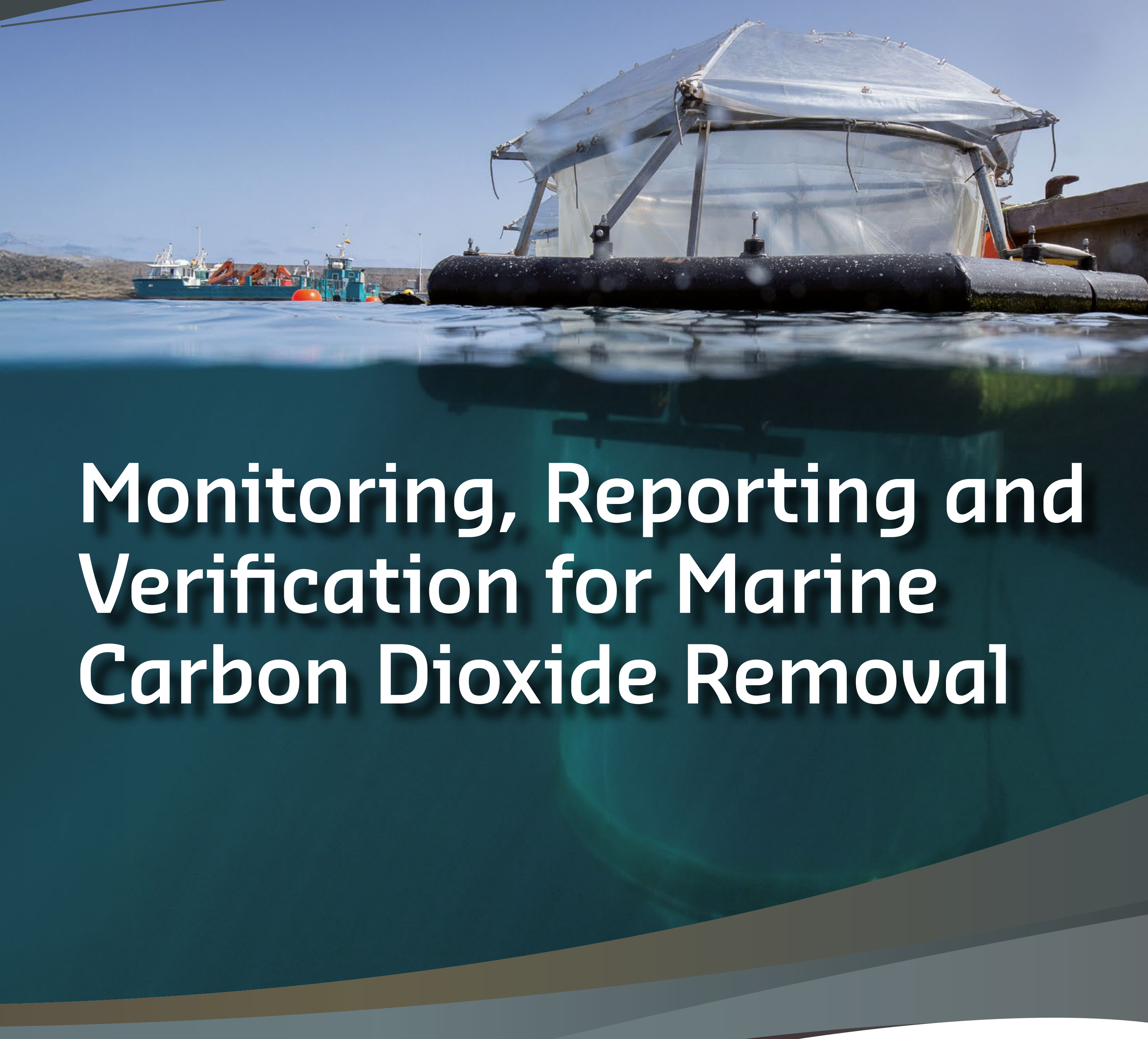
Future Science Brief Nº 13 November 2025



Monitoring, Reporting and Verification for Marine Carbon Dioxide Removal

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European Marine Board IVZW

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European Marine Board IVZW Future Science Brief N° 13

This Future Science Brief is a result of the work of the European Marine Board Expert Working Group on Marine Carbon Dioxide Removal. See Annex 1 for the list and affiliations of the Working Group Members.

