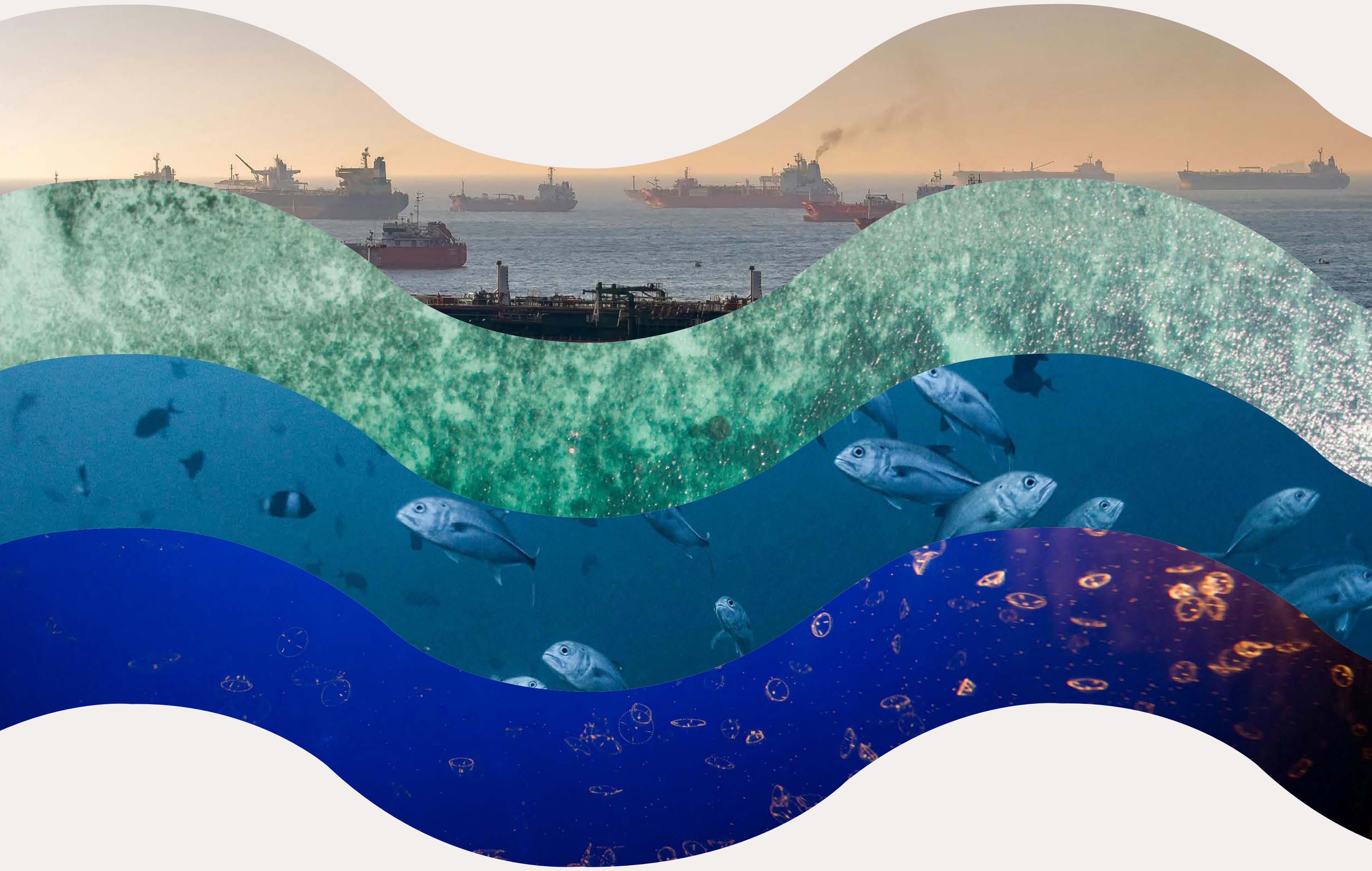
MARINE CARBON DIOXIDE REMOVAL TECHNOLOGIES: HOPES AND THREATS



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About the Ocean & Climate Platform

The Ocean & Climate Platform (OCP) is an international network of more than 120 organisations from civil society, including NGOs, research institutes, foundations, businesses, local authorities, and intergovernmental organisations. Created in the lead-up to COP21 in Paris with the support of France and the Intergovernmental Oceanographic Commission of UNESCO, the OCP aims to promote scientific expertise on the role played by the ocean and its ecosystems in the global climate system, and to advocate for stronger integration of ocean-climate-biodiversity interactions in decision-making. Acting as an interface between science and policy, the OCP provides a space for reflection and dialogue between the scientific community, civil society, and policymakers, fostering a common and holistic approach to ocean health in the context of climate change and biodiversity loss.

Producing, synthesising and sharing knowledge on the ocean, climate and biodiversity

Since 2018, the OCP has mobilised its network of scientists and science communicators to review and promote knowledge on the ocean, climate and biodiversity drawn from major scientific reports. In 2019, it published *Ocean and Climate: New Challenges*, based on the Special Report of the Intergovernmental Panel on Climate Change on the Ocean and Cryosphere in a Changing Climate. In 2023, it released *What Ocean for Tomorrow? Marine Ecosystems in the Face of Climate Change*, an overview of the knowledge presented in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change on the interactions between marine ecosystems, climate change and sustainable development. More recently, in 2024, it published *Fisheries and Aquaculture in the Face of Climate Change: Challenges and Perspectives*, a synthesis of the knowledge drawn from the latest reports of the Intergovernmental Panel on Climate Change, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the Food and Agriculture Organisation of the United Nations and the World Ocean Assessment.

In 2026, continuing its mandate to foster reflection and dialogue on emerging issues at the ocean-climate-biodiversity nexus, the OCP is publishing the report *Marine Carbon Dioxide Removal Technologies: Hopes And Threats,* a synthesis of scientific knowledge on marine geoengineering.

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Summary

In the face of the climate emergency, reaching carbon neutrality requires not only the drastic reduction of greenhouse gas emissions, but also the compensation of "residual" emissions with atmospheric carbon dioxide removal (CDR) approaches. Climate scenarios as synthesised by the Intergovernmental Panel on Climate Change (IPCC) estimate the need for the removal of 7 to 9 billion tons of CO_2 per year, an amount which varies depending on the decarbonisation pathways nations will implement. In this context, exploratory marine carbon dioxide removal (mCDR) technologies are being developed, aiming to strengthen the ocean's natural capacity to absorb atmospheric CO_2.

The ocean plays a key role in the carbon cycle, capturing each year about 25% of anthropogenic carbon dioxide emissions through two key processes (or "pumps"): the physical or **solubility pump***, which dissolves and locks away CO_2 in cold and deep water layers, and the **biological pump***, which relies upon planktonic communities and photosynthesis. mCDR technologies aim to **strengthen these natural processes** through three types of approach: biological (ocean iron fertilisation, macroalgae farming, blue carbon ecosystem restoration), chemical (ocean alkalinity enhancement, direct carbon capture) and physical (artificially pumping surface waters towards deeper layers).

While some optimistic scenarios predict that these technologies could sequester several billion tons of CO_2 each year, their technological maturity remains highly uneven, and their risks are poorly understood. Three major challenges to mCDR are identified. Firstly, there is a **clear lack of scientific knowledge** on the actual efficacy of these methods and their impacts on marine ecosystems. Further, there are **significant socio-ecological risks**: pollution at scale, marine food chain disruption, impacts on coastal communities, etc. Finally, **international governance remains fragmented and inadequate,** with no binding legal framework specifically regulating these activities to date. These limitations are accompanied by major ethical concerns, such as the risk that these technologies may discourage decarbonisation efforts or that conflicts of interest may arise from the commodification of carbon credits by private actors.

Introduction:

Removing atmospheric CO_2 to address climate change?

Climate change and greenhouse gas emissions pathways

Climate change results from the accumulation of greenhouse gases (GHG) in the atmosphere, particularly carbon dioxide (CO_2) emitted by human activities. This leads to ocean warming, **acidification***[1], and **deoxygenation***[2]. These impacts directly threaten marine ecosystems and human societies through species redistribution and extinction, sea-level rise, and the increasing frequency and intensity of extreme events such as cyclones and floods[3].

By signing the **Paris Agreement***, states committed to limiting global warming to 2°C, and ideally 1.5°C. This requires achieving **carbon neutrality***, where GHG emissions from human activities are reduced as much as possible and balanced by removals, resulting in a net-zero emissions balance. Global emissions are currently estimated at 40 billion tonnes (Gt) of CO_2 per year, alongside other greenhouse gases such as methane and nitrous oxide. They are mainly generated by electricity and heat production, industry, agriculture, transport, and waste.

Climate scenarios explore how humanity can reduce greenhouse gas emissions based on available technologies, political priorities, and economic considerations. They suggest that some sectors are more difficult to decarbonise, such as aviation, agriculture, and maritime transport, where emissions may persist for several decades. These so-called residual emissions result from technical, economic, social, and political constraints linked to how human activities are organised, and are generally estimated at 7–9 Gt of CO_2 per year.

