae farms could divert light away from phytoplankton which would also negatively impact its growth (Campbell et al., 2019; Ricart et al., 2022). Additionally, macroalgae produce and exude chemicals that can negatively impact marine life and may alter atmospheric chemistry (Leedham et al., 2013; Oschlies et al., 2025). On top of that, macroalgae that get introduced from coastal regions to the open ocean might carry with them contaminants, microbes and parasites, which might be transported to the deep sea if biomass is sunk after cultivation (Levin et al., 2023). Next to seaweed bales, some mCDR start-ups are also planning to sink large amounts of agricultural crop waste to the deep sea. Even though terrestrial biomass would not remove important nutrients from marine life, its removal might deplete the soil of nutrients and in turn negatively impacting soil fertility (Sidik et al., 2024). Sinking biomass to the deep sea could release increased amounts of particulate or dissolved organic matter on its way down, altering microbial production, oxygen consumption, and food supply in the mesopelagic zone and bury benthic biota in the deep sea (Wu et al., 2023; Levin et al., 2023; GESAMP, 2025). The degradation process of organic matter on the seafloor will deplete the oxygen which will make these areas lethal to nearly all marine life (Wu et al., 2023; Levin et al., 2023; GESAMP, 2025). Other effects of enhanced organic enrichment on the seafloor might be the production of hydrogen sulfide, which is highly toxic to most animals and plants, and/or the production of other even more potent greenhouse gases, such as methane and nitrous oxide. Their release could dramatically shift the species composition of deep-sea communities.

Ocean fertilisation (OF) and artificial upwelling (AU), both increase nutrient concentrations in the surface waters and, thus stimulating phytoplankton growth. However, the addition of nutrients might also cause the growth of harmful algae species or shift phytoplankton community composition and/ or also change the nutrient composition of phytoplankton (Baumann et al., 2021; Ortiz et al., 2022; NASEM, 2022). This could have detrimental effects on the whole food chain, e.g. altering the preferred food source of zooplankton resulting in their decline which again will lead to a decrease in fishery yields (Goldenberg et al., 2024). The increased phytoplankton production might result in elevated oxygen consumption due to remineralization by microbes or zooplankton which could in turn reduce oxygen concentration in midwater and deeper waters and increase the release of other greenhouse gases and negatively affect mesopelagic biota (Williamson et al., 2012; GESAMP, 2019). Moreover, deep sea ecosystems could be negatively impacted from enhanced particle sinking flux (NASEM, 2022; Oschlies et al., 2025; Tagliabue et al., 2023; Wallace et al., 2010). Additionally, AU might impact marine biota in the process of pumping them through industrial-scale structures and mix biota as well as redistribute salinity and temperature of different ecosystems and depths, potentially even affecting ocean stratification or disrupting ocean circulation (Oschlies et al. 2010; Kwiatkowski et al., 2015; GESAMP, 2025). A major drawback of AU is that once implemented, it needs to work continuously to be able to keep the additionally added CO_2 stored in the ocean (Oschlies et al., 2010; Keller et al., 2014). If disrupted, the surface ocean would immediately release CO_2 and heat to the atmosphere (Oschlies et al., 2010; GESAMP, 2025).

OAE that is achieved by dissolving alkaline materials could potentially add significantly to levels of trace metals, such as cadmium, nickel, or chromium into the marine environment (Flipkens et al., 2021). Moreover, it might lead to temporary spikes in turbidity, pH and alkalinity at the site of deployment which could negatively affect marine communities (GESAMP, 2025). In addition, several factors may drastically decrease the overall efficiency of this mCDR approach. If too much alkaline material is added too fast, the site of deployment might be supersaturated which leads to spontaneous precipitation of minerals. This would actually result in a decrease of alkalinity (Hartmann et al., 2023; Hashim et al., 2025). Additionally, it has been demonstrated that OAE- induced changes in seawater chemistry support the growth of calcifying phytoplankton, such as coccolithophores, thus reducing the efficacy of OAE by 2–29% by 2100 (Lehmann and Bach, 2025). The calcification reaction releases CO_2 into the surrounding seawater while the coccolithophores take up bicarbonate ions to create their skeleton out of calcium carbonate platelets (Frankignoulle et al. 1994; Monteiro et al. 2016). On top of that, anthropogenic OAE also increases the calcium carbonate saturation state in seawater which reduces the natural dissolution of calcium carbonate from sand (Bach et al., 2024). Thus, by artificially enhancing alkalinity, the natural contribution to increases in alkalinity gets impaired.