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Mesocosm experiment as part of an Ocean Alkalinity Enhancement trial. Credit: Michael Sswat, GEOMAR

First edition, November 2025

In this document, Artificial Intelligence-powered tools Grammarly, ChatGPT and InstaText have been used to assist with the language editing. Artificial Intelligence has not been used for any key writing task, such as producing scientific insights, creating a literature review, drawing scientific conclusions or providing recommendations.

Foreword

The European Union (EU) is committed to achieving the goals of the 2015 Paris Agreement to keep the global temperature rise this century to well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C. With the European Climate Law of 2021, the EU has to reduce emissions by at least 55% by 2030, compared to 1990 levels, reach net zero greenhouse gas emissions by 2050, and negative emissions after 2050. Although reducing emissions is vital to achieving these objectives, deployment of methods to capture carbon dioxide from the atmosphere and storing it long-term, or carbon dioxide removal (CDR), is now considered an option.

The potential of the Ocean to store carbon dioxide is substantial compared to land. Marine CDR methods are currently being explored and tested by publicly funded research and private entities yet the outcomes remain highly sensitive to subsequent human activities and the effects can be unpredictable due to the complexities involved. Subsequently, for marine CDR to be deployed responsibly, high-quality standards in terms of Monitoring, Reporting and Verification (MRV) will be required. MRV is essential to evaluate the efficacy and possible environmental impacts of the methods being tested in controlled field trials, and to assess if they are viable for future deployment at scale. Observing platforms combined with complex modelling methodologies, open data and future Digital Twins, combined with robust regulations, governance and international cooperation will all be required for informed MRV protocols for marine CDR. MRV is also crucial for ensuring that CDR deployments generate the promised climate benefits and for the transparent and ethical regulation of a growing carbon removal market.

In Autumn 2023, the topic of MRV for marine CDR was selected by the European Marine Board (EMB) as a new Working Group topic. EMB Delegates highlighted that learning about the challenges for achieving robust, transparent and scientifically underpinned MRV frameworks for marine CDR, and how to overcome them, will help society and policymakers to make well-informed decisions for achieving climate goals at national, European and international level. The Working Group kicked-off in August 2024 with a meeting at the InnovOcean Campus (Ostend, Belgium) hosted by the EMB Secretariat.

I am pleased to present this strategic document that highlights the need for robust MRV frameworks for marine CDR methods, which, if proven effective, could contribute to climate mitigation. It identifies current knowledge gaps, challenges and uncertainties in developing transparent and standardised MRV systems, and provides a detailed set of recommendations to policymakers and regulators, science funders and to those practitioners at the forefront of these endeavours.

On behalf of EMB, I extend my gratitude to the Working Group Members for their collaborative effort in writing this document within such a remarkably short timeframe. I want to especially mention Helene Muri and Olivier Sulpis for their leadership, and the external reviewers and the experts at the EMB Member organisations for their constructive comments. Finally, I would like to thank the EMB Secretariat, in particular Ángel Muñiz Piniella and Ana Rodriguez, for the coordination of the Working Group from inception right through to publication. It is always appreciated.

Fiona Grant
Chair, European Marine Board
November 2025

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Executive summary

Meeting the goals of the Paris Agreement requires rapid and sustained reductions in greenhouse gas emissions, which is a critical priority. In addition, substantial amounts of carbon dioxide removal (CDR) from the atmosphere through human activities are included in scenarios of the Intergovernmental Panel on Climate Change (IPCC) to limit temperature increase to 1.5°C. Marine CDR (mCDR) methods could support reducing atmospheric CO_2 concentrations by leveraging the Ocean's capacity to absorb CO_2. However, any implementation would require improved observations and understanding of all carbon flows affected by mCDR to ensure accurate accounting of net CO_2 removal. Moreover, if mCDR methods are to be scaled-up to help reach climate targets, a robust, consistent Monitoring, Reporting and Verification (MRV) framework must be developed to ensure transparent, accurate and reproducible accounting of net CO_2 removal and potential impacts of mCDR methods. This document hence focuses on MRV for mCDR methods.