Thus, to achieve carbon neutrality, residual emissions must be offset by at least equivalent removal of atmospheric CO_2. This approach is known as **carbon dioxide removal (CDR)*.** It encompasses human interventions designed to artificially capture CO_2 from the atmosphere and durably store it in natural or engineered reservoirs. Experts also consider using CDR to remove already emitted CO_2, a “historical stock” with deleterious impacts on the climate. CDR falls under **geoengineering***, which encompasses technologies aimed at deliberately altering environmental conditions in order to mitigate or compensate for the impacts of climate change. In the absence of a rapid and complete elimination of human GHG emissions, addressing climate change could therefore depend on the development of CDR technologies, provided they can be reliable, permanent, and safe for the environment and societies.

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[1] Terms marked with an asterisk (*) are defined in the glossary at the end of this report.

[2] Ocean & Climate Platform (2019), Ocean & climate change: New challenges. Focus on 5 key themes of the IPCC Special Report on the Ocean and Cryosphere, https://ocean-climate.org/en/ocean-climate-change-new-challenges-focus-on-5-key-themes-of-the-ipcc-special-report-on-the-ocean-and-cryosphere/

[3] Ocean & Climate Platform, 2024, Fishing and Aquaculture in a Changing Climate: Challenges and Perspectives, https://ocean-climate.org/en/fishing-and-aquaculture-in-a-changing-climate-challenges-and-perspectives/

The promises of marine carbon dioxide removal

Some technologies already remove atmospheric CO_2. Currently, CDR accounts for 2.1 Gt of CO_2 per year and is dominated by conventional land-based approaches, particularly reforestation[4]. However, scaling up to remove significantly larger quantities of CO_2 remains a technical challenge and entails substantial risks for biodiversity and people[5]. “Novel” approaches are also being developed, including direct air carbon capture, biochar (a charcoal-like substance made from organic waste that traps carbon in the soil), or bioenergy (energy generated from living matter like plants or wood) with CO_2 capture and storage. These technologies have achieved only limited success so far and entail biodiversity risks, high costs and energy requirements, along with potential land-use conflicts. Such limitations raise questions about the relevance of these methods for atmospheric CO_2 removal in the short to medium term.

Given the current limitations of land-based CDR, an increasing number of researchers and entrepreneurs are turning to the ocean. Known as a vast natural **carbon pump*** (Figure 3), the ocean absorbs around 25% of anthropogenic CO_2 emissions each year[6]. This capacity relies on physico-chemical and biological processes that enable the ocean to capture large amounts of CO_2 and store part of it in its depths.

New CDR approaches seek to enhance the ocean’s natural carbon pump to increase the amount of CO_2 it removes. These methods, which are the focus of this report, are grouped under the term marine CDR (mCDR) (Figure 4). Among the ideas being experimented with are those aimed at boosting phytoplankton growth (Box 1) or altering seawater chemistry. These approaches are presented as potential contributors to climate change mitigation. However, their actual potential, costs, and long-term effects remain uncertain.

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[4] This number comes from the main report on the topic, the *State of Carbon Dioxide Removal Report*. https://www.stateofcdr.org/

[5] Alexandra Deprez et al. (2024), Sustainability limits needed for CO2 removal, Science. https://www.science.org/doi/abs/10.1126/science.adj6171

[6] See the Ocean & Climate Platform’s scientific factsheet: “The Ocean Carbon Pump”. https://ocean-climate.org/en/presentation-of-the-ocean-and-climate-scientific-items/the-ocean-carbon-pump/

A growing controversy

Research on mCDR and investment in the development of these technologies are growing, driven by both scientists and private actors. The GESAMP agency, a group of independent experts advising the UN on marine environmental protection, has identified nearly 200 mCDR projects, most of them led by start-ups[7]. In a context where the climate emergency is driving the search for new decarbonisation solutions, the efficacy and safety of mCDR technologies are fuelling particularly intense scientific and societal debates due to their high degree of uncertainty and ethical considerations.

Projections estimate that certain mCDR approaches could lead to the removal of several billion tonnes of CO_2 per year (Figure 4). However, these represent only the most optimistic development and deployment scenarios. Moreover, these scenarios do not sufficiently take into account the full range of material and energy requirements that would be involved in their large-scale deployment.

Capturing and sequestering several billion tonnes of CO_2 per year would significantly alter the ocean's physical, chemical, and biological cycles on a large scale. Such disruption of long-established and complex processes poses major risks to biodiversity, including large-scale pollution events, changes in nutrient availability, and ecosystem degradation (Figure 4). These ecological impacts could trigger cascading effects for coastal populations and humanity more broadly, whose well-being depends on a healthy ocean. Given the ocean's size and complexity, as well as the limited number of in situ experiments, the large-scale consequences of such interventions remain difficult to predict.

At the heart of the controversy surrounding mCDR is also the risk that a technological promise could undermine efforts to reduce GHG emissions. States could justify weakening their decarbonisation efforts by relying on the most optimistic mCDR development scenarios.

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[7] Available on the GESAMP website
https://www.gesamp.org/work/groups/41/ocean-climate-intervention-projects-2

Box 1.

THE ORIGINS OF MARINE GEOENGINEERING

In the 1990s, based on the work of American oceanographer John Martin (1935–1993), the first field trials of marine geoengineering were conducted in the equatorial Pacific Ocean. These experiments tested the hypothesis that **fertilising*** the ocean with iron could enhance phytoplankton productivity and thereby remove CO_2 from the ocean. As this carbon enters the food chain, part of it could sink to the ocean floor and remain sequestered in the long term. While the early experiments showed an increase in plankton production, none demonstrated with certainty that the captured CO_2 remained stored. Other evidence also suggests that these trials could have significant ecological impacts: fertilisation acts in an uncontrolled manner on plankton communities, favouring certain species over others. This resulting imbalance in plankton biodiversity could cascade through the entire marine ecosystem, compounded by the effects of decomposing biomass, which would consume available oxygen, reducing the amount available to marine organisms.

Nevertheless, some private actors have pursued this approach as a commercial opportunity, since removed CO_2 can be used to generate **carbon credits***. This was notably the case of Russ George, who in 2012 conducted a large fertilisation experiment off the coast of Canada without scientific oversight and in violation of international treaties, in particular the **London Convention and Protocol***. Around ten experiments have since been carried out, triggering significant scientific and political controversy that contributed to the marginalisation of fertilisation in favour of ocean alkalinity enhancement, which has since gained traction. Today, however, both academic and private actors are seeking to revive fertilisation experiments, such as the ExOIS consortium, once again raising questions about scientific novelty, environmental impacts, and compliance with international law.

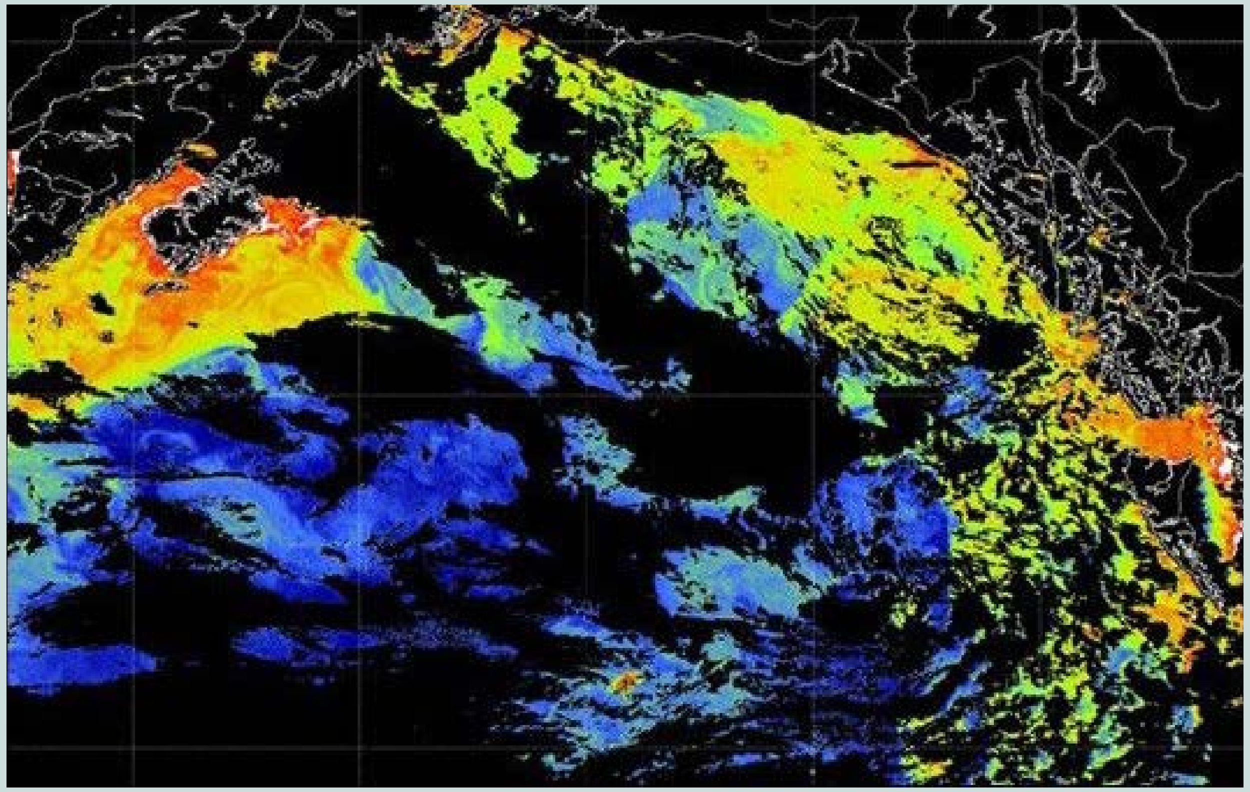

Figure 1. Development of a phytoplankton bloom covering an area approximately 30 km in diameter, induced by iron fertilisation during the SERIES experiment (North Pacific, 2002), as observed by satellite (SeaWiFS, NASA). The red-yellow area corresponds to a high concentration of chlorophyll associated with phytoplankton.