There is a need for effective mechanisms to assess and manage potential effects of research projects on the environment. The amendment of 2013 to the London Protocol on marine geoengineering entails in its Annex 5 such an assessment framework (Ginzky and Oschlies, 2024).

3.2 Effective MRV mechanisms to verifiably quantify the carbon captured and the permanence of the removal

A big challenge for mCDR start-ups is how to reliably quantify the carbon that is captured. This issue lies at the core of their credibility and market acceptance. Accurate accounting has direct implications for trust, funding, and long-term scalability. The following informs on how mCDR start-ups currently deal with this challenge or evade it.

Most of the marine based CDR approaches depend on indirect carbon removal. For example, by cultivating biomass or elevating phytoplankton growth, carbon dioxide is removed by the cultivated algae, seaweed or phytoplankton and incorporated as biomass (Ricart et al., 2022). Subsequently sinking this biomass should export the captured carbon from the surface water for permanent storage in the deep ocean. Other methods aim to decrease the carbon dioxide concentration in the seawater. As a result, more carbon dioxide will be drawn from the atmosphere into the now CO_2 depleted surface seawater to establish a concentration equilibrium again. These dependencies on indirect carbon removal complicate the validation for most marine based CDR approaches. It is difficult to measure how much carbon dioxide gets converted into biomass, how much additional biomass is created by the intervention and what fraction of this biomass is finally exported to the ocean floor without being remineralized on its way down and for how long this carbon will be staying in the ocean floor (in case of biological methods). Additionally, there are contentious opinions whether all seaweed ecosystems, farmed or wild, may even sequester the significant amounts of carbon previously thought (Gallagher et al., 2022; Ricart et al., 2022; Duarte et al., 2025). In the case for OAE it will be challenging to assess how much CO_2 will be actually diffusing from the atmosphere into the sea and to distinguish between natural, anthropogenic and CDR caused CO_2 diffusion or to monitor for secondary precipitation, biotic calcification, and other potentially occurring changes to marine ecosystems (Lehman and Bach, 2024; Bach et al., 2024).

The increasing amount of operating mCDR start-ups, partially even on a commercial scale, demonstrate the extent of unsupervised geoengineering techniques being conducted in several parts of our oceans. The scientific knowledge and realistic risk assessments of most mCDR techniques are still in their infancy, which highlights the urgent need for further responsible research. However, the literature review of the various start-ups showed that many of them give no further information on their MRV protocols or might not even have one in place yet. Some of the companies are working together with academic institution with the aim to create a robust MRV protocol. In contrast, there are several mCDR start-ups that design their own MRV protocols or generate protocols in collaboration with carbon credit trading or market platforms – which might constitute a conflict of interest.

These results show that robust monitoring, reporting, and verification (MRV) protocols are needed to determine the additional amount of greenhouse gas removed by a mCDR activity. The reporting of these monitoring results should be communicated to an independent third party who can subsequently verify the presented monitoring results. This multistep process of MRV results in certifiable carbon credits that can be sold in a voluntary or regulated carbon market (Ho et al., 2023; Smith et al., 2023; Palter et al., 2023). Having credible MRV protocols in place increases the attractiveness of a mCDR start-up towards companies that want to invest in carbon credits[2].

To be able to be properly credited, mCDR methods would need to prove that their carbon removed would not have occurred without their conducted intervention (additionality) and further that their intervention would not lead in the near future to the decreased carbon removal capacity in other regions/parts of the ecosystem or to the additional production of other greenhouse gases (leakage). Secondly, the used method needs to prove that the removed carbon will be stored for centuries to millennia (durability/permanence) (Smith et al., 2023; Palter et al., 2023; Oschlies et al., 2025).