MRV is a comprehensive framework that quantifies net greenhouse gas removals, including CO_2 and non-CO_2 gases, relative to a counterfactual/baseline, assesses the durability of carbon storage, and evaluates uncertainties. MRV also encompasses Life Cycle Assessments (LCAs) of supply-chain emissions and resource use. MRV should also encompass the quantification of environmental and ecological impacts known as environmental MRV (eMRV). Robust MRV involves integrating observational and modelling methods across relevant spatial and temporal scales, provides transparent reporting of results, and enables independent third-party verification to support credible carbon accounting, governance and market mechanisms for mCDR.

At present, all mCDR methods remain at early research or small pilot scale, with none yet demonstrated at large-scale deployment. Consequently, mCDR methods do not have sufficiently robust, comprehensive MRV in place to enable credible large-scale implementation. The MRV landscape remains fragmented, with jurisdictions at different stages of development and varying, overlapping protocols for different mCDR methods. Key MRV challenges include: accounting for greenhouse gases beyond CO_2; defining baselines and additionality, where additionality refers to the CO_2 removed by mCDR that would not have been removed from the atmosphere in the absence of mCDR; quantifying the duration of carbon storage; performing LCAs; evaluating environmental impacts; and addressing the co-deployment of different mCDR methods.

The recommendations of this Future Science Brief highlight current knowledge gaps and the need to establish standardised MRV protocols for mCDR. This document aims to clarify the current scientific, technical and policy challenges that must be addressed to develop appropriate and reliable MRV for any future mCDR activities. It does not take a position on whether mCDR should be pursued. However, the development of robust, method-specific MRV protocols, demonstrated to detect, attribute, and verify net removals while transparently accounting for uncertainties in a manner suitable for policy and market use, is vital if mCDR approaches are to be scaled up or deployed alongside other methods. CDR is not a substitute for reducing emissions, but it may serve as a supplementary measure to help achieve the goals of the Paris Agreement.

We recommend that rapid reductions in CO_2 emissions remain the top priority in efforts to reach these goals.

Further to this, we recommend:

Recommendations for policymakers and regulators:

(1) Develop a standardised, comprehensive, regulatory framework for MRV, to overcome the fragmentation, inconsistencies and lack of global governance of existing MRV systems;

(2) Standardise the collection and reporting of mCDR MRV information across diverse regulatory fora, rather than relying on non-binding standards from private initiatives;

3) Develop regulations for baseline monitoring that cover both carbon and ecology (water chemistry, biodiversity, habitat). Use these baselines to establish additionality for MRV and to detect/attribute ecological effects, with pre-defined indicators and adaptive triggers;

(4) Develop cost-effective, standardised and sustained long-term monitoring and observing systems for carbonate system variables that verify durability and net CO_2 removal of mCDR, and complement these with modelling and machine learning when high-frequency or long-term measurements are not feasible;

5) Limit scaling and co-deployment of mCDR methods until MRV protocols for individual methods have been proven and assess changes in efficacy and the practicalities of undertaking robust MRV in co-deployment scenarios; and

(6) Consider the requirements of key legislation, such as the Water Framework Directive, the Marine Strategy Framework Directive, the Nature Directives (Birds and Habitats Directives), the Nature Restoration Regulation, the Nitrates Directive and the Maritime Spatial Planning Directive, for the implementation and monitoring of mCDR methods in the European Union.