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GEOENGINEERING AND MARINE CARBON DIOXIDE REMOVAL

1 THE MAIN TYPES OF GEOENGINEERING

Two main types of geoengineering are generally distinguished (Figure 2):

- **Firstly, the reduction of incoming solar radiation by reflecting part of the sun's rays into space** gathers a group of approaches known as **solar radiation management*** (SRM). These technologies seek to limit atmospheric warming without addressing the CO_2 and other greenhouse gases (GHGs) that are the root cause of climate change. Highly controversial, they remain largely experimental at this stage, although prospects for deployment are becoming increasingly tangible. Examples include technologies that create reflective white foam on the ocean surface or the injection of sulfur-based aerosols into the stratosphere to reflect incoming solar radiation.

- **Secondly, CDR.** These approaches aim to use technologies or enhance natural processes that capture atmospheric CO_2 and ensure its long-term sequestration. Carbon sequestration can occur in terrestrial or marine soils, or through the restoration of forests, seagrass meadows, and other ecosystems that incorporate carbon into their natural growth cycles. Technological approaches are also being explored, including direct air carbon capture facilities that remove CO_2 directly from the atmosphere. These tend to be more controversial than ecosystem restoration because they are generally riskier and less mature.

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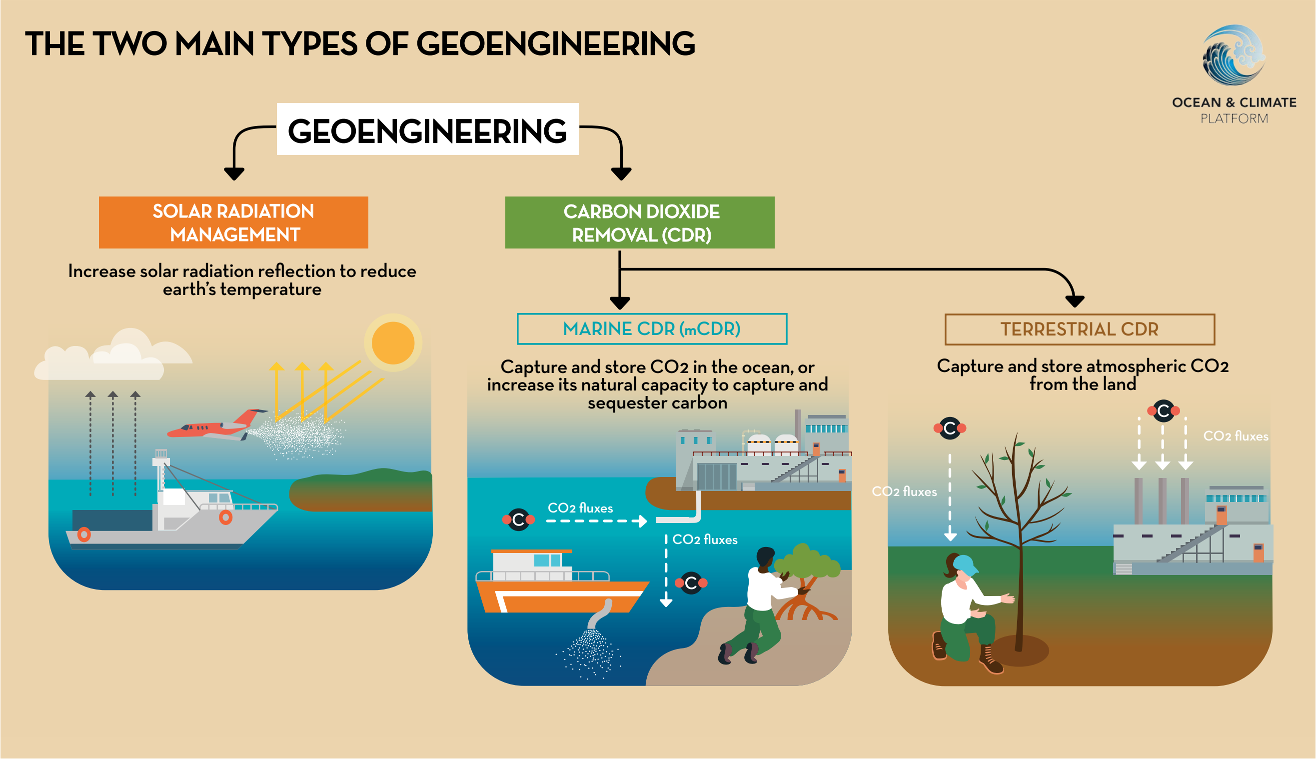

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Figure 2. Diagram illustrating the two main categories of geoengineering: SRM and CDR

2 THE OCEAN: A NATURAL CARBON PUMP

The ocean is a vast reservoir that plays a central role in the global carbon cycle (Figure 4). It contains around fifty times more carbon than the atmosphere. Its capacity to absorb carbon relies on two main processes:

- First, physico-chemical processes allow CO_2 to dissolve in seawater and be transported to the deep ocean through marine currents. This **solubility pump*** accounts for the vast majority of the anthropogenic CO_2 absorbed by the ocean.

- Second, biological processes capture carbon through plankton photosynthesis and the marine food web, with part of this carbon subsequently transferred to the deep ocean as organic matter. "Blue carbon" ecosystems — including mangroves, seagrass meadows, and salt marshes — also contribute to this **biological carbon pump*.**

Carbon fluxes and long-term carbon storage must be distinguished. Although the ocean and the life it supports absorb approximately 300 billion tonnes of CO_2 each year, the vast majority is rapidly released back into the atmosphere, primarily through organisms' respiration, which converts oxygen into CO_2. Only a small fraction of these 300 billion tonnes, around 10 billion (equivalent to roughly one quarter of anthropogenic emissions), is captured and sequestered in the deep ocean for several hundred years, and in some cases, much longer.