Therefore, legitimate scientific research into the efficacy, feasibility, scalability and permanence of carbon storage for different mCDR techniques is urgently needed. It has to be assessed which mCDR approaches would not only result in a net carbon removal but also permanently store the removed carbon and which are feasible to operate on big scales. The main focus of mCDR activities should be the restoration and afforestation of marine ecosystems that provide next to their carbon sequestration capacities a range of invaluable ecosystem services and support biodiversity with low risks associated with their application (Johnson et al., 2024). Otherwise, few or no climate mitigation will be achieved while wasting important resources through investments into technical mCDR approaches with little probabilities of being able to remove CO_2 on the scales needed or permanently store the removed carbon (Doney et al., 2024; Palter et al., 2023). Additionally, mCDR start-ups need to conduct life cycle assessments (LCA) that account for the additional CO_2 emissions from manufacturing, transportation, deployment, and monitoring of the respective mCDR technique before any marine intervention is carried out, to confidently calculate the net carbon removed (Grubert, 2021; Bach et al., 2024).

3.3 Ethical concerns

The prospect of earning substantial amounts through the sale of carbon credits raises the question of how to share the resultant financial benefits fairly as well as how to involve potential stakeholders and take all interests equally into consideration.

It is of importance that mCDR measures are respectful of legal provisions both at international and national level. Compliance with designated marine protected areas (MPAs) and also respecting and adhering to indigenous people's rights are important aspects.

Our literature review has shown that there are already start-ups that are seeking permission to operate within MPAs that are collaboratively governed with indigenous partners. In such

[2] For example: https://www.forbes.com/sites/alanohnsman/2023/05/31/boeing-bets-on-startup-equatic-with-massive-co2-removal-hydrogen-deal/

instances it has to be ensured that all interests are equally represented or maybe to even exclude from the very beginning mCDR activities in areas that are of importance for indigenous partners. In addition, a few mCDR start-ups are providing their services for free to third world countries, but in exchange the start-up receives all carbon credits that are created through this intervention. Moreover, a lot of field trials are not conducted in the country where the headquarters of the start-ups are based. Therefore, a legal framework is urgently needed to ensure that mCDR interventions undertaken in another country do not damage their marine environment or resources.

4 Legal framework

mCDR start-ups have to comply with national and international provisions. The applicability of national provisions may depend on many criteria, for example the location of the headquarters of the enterprise, the location of the project and/or the location of the loading of material used. It might be the case that mCDR start-ups have to abide by legislation of several states depending on the applicability of the national regulations.

For example, according to German law, all mCDR techniques are currently prohibited, except for research projects involving ocean fertilization (OF). Thus, field trials for artificial upwelling (AU), biomass sinking or ocean alkalinity enhancement (OAE), are prohibited under German law, both for research and deployment. However, the respective law is currently under revision in order to enable also research on the new emerging mCDR techniques[3]. The German provisions apply for German nationals (persons or enterprises), for vessels under the German flag, for projects undertaken in German waters as well as in the Exclusive Economic Zone of another state, or when the material used is loaded in a German harbour.

At international level, the amendment of 2013 to the London Protocol is most relevant. The amendment was approved by the Parties of London Protocol unanimously. It states that in the case of OF only legitimate scientific research may be allowed, whereas deployment activities are prohibited. Annex 5 of this amendment states criteria for the distinction of legitimate scientific research and deployment. It also provides a general assessment framework for marine geo-engineering techniques as well as consultation and participation requirements. In addition, Paragraph 8 of Annex 5 states, that "economic interests do not influence the design, conduct and/or outcomes of the proposed activity. There should not be any financial and/or economic gain arising directly from the experiment or its outcomes. This does not preclude payment for services rendered in support of the experiment or future financial impacts of patented technology." Selling carbon credits could be interpreted as "financial and/or economic gain arising directly from the experiment or its outcomes". With this understanding, start-ups selling carbon credits would not be in line with the conditions of "legitimate scientific research" pursuant to Annex 5. The amendment has not yet entered into force. Thus, its proposed legal provisions are so far not legally binding (Ginzky and Oschlies, 2024).