Recommendations for national, European and philanthropic science funders:

(7) Fund projects to establish baseline carbon fluxes and sinks, particularly those that support development of instruments allowing high-frequency, long-term, *in situ* carbonate system measurements. These baselines are essential for MRV, as accurate long-term data enhances the assessment of how different mCDR methods contribute to carbon storage;

(8) Fund projects that produce observational data for the purpose of validating and refining models, particularly on deep-Ocean processes. Such projects will help fill critical gaps in our understanding of deep-Ocean dynamics, thereby enhancing the accuracy of models used for MRV for mCDR. This is essential for developing better strategies for possible deployment and understanding the potential impacts on marine environments;

(9) Fund projects to investigate how biological processes respond to environmental change as part of MRV assessments, to ensure the direction and magnitude of these changes are acceptable and do not comprise Ocean health. Accurately assessing how biological processes adapt to environmental shifts will directly impact both the effectiveness and the sustainability of various mCDR methods;

(10) Fund projects to close knowledge gaps on the long-term efficacy, environmental impacts and scalability of mCDR methods. This includes projects aimed at understanding the dynamics and fate of organic carbon and total alkalinity, providing insight into the effectiveness of mCDR methods in carbon storage and their impacts on overall carbon cycling;

(11) Require transparent data-sharing policies, as well as open-access publications and project outcomes in all funded projects related to MRV and mCDR;

(12) Support practical applications of real-world MRV for mCDR, to complement the fundamental research behind mCDR methods; and

(13) Support multidisciplinary and trans-disciplinary MRV research projects that scope and map the regulatory landscape, while actively engaging stakeholders and local communities. These projects should involve a broad range of experts, promote collaboration and facilitate community involvement so that MRV projects benefit both society and the environment.

Recommendations for MRV scientists, practitioners and project planners:

(14) Establish robust local-, regional-, and large-scale baselines in terms of carbon fluxes and sinks to support quantification of additional carbon removal;

(15) Quantify uncertainties in MRV protocols for CO_2 removal across different scales, including instrumental precision, measurement accuracy, temporal and spatial variability, and model prediction fidelity;

(16) Determine thresholds for unacceptable ecological and environmental side effects that would trigger policy or management response, such as the cessation or temporary suspension of a mCDR deployment. These thresholds should be set independently of method performance and should be integrated into broader cost-benefit or Life Cycle Assessments that weigh ecological risks against potential carbon removal benefits;

(17) Quantify the durability of the CO_2 removal, in addition to its magnitude, as part of MRV for mCDR methods. This involves assessing how long the captured CO_2 will remain stored, quantifying uncertainty of such estimates, and the potential for any future release back into the atmosphere;

(18) Establish how interactions between various mCDR methods being co-deployed may be credited within MRV and carbon removal accounting frameworks;

(19) Conduct rigorous Life Cycle Assessments (LCAs) to quantify the net carbon removal effects through mCDR methods. This analysis should consider all stages, from production to long-term storage of carbon, to understand the carbon footprint and impacts of the mCDR methods employed;

(20) Develop standardised environmental MRV (eMRV) guidance and baselines, including protocols, methods, Quality Assurance/Quality Control, and data standards for detecting and attributing ecological impacts and non-CO_2 forcers;

(21) Describe environmental and ecological risks in MRV assessments, at least qualitatively. Any potential risks to ecosystems and biodiversity should be considered alongside the benefits of carbon removal efforts and should be quantified where possible; and

(22) Follow ethical principles and codes of conduct for research and prioritise funding from transparent sources. Scientists and practitioners should commit to being transparent (in terms of data - ensuring FAIR data stewardship, approaches and funding), be independent of funding bodies, and seek financial support from sources where the origin and purpose of the funds are clear, e.g. from the European Commission or national research councils.

2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

Contribution to the UN Decade Challenges

This Future Science Brief and its recommendations support the UN Decade of Ocean Science for Sustainable Development's (Ocean Decade) challenges (C1 – C10) in the following ways:

- **'Unlock ocean-based solutions to climate change' (C5)** by recommending to establish robust, globally consistent monitoring, reporting and verification (MRV) framework for marine carbon dioxide removal (mCDR) methods, as a possible additional measure that may be required to complement rapid CO_2 emissions reduction.
- **'Expand the Global Ocean Observing System' (C7)** by promoting continued support for sustaining long-term Ocean carbon observing systems, as well as establishing new *in situ* observing facilities, and addressing knowledge gaps and uncertainties in current modelling capabilities.