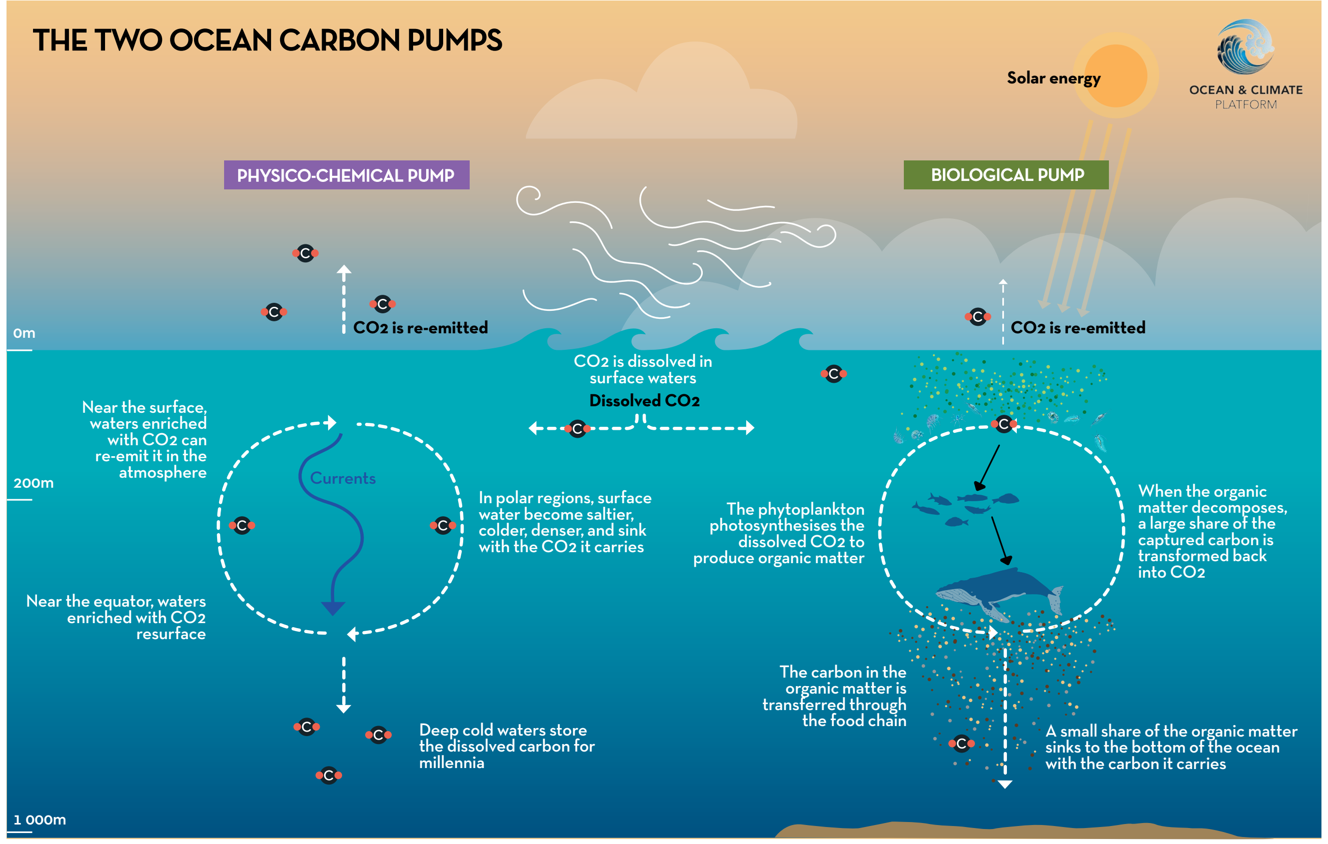

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Figure 3. The ocean's carbon pumps: the physical/solubility pump dissolves and stores CO_2 in the deep ocean, while the biological pump converts it through photosynthesis and transfers part of it to the seafloor through marine food webs.

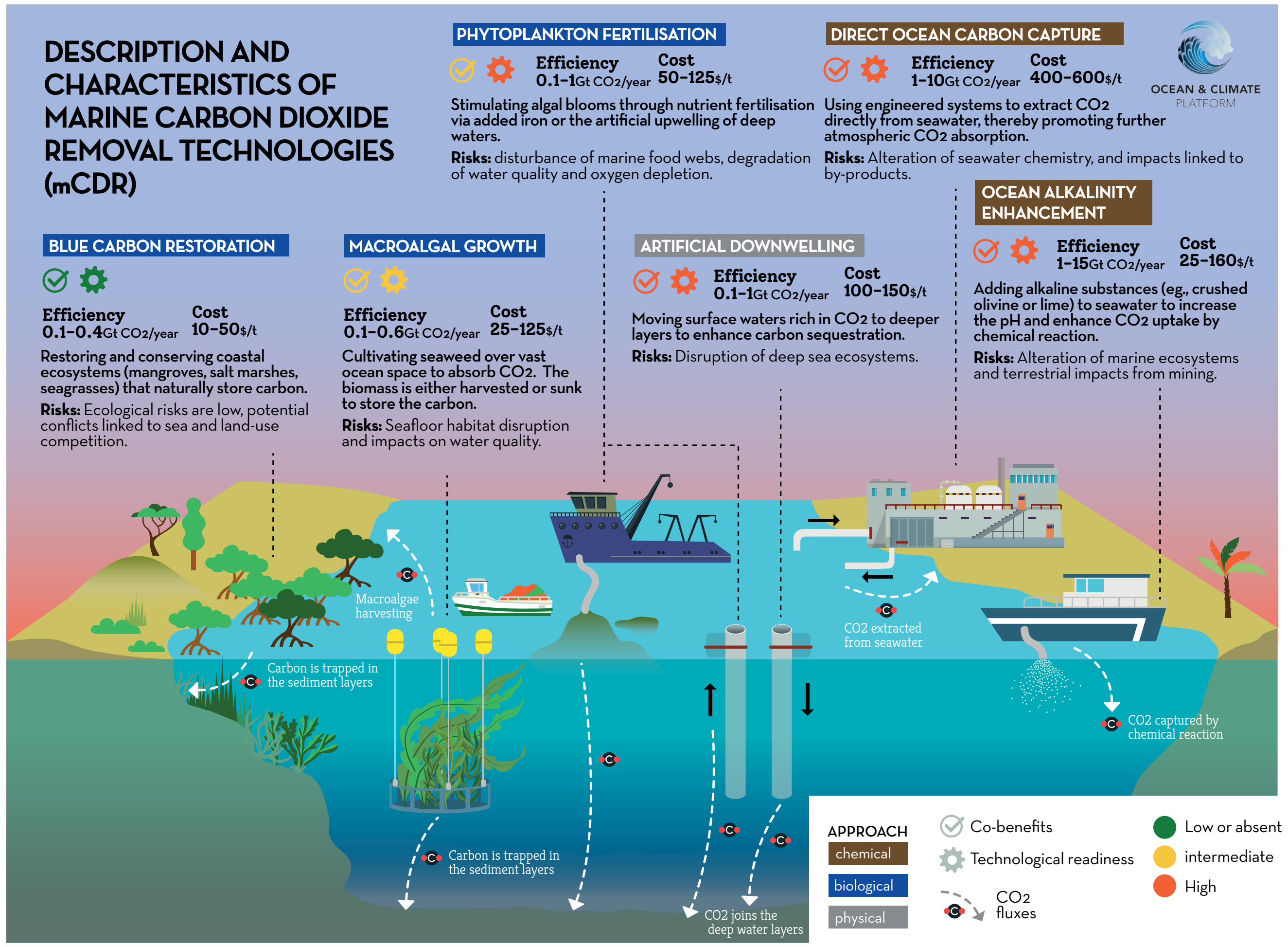
3 MARINE CARBON DIOXIDE REMOVAL TECHNOLOGIES

Three main categories of marine Carbon Dioxide Removal (mCDR) technologies are being explored (Figure 4):

First, biological techniques that rely on photosynthesis. This category involves the restoration of blue carbon* ecosystems, including mangroves, salt marshes, and seagrass meadows, which naturally capture and store CO_2. Conserving and restoring these ecosystems remains the only mCDR approach currently considered free from major ecological risks. It also generally provides significant co-benefits for marine biodiversity conservation. However, its mitigation potential remains limited: current projections suggest that it could remove up to 0.4 Gt of CO_2 per year, equivalent to roughly 1% of global anthropogenic emissions. Other biological approaches include **macroalgae cultivation*** and **ocean iron fertilisation***. Although these methods may offer greater theoretical carbon removal potential than blue carbon restoration, they are associated with higher risks and remain less technologically mature.

Second, chemical techniques that aim to alter the chemical balances of the ocean. These notably include **direct ocean capture*** which relies on a range of processes designed to separate CO_2 from seawater using electrical currents and chemical treatments. The main challenge is technical and economic: extracting CO_2 from seawater remains difficult and expensive. **Ocean alkalinity enhancement*** involves adding alkaline substances (such as minerals or chemical compounds) or removing acidic components from seawater to increase its alkalinity, its capacity to neutralise acids. Dissolved CO_2 then reacts to form bicarbonate (HCO^{3-}) and carbonate (CO_3^{2-}) ions, increasing the ocean's ability to absorb additional atmospheric CO_2. These approaches face significant technical constraints related to the sourcing, processing, and distribution of alkaline materials in the marine environment, and their efficacy remains uncertain. Beyond questions of efficacy, they could contribute to large-scale marine pollution, particularly through the release of metals such as nickel from source minerals.

Third, physical techniques that rely on the movement of water masses. The only physical mCDR technique currently under discussion is **artificial downwelling***. This approach involves transporting CO_2-rich surface waters to the deep ocean using pumps, aiming to replicate the natural physical carbon pump and increase long-term carbon sequestration at depth. At present, this technique remains entirely theoretical. Its implementation could require enormous amounts of energy, potentially conflicting with the broader objective of reducing greenhouse gas emissions from human activities.


DESCRIPTION AND CHARACTERISTICS OF MARINE CARBON DIOXIDE REMOVAL TECHNOLOGIES (mCDR)

PHYTOPLANKTON FERTILISATION
Efficiency 0.1–1Gt CO2/year
Cost 50–125$/t
Stimulating algal blooms through nutrient fertilisation via added iron or the artificial upwelling of deep waters.
Risks: disturbance of marine food webs, degradation of water quality and oxygen depletion.

DIRECT OCEAN CARBON CAPTURE
Efficiency 1–10Gt CO2/year
Cost 400–600$/t
Using engineered systems to extract CO2 directly from seawater, thereby promoting further atmospheric CO2 absorption.
Risks: Alteration of seawater chemistry, and impacts linked to by-products.

BLUE CARBON RESTORATION
Efficiency 0.1–0.4Gt CO2/year
Cost 10–50$/t
Restoring and conserving coastal ecosystems (mangroves, salt marshes, seagrasses) that naturally store carbon.
Risks: Ecological risks are low, potential conflicts linked to sea and land-use competition.