In 2023 and 2022 the Parties of London Protocol agreed upon statements on marine geo-engineering which stated that new emerging marine geoengineering techniques such as biomass sinking and OAE may pose a risk to the marine environment and that they are therefore of concern. They further agreed to work towards regulatory solutions and urged Parties to apply Annex 5 for the assessment of potential projects. Finally, the statement of 2023 stressed that "activities other than legitimate scientific research should be deferred"[4].

[3] https://www.bundesumweltministerium.de/fileadmin/Daten_BMU/Download_PDF/Glaeserne_Gesetze/21._LP/hseg/Entwurf/hseg_refe_2025_bf.pdf

[4] The statement of 2022: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC_LP/LP%20LC%20Statement%20on%20Marine%20Geoengineering_%20LC%2044-17%20annex%202.pdf and the statement of 2023: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC_LP/2023%20STATEMENT%20ON%20MARINE%20GEOENGINEERING.pdf

While the legal relevance of these kinds of statements is contentious, a political commitment could hardly be denied. Therefore, it is strongly recommended that deployment activities should not be permitted for the time being and that Annex 5 of the 2013 amendment should be used for the assessment of potential projects.

5 Conclusions

Our review of operating mCDR start-ups highlighted not only their rapid developments in numbers, but also their advancing operations of mCDR techniques even on commercial scales that are being already conducted unsupervised in several parts of our ocean. Bigger companies which intend to offset their emissions through the purchase of carbon credits from these start-ups enable to a large extent the already occurring pre-commercial or commercial deployment of mCDR techniques that have not yet been subjected to legitimate scientific evaluation and validation.
mCDR techniques are attributed a high estimated potential of removing 1–100 Gt carbon dioxide per year (IPCC, 2022; Morganti et al., 2025). However, in reality all implemented CDR methods, land- and marine-based, are currently removing only 2 Gt of carbon dioxide per year (Morganti et al., 2025). Excluding restoration and reforestation of ecosystems, only 1 % out of this 2 Gt (0.0013 Gt per year) removal capacity remains, of which mCDR techniques constitute only a neglectable fraction (Smith et al., 2023; Service et al., 2024).
Therefore, the capture of carbon dioxide via mCDR techniques cannot replace reliable and sustainable climate mitigation measures. In order to mitigate or slow down climate change priority should be given to drastic reductions in generated greenhouse gas emissions as well as the preservation and restoration of existing natural ecosystems that capture and store carbon dioxide.
As a consequence, financial resources, research and efforts should first and foremost focus on maintaining and restoring viable and resilient marine ecosystems, such as seagrasses, mangroves and coral reefs. They provide a range of essential ecosystem services for humanity and support biodiversity next to their carbon storage potential (Lovelock & Duarte, 2025). Marine ecosystems already face anthropogenic stressors and pressures next to climate change, including overfishing, destructive fishing practises, nutrient pollution, biodiversity loss and plastic pollution.
It is not our intention to argue generally against start-ups. Start-ups are often the mission link between innovation and larger, less flexible companies. They could develop innovative solutions being scaled up later by either themselves or by bigger companies. However, it is important to ensure that also innovations by mCDR start-ups need to comply with essential requirements such as the prevention of potentially irreversible risks for the marine environment, effective MRV mechanisms and the respect of interests of others, in particular local and indigenous communities.
The regulatory concept of the amendment of 2013 to the London Protocol shall ensure that only high-quality research is undertaken to enable an informed decision by Parties based on scientifically reliable data and information. The concept also stresses that for the time being due to the very limited knowledge basis deployment of mCDR techniques is not justifiable for OF projects. The unanimously by Parties of the London Protocol adopted statements on marine geo-engineering of 2022 and 2023 could well be understood as a strong encouragement, if not a commitment, to use Annex 5 of this amendment to the London Protocol as “best practice” when assessing potential research projects. The statement of 2023 clearly stated, that deployment activities are not yet ready to be permitted.

Marine CDR interventions that do not verifiably remove greenhouse gases and/or harm marine ecosystems cannot be justified as climate solutions. Equally, infringements on the rights or well-being of local and indigenous communities could render such actions unacceptable. Both should be prevented to maintain environmental integrity and public trust.

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