Contribution to the EU Mission: Restore our Ocean and Waters

This Future Science Brief and its recommendations support the objectives of the EU Mission: Restore our Ocean and Waters in the following ways:

- **'Make the sustainable blue economy carbon-neutral and circular'** by promoting rapid CO_2 emissions reduction, and by demanding a robust, globally consistent monitoring, reporting and verification (MRV) framework for marine carbon dioxide removal (mCDR) methods, encompassing greenhouse gas removal monitoring, transparent result reporting, and third-party verification.

And the cross-cutting enabling action:

- **'Digital Ocean and Water Knowledge System'** by highlighting the need for sustaining long-term Ocean carbon observing systems, as well as establishing new *in situ* observing facilities, and addressing knowledge gaps and uncertainties in current modelling capabilities.

The European Marine Board acknowledges that while the Working Group members who wrote this document and its recommendations represent diversity in terms of European geographical location (see Annex 1), professional background, gender and career level, their views may not represent ideas from all forms of diversity. This document has a European focus, but its messages and recommendations are relevant to stakeholders globally. The diversity in expertise in the Working Group has been crucial in highlighting different views and perspectives from different communities and to address the complexity of the topic, leading to the common messages in this document.

1 Introduction and scope

Meeting the Paris Agreement's (Paris Agreement, 2015) temperature goal of limiting warming to well below 2°C, and pursuing efforts to limit it to 1.5°C, requires deep and sustained reductions in greenhouse gas (GHG) emissions as the highest priority. Carbon dioxide removal (CDR) cannot substitute these reductions but may be needed to complement them to address residual emissions and remove legacy carbon from the atmosphere (IPCC, 2018). In this Future Science Brief, we adopt the definition of CDR from the Intergovernmental Panel on Climate Change (IPCC, 2022): *"Human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or Ocean reservoirs or in products. This includes human enhancement of natural removal processes but excludes natural uptake not caused directly by human activities"*. In the context of CDR, the term sequestration refers to storage of more than 100 years, isolated from the atmosphere.

Marine CDR (mCDR) methods, sometimes included in the portfolio of Ocean-based climate interventions, leverage oceanic processes to enhance CO_2 uptake from the atmosphere. Marine CDR focuses on removing CO_2 that has entered the atmosphere as a result of past anthropogenic emissions. CDR is sometimes referred to as Greenhouse Gas Removal (GGR) and is part of the broader concept termed Geoengineering (The Royal Society, 2009) or Climate Intervention (NRC, 2015).