MACROALGAL GROWTH
Efficiency 0.1–0.6Gt CO2/year
Cost 25–125$/t
Cultivating seaweed over vast ocean space to absorb CO2. The biomass is either harvested or sunk to store the carbon.
Risks: Seafloor habitat disruption and impacts on water quality.

ARTIFICIAL DOWNWELLING
Efficiency 0.1–1Gt CO2/year
Cost 100–150$/t
Moving surface waters rich in CO2 to deeper layers to enhance carbon sequestration.
Risks: Disruption of deep sea ecosystems.

OCEAN ALKALINITY ENHANCEMENT
Efficiency 1–15Gt CO2/year
Cost 25–160$/t
Adding alkaline substances (eg., crushed olivine or lime) to seawater to increase the pH and enhance CO2 uptake by chemical reaction.
Risks: Alteration of marine ecosystems and terrestrial impacts from mining.

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Figure 4. Overview of mCDR technologies. This figure summarises the principal ocean-based approaches designed to sequester atmospheric CO_2. For each method, the infographic presents estimated annual removal potential (Gt CO_2 per year), operational costs per tonne of CO_2 removed, as well as levels of technological maturity and potential for these technologies to have social and ecological co-benefits[8].

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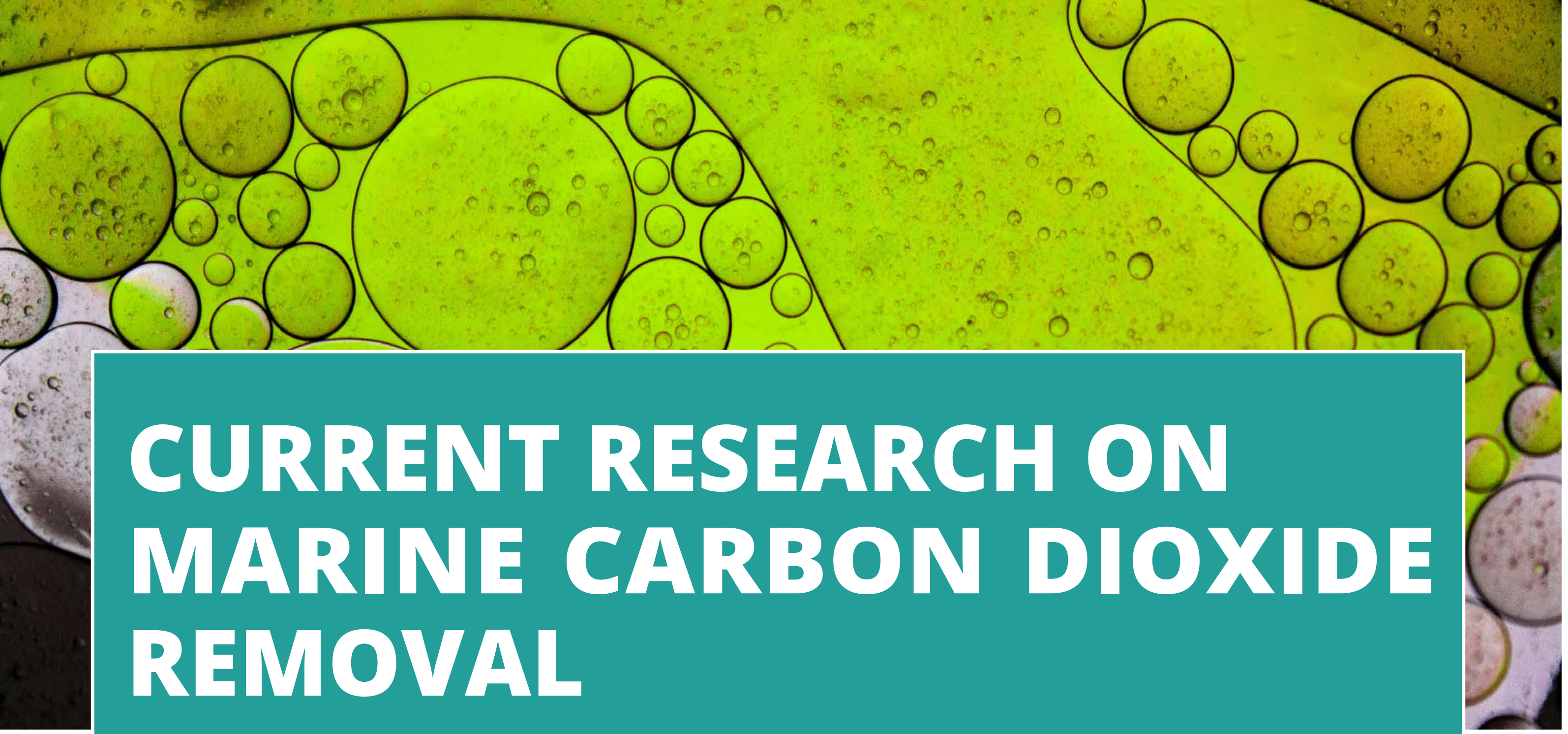
[8] The data and information presented are drawn from a report by the United States National Oceanic and Atmospheric Administration (NOAA): https://sciencecouncil.noaa.gov/wp-content/uploads/2023/06/mCDR-glossy-final.pdf and from a review article: Brun et al. (2026), *Three challenges to marine carbon dioxide removal*, npj Ocean Sustainability.



CURRENT RESEARCH ON MARINE CARBON DIOXIDE REMOVAL

1 FUNDAMENTAL RESEARCH, LABORATORY STUDIES, AND FIELD EXPERIMENTS

Fundamental research: improving our understanding of the carbon cycle

In the context of mCDR, fundamental research focuses primarily on the carbon cycle (Figure 4), which remains complex and poorly understood, largely due to a lack of observational data[9]. These knowledge gaps make it difficult to assess the impacts of mCDR. Strengthening fundamental research on the carbon cycle could be pursued through three main avenues:

- Expanding monitoring networks for key variables such as temperature, salinity, oxygen, and carbon;
- Improving carbon cycle **modelling***;
- Integrating mCDR technologies into these models to simulate their effects.

Such research extends beyond mCDR itself and also contributes to improving predictions of the future impacts of climate change.

Laboratory and mesocosm experiments: testing the efficacy and impacts of mCDR

A **mesocosm*** is a controlled experimental system that reproduces a simplified ecosystem. In the context of mCDR, mesocosm experiments may use large floating enclosures to test different technologies and evaluate both their efficacy and their effects on water quality and species. Similar experiments can also be conducted in laboratories using aquariums or large tanks. For example, a 2023 study conducted by researchers at the University of Antwerp showed that ocean alkalinity enhancement through the addition of olivine minerals led to the accumulation of toxic metals in amphipods — small crustaceans approximately two centimetres long — affecting their growth and reproduction[10]. However, mesocosm studies rely on important simplifications of natural marine ecosystems and are, by nature, limited in both space and time. For this reason, many scientists suggest the need to complement these approaches with experiments conducted in natural environments, a prospect that raises important questions.

9/ Observations used to measure CO_2 fluxes between the atmosphere and the ocean are carried out using ships or buoys. A recent study estimates that SOCAT-based observations cover only about 1.5% of the ocean: Gloege, L., McKinley, G. A., Landschützer, P., Fay, A. R., Frölicher, T. L., Fyfe, J. C., et al. (2021). *Quantifying errors in observationally based estimates of ocean carbon sink variability*. Global Biogeochemical Cycles, 35, e2020GB006788. https://doi.org/10.1029/2020GB006788

10/ Flipkens, G., Horoba, K., Bostyn, K., Geerts, L. J. J., Town, R. M., Blust, R., Acute bioaccumulation and chronic toxicity of olivine in the marine amphipod Gammarus locusta, Aquatic Toxicology, Volume 262, 2023, 106662, ISSN 0166-445X. https://doi.org/10.1016/j.aquatox.2023.106662

Field experiments: studying mCDR under "real-world" conditions

Field experiments refer to trials conducted directly in the ocean to test and monitor the impacts of mCDR technologies at various scales. The best-known examples are ocean fertilisation and ocean alkalinity enhancement, both of which have already been the subject of several experimental trials (Box 1). A major limitation of these experiments lies in the difficulty of measuring all relevant parameters needed to distinguish mCDR-induced impacts from the natural variability of marine environments. For example, because the ocean continuously exchanges CO_2 with the atmosphere across its entire surface, directly measuring a CO_2 flux and attributing it to a specific mCDR intervention can be extremely challenging. Beyond these technical limitations, field experiments remain controversial. They may pose risks to marine ecosystems and coastal communities and could divert funding away from other climate-related research priorities. These concerns have fueled debate over whether such experiments should proceed. As a result, significant disagreement remains regarding the appropriateness of large-scale field trials. Some environmental organisations have called for bans on the most risky experiments. Meanwhile, proponents argue for a gradual approach, beginning with small-scale trials and expanding only if sufficient evidence demonstrates their safety.