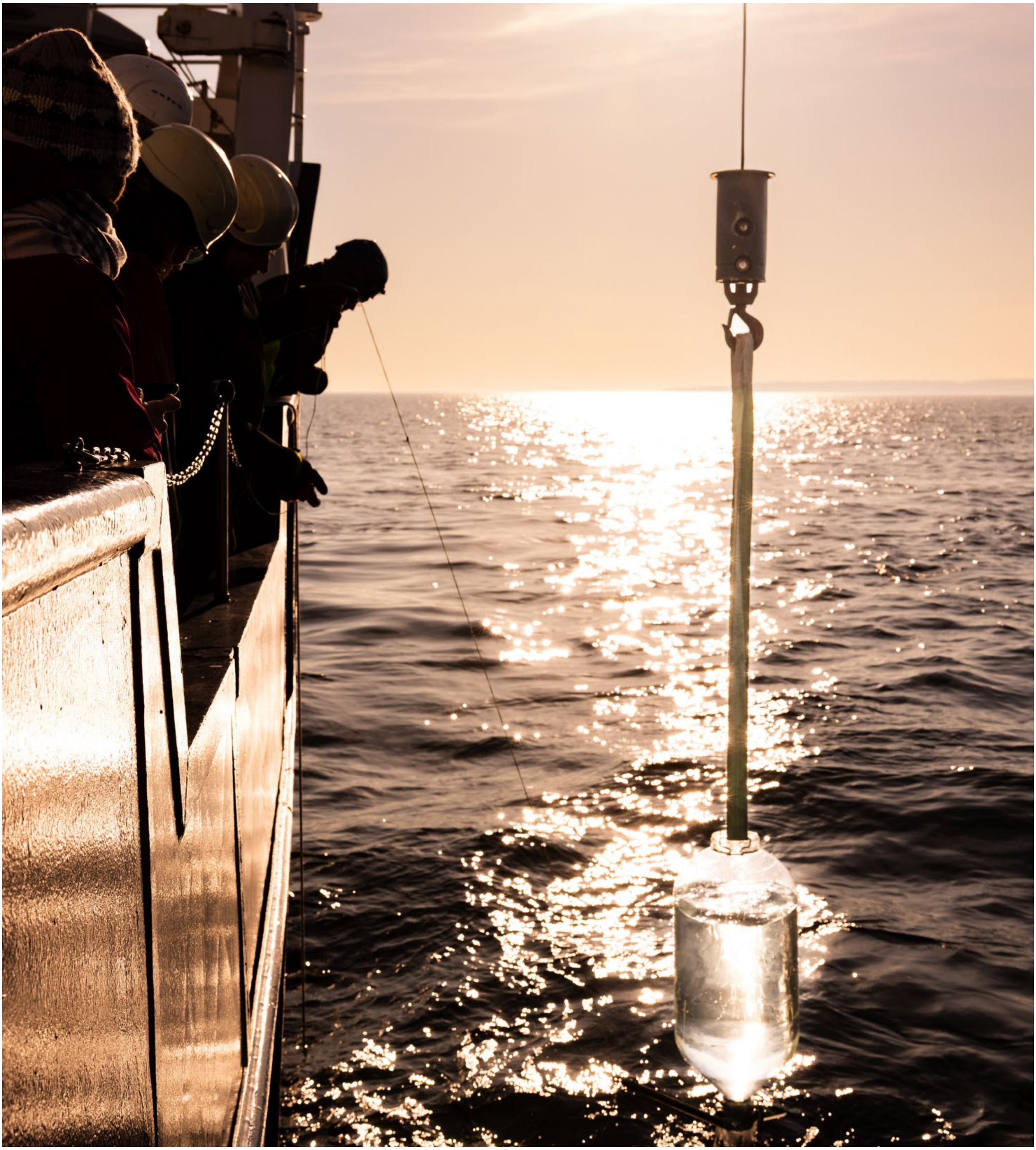
The Ocean absorbs approximately 25% of all annually emitted CO_2 from human activities (~10.5 gigatonnes of CO_2 per year), and is the largest dynamic carbon reservoir on Earth, holding approximately 37,000 billion tonnes of carbon (Friedlingstein et al., 2025). These numbers highlight, on the one hand the importance of the Ocean in the natural carbon cycle and on the other, the potential to remove and store even more carbon (Archer et al., 2009). Marine CDR has the potential to contribute to limiting global warming when deployed alongside substantial and sustained reductions in greenhouse gas emissions, such that atmospheric CO_2 concentrations decline sufficiently to meet the Paris Agreement's temperature goal.

Monitoring, reporting and verification (MRV) is a structured process to collect, disclose and independently verify data on CDR activities, including quantified removals, durability, uncertainties and environmental impacts. MRV for mCDR is needed to rigorously quantify net CO_2 removal and storage durability and to demonstrate whether activities deliver sustained reductions in atmospheric CO_2, while ensuring environmental integrity. Any inventory, or market claims must be grounded in such evidence. Currently, the MRV landscape remains fragmented, with varying and overlapping MRV protocols for different mCDR methods at varied stages of development across jurisdictions. This makes navigation through the MRV landscape, and any meaningful comparisons, particularly challenging.