2 CAN THE EFFICACY AND POTENTIAL IMPACTS OF MARINE CARBON DIOXIDE REMOVAL BE MEASURED?

Field experiments must ultimately answer **two key questions:**

- Are mCDR technologies effective at capturing and permanently sequestering CO_2?
- What are the positive and negative impacts of these technologies on the environment and the functioning of marine ecosystems?

Addressing these questions requires three complementary and non-interchangeable approaches:

- **Monitoring, Reporting, and Verification* (MRV) protocols** are used to certify that deployed technologies can effectively capture and durably store CO_2. These protocols rely on direct and indirect measurements of carbon, nutrient, and oxygen fluxes in both the atmosphere and the ocean and may be supplemented by model-based results. However, reliance on modelling alone, without direct observation, does not necessarily constitute definitive proof of mCDR efficacy.
- **Impact assessments*** compare the state of socio-ecosystems before and after an experiment and evaluate the consequences of the activities deployed. In practice, however, the vast scale of the ocean, the connectivity of marine ecosystems, and the complexity of socio-ecosystems make it difficult, if not impossible, to identify all potential impacts. The key question thus lies in whether there is sufficient evidence for each technique to demonstrate its safety for ecosystems and human societies before deployment. Furthermore, assessing cumulative impacts remains a significant scientific challenge.
- **Life-cycle assessments* (LCAs)** are used to identify the energy requirements and the environmental, social, and economic impacts of a project from its beginning to its end. For mCDR, LCAs allow for the accounting of all carbon emissions associated with a project, as well as the material, energy, and transportation costs linked to the processes and infrastructure involved. However, life-cycle assessments are not systematically conducted or incorporated into mCDR feasibility studies, underestimating the challenges associated with scaling up these approaches, particularly regarding energy and material requirements.

3 PUBLIC AND PRIVATE ACTORS

In its early years (1980s-2000s), most mCDR research was conducted by academic institutions and supported by public funding, particularly for ocean fertilisation. Over time, private actors began to engage with the sector, recognising potential commercial and economic opportunities (Box 1).

Today, tens — if not hundreds — of emerging start-ups are active in the mCDR space. These companies are exploring a wide range of approaches, from ocean alkalinity enhancement and large-scale seaweed cultivation, to direct ocean carbon capture. They are also involved in related activities such as carbon removal monitoring, reporting and verification, certification, and environmental impact assessments. This diversity of technologies, business models, and geographical contexts makes it difficult to comprehensively track all actors involved and to develop regulatory frameworks capable of addressing such varied activities.

At present, mCDR companies are financed through a combination of public grants, philanthropic funding, private investment, and pre-sale of carbon credits (see Box 2). Research on mCDR is also supported by public institutions, particularly academic organisations, which may collaborate with or provide expertise to private companies. Given the ethical questions raised by field experiments and technology deployment, a number of voluntary best-practice guidelines have recently been developed to help guide mCDR research. These include guidance produced by organisations such as the American Geophysical Union[11], which encourages adherence to the principles of climate justice, transparency, and meaningful public participation. Although these frameworks were explicitly designed to inform mCDR projects, they remain non-binding, relatively general in scope, and are not yet integrated into formal governance systems.

More broadly, climate research and ocean observation programs are being affected by the current international political and economic context, including significant budget reductions in some countries[12]. Growing interest in mCDR research, combined with concerns surrounding private-sector influence and investment, may strengthen the case for increased public funding to support more independent scientific research. At the same time, directing additional public resources toward mCDR research could come at the expense of other critical areas of climate action, including emissions reduction and climate adaptation research. Striking the appropriate balance is particularly challenging in a geopolitical and economic context characterised by increasing competition for limited research funding and the accelerating impacts of climate change.

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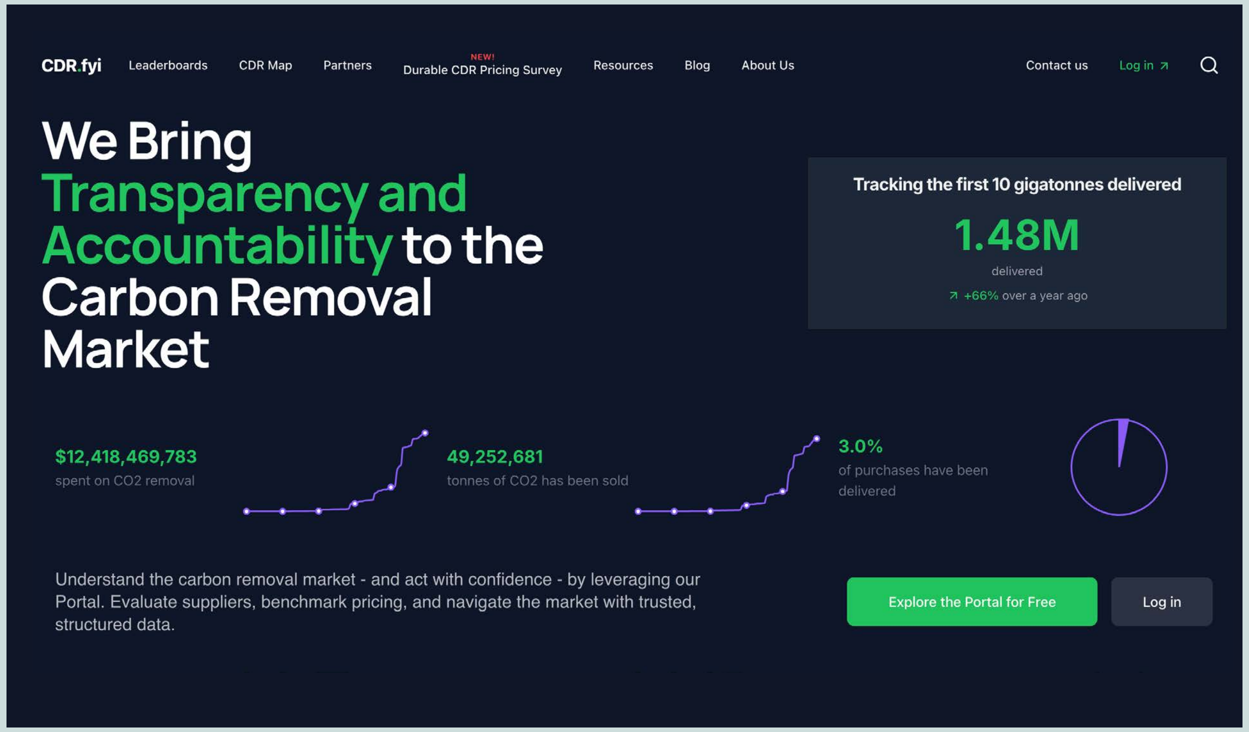
[11] The American Geophysical Union's guidance on field trials for carbon dioxide removal identifies five key principles for their deployment: (i) responsible research, (ii) integrated climate justice, (iii) inclusive public participation, (iv) transparency, and (v) informed governance.
American Geophysical Union. Ethical Framework Principles for Climate Intervention Research. ESS Open Archive. October 17, 2024.
https://essopenarchive.org/doi/full/10.22541/essoar.172917365.53105072/v1

[12] Last year, the Trump administration announced plans to cut the budget of the U.S. National Oceanic and Atmospheric Administration (NOAA), affecting global ocean observation. https://www.theguardian.com/us-news/2025/apr/23/noaa-non-science-trump-cuts

Box 2.

UNDERSTANDING CARBON CREDITS

Carbon credits are certificates that verify the removal of a given quantity of carbon by a CDR technique. They are sold by private actors to emitting companies seeking to offset their emissions. These transactions take place within the **voluntary carbon market*** as they occur outside of legally binding decarbonisation obligations. In recent years, the emergence of mCDR and the first experimental trials have been accompanied by the pre-sale of carbon credits. In New Zealand, for example, the company Gigablue, which is conducting ocean fertilisation trials, has signed an agreement to sell more than 200,000 tonnes of carbon credits to the aviation company SkiesFifty, which must be removed by 2029. The website www.cdr.fyi tracks carbon credit sales worldwide. Of the 736,000 mCDR carbon credits sold to date (June 2026), representing an equivalent number of tonnes of CO$_2$, less than 4% are considered to have been delivered — that is, verified either by the company itself or by an independent third party. Moreover, the majority of these credits have been sold by a single company, Running Tide[13].



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1.48M
delivered
↗ +66% over a year ago

$12,418,469,783
spent on CO2 removal

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tonnes of CO2 has been sold

3.0%
of purchases have been delivered

Understand the carbon removal market - and act with confidence - by leveraging our Portal. Evaluate suppliers, benchmark pricing, and navigate the market with trusted, structured data.

Figure 5. The website www.cdr.fyi reports more than $12 billion worth of carbon credits sold to date, of which only 3% have so far been issued by companies. This last figure is also uncertain in the absence of a centralised and independently verified register.

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[13] Running Tide has been the subject of significant controversy regarding the scientific validity and verification of its carbon credits. An investigation published by WIRED in December 2025 highlighted, in particular, the lack of independent validation for many of the credits sold, uncertainties surrounding the actual effectiveness of the claimed carbon sequestration, and the potential environmental impacts of the company's operations in Iceland.
https://www.wired.com/story/how-the-next-big-thing-in-carbon-removal-sunk-without-a-trace/

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MARINE CARBON DIOXIDE REMOVAL, A RISKY GAMBLE

Given the still-limited knowledge regarding the effectiveness and risks of mCDR technologies, they cannot be considered an immediate solution to climate change. More specifically, these technologies currently face three major limitations (Figure 6):

- A lack of knowledge concerning their actual effectiveness and their impacts on carbon storage, ecosystems, and societies;
- Ecological and social risks associated with their development and potential deployment;
- Fragmented and insufficient international governance to regulate them.

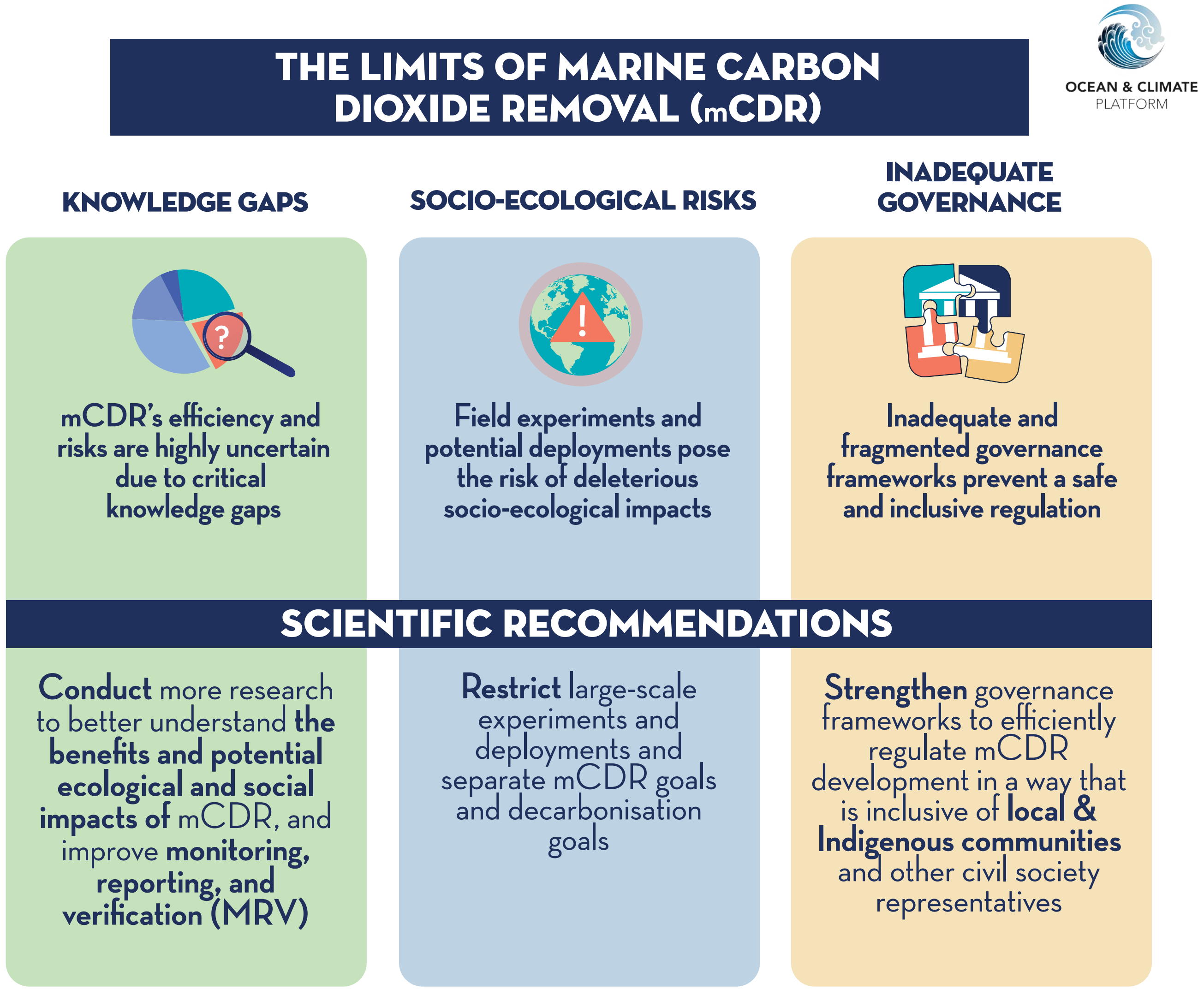

Figure 6. The main challenges associated with mCDR are the lack of scientific knowledge, socio-ecological risks, and inadequate governance. These limitations, as well as recommendations for addressing them, are drawn from the scientific literature and summarised in a recently published article[14].

[14] See: Brun V. et al. (2026), Three Challenges to Marine Carbon Dioxide Removal, *npj Ocean Sustainability*.

1 A LACK OF KNOWLEDGE TO ASSESS THE EFFECTIVENESS AND RISKS OF mCDR

Based on current knowledge, none of the mCDR technologies is sufficiently mature or well understood to be deployed, except for blue carbon ecosystem restoration[15]. In addition to the lack of knowledge on ecosystems' responses to mCDR and the effectiveness of these methods, other questions remain unresolved today: what financial resources could be allocated to field trials? What level of risk is acceptable to consider the development of these technologies? What level of oversight and what constraints should be applied? Beyond scientific and technical uncertainties, the development of mCDR research also raises ethical, political, governance and policy questions. The very act of researching these technologies may gradually increase their legitimacy and social and political acceptability.

2 ECOLOGICAL AND SOCIAL RISKS

Beyond the ecological risks associated with mCDR (Box 1 & Figure 4), these technologies are already affecting local communities in areas where pilot projects have been proposed or implemented. In Cornwall, for example, an ocean alkalinity enhancement project led by Planetary Technologies generated significant local opposition, notably through the "Keep Our Sea Chemical Free!" campaign, ultimately leading to the project's cancellation[16]. Critics highlighted the lack of public consultation, concerns over potential ecological impacts on coastal environments, scientific uncertainties regarding effects on marine ecosystems, and the intention to generate and sell carbon credits linked to the initiative.

Controversies surrounding mCDR projects are therefore not only driven by environmental concerns, but also by issues of governance, procedural justice, and social acceptability. Impact assessments do not systematically evaluate the potential cost-benefit balance of these approaches, nor the transparency and inclusiveness of decision-making processes. As a result, tensions and conflicts with local stakeholders may intensify, while existing grievances can be further exacerbated.

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[15] According to NOAA's classification of CDR technology readiness levels, blue carbon conservation and restoration is the only mCDR approach associated with a high level of technological maturity. https://repository.library.noaa.gov/view/noaa/52072

[16] A documentary was produced on the topic, it is available on YouTube.

3 A FRAGMENTED AND INADEQUATE GOVERNANCE

The current legal framework is not adapted to the specific characteristics of mCDR technologies. Although general principles of international law apply, such as the precautionary principle and the polluter-pays principle, no instrument of international law has been specifically designed to regulate mCDR. This regulatory gap, therefore, leaves important questions unanswered, particularly regarding the deployment of field trials and liability in the event of environmental impacts.

For the time being, existing frameworks primarily aim to prevent environmental harm. For example, the **Convention on Biological Diversity*** established a *de facto* moratorium in 2010, requiring that no geoengineering activity take place without a sufficient scientific basis and adequate risk assessment. Similarly, the **London Convention and Protocol***, which regulates the dumping of waste at sea, restricts ocean fertilisation to "legitimate scientific research" and seeks to extend this approach to other mCDR technologies. However, these decisions are not legally binding, and the effect of the London Protocol will remain limited until the 2013 amendments concerning marine geoengineering enter into force.

Furthermore, because marine ecosystems are interconnected, any mCDR activity may have transboundary consequences, even if it is carried out within the waters of a single State. The new **BBNJ Agreement* on the high seas,** which recently entered into force, could provide a framework relevant to the environmental safety of these activities. Although it offers tools for regulating and assessing the environmental impacts of activities taking place on the high seas, how these provisions may apply to mCDR remains to be clarified.

Other recent developments are also influencing the debate. In May 2024, the International Tribunal for the Law of the Sea issued a landmark advisory opinion stating that GHG emissions from human activities constitute a form of marine pollution under the United Nations Convention on the Law of the Sea. Signatory States therefore have an obligation to take all necessary measures to prevent such pollution and protect the marine environment from warming, sea-level rise and ocean acidification. Although not legally binding, this opinion could contribute to the evolution of international norms and influence how States regulate mCDR in the future.

Box 3.