MRV is fundamentally challenging due to the dynamic and heterogenic Ocean environment. To be effective, efficient, transparent and reproducible, mCDR needs a globally consistent, accurate and robust framework for MRV (Boyd et al., 2023). This MRV framework should include monitoring (measuring or quantifying) the amount of GHG removed by a mCDR method and comprehensively reporting those removal results to enable verification by a third party (Ho et al., 2023). While mCDR removes CO_2 from the atmosphere, MRV must quantify net CO_2 removal and storage durability and account for any associated non-CO_2 GHG emissions or reductions, reporting the net climate outcome, with uncertainties, as CO_2-equivalents. The notion of a net removal arises from the concept of additionality. In the context of mCDR, additionality means carbon removals must represent CO_2 uptake in the Ocean that wouldn't have occurred naturally, i.e. it would only happen in the presence of the mCDR intervention. This requires a comparison of results against a baseline state. Only removal beyond natural processes or existing practices counts as additional removal. Proving additionality is crucial to ensure legitimate climate benefits and MRV integrity. Therefore, monitoring must include observational and modelling methods, to cover the wide range of spatial and temporal scales at which GHG removal and impacts occur. MRV methodologies that quantify the environmental and ecological impacts of mCDR methods are sometimes referred to as environmental MRV, or eMRV (Eisaman, 2024). In addition to tracking carbon fluxes and storage, eMRV explicitly monitors changes in marine ecosystems, biodiversity and other environmental indicators to assess potential co-benefits and risks associated with mCDR methods.

Implementing mCDR entails various trade-offs and associated "costs" that can be related to environmental, economic and social factors, such as: (a) Energy and resource demands, including the production, transportation and deployment of materials; (b) Environmental impacts related to altered nutrient dynamics, marine biodiversity threats and Ocean chemistry changes; (c) Economic barriers caused by high capital expenditure (CAPEX) and operational expenditure (OPEX) that create feasibility challenges, including significant investment in large-scale infrastructure and high operational and maintenance costs; and (d) Leakage and permanence risks, caused by the uncertainties surrounding the long-term stability of carbon storage. In addition to assessing techno-economic costs, engaging local communities, establishing robust governance frameworks, fostering public trust, and ensuring equity are all essential components of responsible mCDR methods. By making evidence transparent and comparable, MRV allows decision-makers to evaluate these trade-offs and costs consistently across methods and contexts.

As mCDR methods develop, it is important to identify and close knowledge gaps and develop standardised, consistent and transparent MRV protocols. This document describes various mCDR methods (Chapter 2); the challenges in establishing effective MRV (Chapter 3); and the current capacity of observing (Chapter 4) and modelling systems (Chapter 5). The document then identifies existing regulations and governance (Chapter 6); outlines current and necessary MRV protocol developments (Chapter 7); summarises the main knowledge gaps and uncertainties (Chapter 8); and concludes with recommendations for policymakers, regulators, research funding and practitioners (Chapter 9). Boxes serve to provide in-depth focus on restoration of coastal blue carbon for carbon credits, and challenges of MRV for selected mCDR methods.



Credit: Michael Sswat, GEOMAR.

Global comparative study on Ocean Alkalinity Enhancement. To ensure comparability across the studies, the containers used, the way they are filled, the way the alkalinity is added and the measurements taken are all standardised.

2 Marine CDR methods

The Ocean has played a crucial role in stabilising climate by naturally mitigating increases in atmospheric CO_2 over timescales ranging from thousands to hundreds of thousands of years (Kump et al., 2009). Informed by the geological record, ideas have been proposed to accelerate the natural processes by which the Ocean can remove excess CO_2 from the atmosphere.

We categorise mCDR methods (Figure 2.1) into biotic and geochemical methods. Other classifications have also been proposed, such as the separation into nature-based and technological methods. We refrain from this distinction, because the perception of nature-based versus technological may depend on the detailed deployment approach, and because nature-based or natural solutions are not self-evident categories, but ones that are delimited by people acting in social groups where the designation of solutions as "natural" is influenced by social constructs rather than being inherently evident (Bellamy & Osaka, 2020).

We only focus on methods that strictly fall into the mCDR category and not wider marine geoengineering. Marine geoengineering can also include methods such as marine cloud brightening and Ocean surface brightening, e.g. through microbubbles. These methods are considered to be solar radiation modification (SRM) and aim to cool through interacting with solar radiation rather than removing CO_2 from the atmosphere, which remains the focus of this document. Below we provide an overview of key mCDR methods, the current state of research, and key research gaps, particularly regarding MRV. An overview of different mCDR methods and their attributes (e.g. Technology Readiness Level, key uncertainties, etc.) is available in Table 8.1, at the end of the document.