A POLICY BRIEF TO BETTER INFORM THE GOVERNANCE OF mCDR

As interest in mCDR grows, major questions remain regarding its effectiveness, environmental risks, and their social and economic implications. To inform debates on this emerging and complex issue, the Ocean & Climate Platform has developed a set of recommendations for decision-makers[17], aimed at promoting safe and equitable research while preventing premature deployment.
It should be noted that marine CDR technologies are not, to date, climate change mitigation solutions, and that the priority must remain the urgent and substantial reduction of greenhouse gas emissions. Scientific research is nevertheless necessary to better understand their potential, limitations, and risks, provided that it is governed by robust safeguards, particularly environmental and social ones. Finally, it appears essential to strengthen and harmonise the governance framework for marine CDR, which is currently fragmented, in order to regulate research and avoid any premature deployment of these approaches.

[17] / Ocean & Climate Platform (2026), Navigating Hopes and Threats: How Precaution Should Guide Marine Carbon Dioxide Research and Governance, Policy Brief.

4 ETHICAL QUESTIONS

The development of mCDR activities also raises ethical questions, including:

- **Intergenerational justice and mitigation deterrence.** The promise of a technological solution to climate change through geoengineering poses a dual risk to the ecological transition. On the one hand, it represents an uncertain gamble on the future: incorporating unproven technologies into long-term decarbonisation strategies effectively shifts the burden of action, and potentially amplifies climate impacts, onto future generations. On the other hand, this prospect could divert attention and substantial financial resources away from the urgent mitigation of and adaptation to climate change; this is referred to as a **moral hazard***. Planning for a large-scale, albeit uncertain, reliance on mCDR may therefore weaken collective action by making decarbonisation efforts appear unnecessary in the eyes of both the public and decision-makers.

- **Assessing and weighing actual CDR needs.** While IPCC reports emphasise the need for CDR, to meet the objective of limiting global warming to 1.5°C or 2°C, the volumes of CDR required are not the result of an absolute fatality but rather of political choices. Current pathways often incorporate socio-economic assumptions (continued material growth, delayed implementation of sufficiency measures) that mechanically increase future dependence on carbon removal technologies. Assessing these needs, therefore, constitutes a major ethical issue, as alternative societal choices based on immediate structural transformations would drastically reduce the need for CDR.

- **The risks of large-scale manipulation of the Earth system.** Geoengineering proposes to mitigate anthropogenic climate change through technological interventions in the Earth system. However, the science of these complex systems demonstrates that human interventions in the biosphere carry significant risks of unforeseen feedbacks. Environmental history illustrates this limitation: past failures involving the introduction of species to control other invasive species remind us that modifying complex systems often produces harmful unintended consequences.

- **The commodification of mCDR and conflicts of interest.** The role of the private sector raises ethical concerns regarding the commodification of a response to a global problem. As with biomedical research, for example, the development of mCDR seeks to provide solutions to a global crisis affecting humanity as a whole. However, the development and commercialisation of technologies, infrastructure or associated carbon credits could enable companies to generate substantial profits. Similar to the regulation of the pharmaceutical industry, mCDR therefore requires robust regulatory frameworks governing research practices, data transparency and result sharing, in order to ensure that financial interests do not take precedence over the public interest.

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Conclusion: a growing controversy

While the climate urgency calls for concrete, rapid and effective action, the large-scale reduction of greenhouse gas emissions remains the absolute priority for preserving a habitable future for our planet and the life it supports. At this stage, marine carbon dioxide removal technologies cannot be considered proven solutions for climate change mitigation. Their actual potential, costs and externalities, energy and material requirements, and their impacts on marine ecosystems and human societies, remain too uncertain. If certain mCDR approaches are to be pursued, they should be developed within a strictly regulated, transparent, independent and research-oriented framework, excluding any premature deployment. Experimental activities should be limited to technologies presenting low risks and, where possible, co-benefits for biodiversity and coastal communities. They should also be accompanied by robust monitoring, reporting and verification protocols, comprehensive impact assessments, life-cycle analyses, and meaningful participation of affected stakeholders. In this context, mCDR should be regarded as a field of research rather than a technological promise ready for large-scale deployment. Its development raises major scientific, ecological, social, legal and ethical questions: risks of irreversible damage, an international governance framework that remains fragmented, the commodification of carbon credits, conflicts of interest, and the potential undermining of decarbonisation efforts. Caution requires focusing on the priorities: reducing GHG emissions, strengthening the protection of marine ecosystems, and considering mCDR only under robust scientific and democratic safeguards.

Glossary

Artificial upwelling/downwelling	The use of technologies to induce the forced upwelling or downwelling of water, to stimulate phytoplankton production or store carbon at depth.
BBNJ Agreement	Agreement on Biodiversity Beyond National Jurisdiction, adopted in June 2023 and entered into force in January 2026. It establishes, among other things, procedures for the implementation of area-based management tools such as marine protected areas, environmental impact assessments, the fair and equitable sharing of genetic resources, capacity building, and the transfer of marine technology.
Biological carbon pump	Collection of biological processes in the ocean that transfer carbon from surface waters to the deep ocean through marine food webs.
Blue carbon	Carbon captured and stored by coastal and marine ecosystems such as mangroves, seagrass meadows and salt marshes.
Carbon credits	Certificate representing the removal of a defined quantity of carbon through a carbon dioxide removal (CDR) technique. These credits are sold to companies to offset their emissions.
Carbon dioxide removal (CDR)	Human interventions designed to remove greenhouse gases from the atmosphere and durably store them in natural or engineered reservoirs.
Carbon neutrality	Situation in which CO_2 emissions generated by human activities are reduced as much as possible and then balanced by equivalent removals, resulting in net-zero CO_2 emissions.
Convention on Biological Diversity (CBD)	International convention adopted in 1992 at the Rio Earth Summit. It entered into force in 1993 and has been ratified by 196 Parties. It aims to conserve biodiversity, ensure the sustainable use of its components, and promote the fair and equitable sharing of benefits arising from the use of genetic resources.
Deoxygenation of the ocean	Progressive decrease in the level of dissolved oxygen in marine waters, mainly caused by global warming and nutrient pollution.
Geo-engineering	Set of technologies aimed at deliberately altering environmental conditions to mitigate or compensate for the impacts of climate change.
Impact assessment	Studies that evaluate the environmental impacts of a project by comparing them against a baseline condition established beforehand.
Life cycle assessment	Method for assessing the environmental impacts of a product or technology across its entire life cycle, including preparation, deployment and end-of-life stages.

Macroalgae cultivation	An mCDR technique involving the large-scale cultivation of macroalgae to absorb CO_2. The resulting biomass is either harvested and used or stored on land, or allowed to sink naturally or artificially to the seabed.
Marine carbon dioxide removal (mCDR)	Carbon dioxide removal technologies that seek to artificially enhance the ocean's natural capacity to remove atmospheric CO_2 (see biological carbon pump and solubility pump).
Mesocosm	A medium-scale experimental system designed to replicate and control an ecosystem to study biological and ecological responses to environmental changes.
Modelling	A technique used to represent an object, system or process in a virtual environment using computers and specialised software in order to test its functioning and predict its behaviour.
Monitoring, reporting, and verification (MRV)	Scientific methods combining in situ measurements, sensors, and ocean modelling to accurately quantify and certify the CO2 effectively removed from the ocean and atmosphere, as well as the durability of its storage.
Moral hazard	When the perception of the existence of a technological solution to climate change may reduce efforts to decrease greenhouse gas emissions.
Ocean acidification	Decrease in ocean pH caused by increasing concentrations of CO_2 dissolved in seawater.
Ocean alkalinisation	Increase in ocean pH resulting from the addition of alkaline substances (carbonate or silicate rocks) to seawater.
Ocean fertilisation	A human intervention that aims to enhance phytoplankton production through photosynthesis by adding limiting nutrients such as iron.
Paris Agreement	International treaty adopted in December 2015 as part of COP21 and entered into force in November 2016. Signed by 195 countries, it aims to strengthen the global response to climate change. One of its main objectives is to limit global temperature rise to 1.5°C above pre-industrial levels.
Solar Radiation Management (SRM)	Geoengineering approaches that aim to reduce incoming solar radiation by reflecting a portion of the sunlight into space to cool the atmosphere.
Solubility pump	The collection of physico-chemical processes in the ocean that enable the dissolution of CO_2 and its transfer to deeper waters.
The London Convention and Protocol	International treaty adopted in 1972 and entered into force in 1975, aimed at preventing marine pollution caused by the dumping of wastes and other matter at sea. The Convention is complemented by the London Protocol, adopted in 1996 and entered into force in 2006, which is intended to eventually replace the Convention.
United Nations Framework Convention on Climate Change	Convention adopted in 1992 at the Rio Earth Summit. It entered into force in 1994 and has been ratified by 198 Parties. This framework for international cooperation aims to stabilise greenhouse gas emissions at a level that would prevent dangerous anthropogenic interference with the Earth system.
Voluntary carbon market	Market that allows companies and individuals to offset their greenhouse gas emissions by purchasing carbon credits without any regulatory obligation or legal requirement.

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