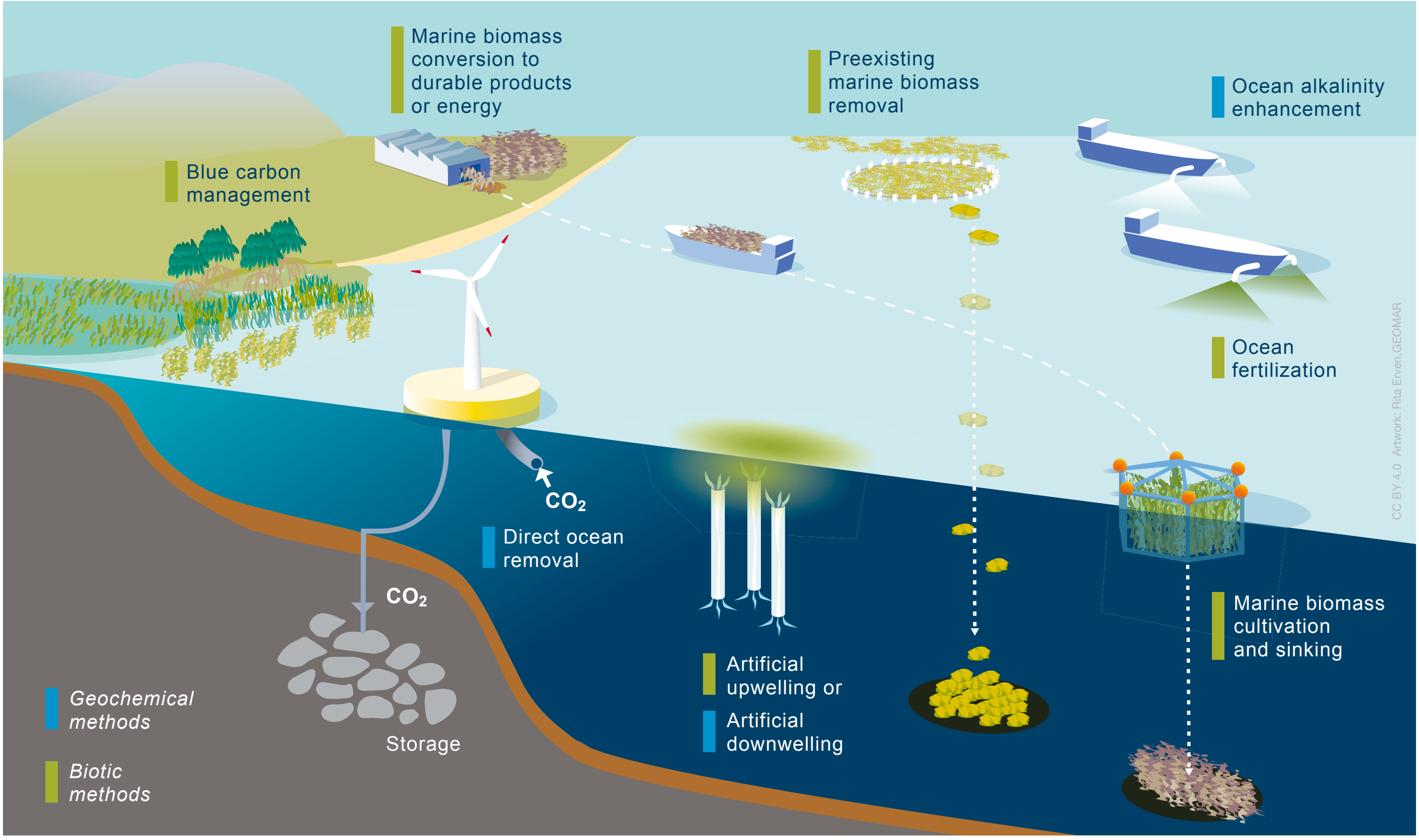
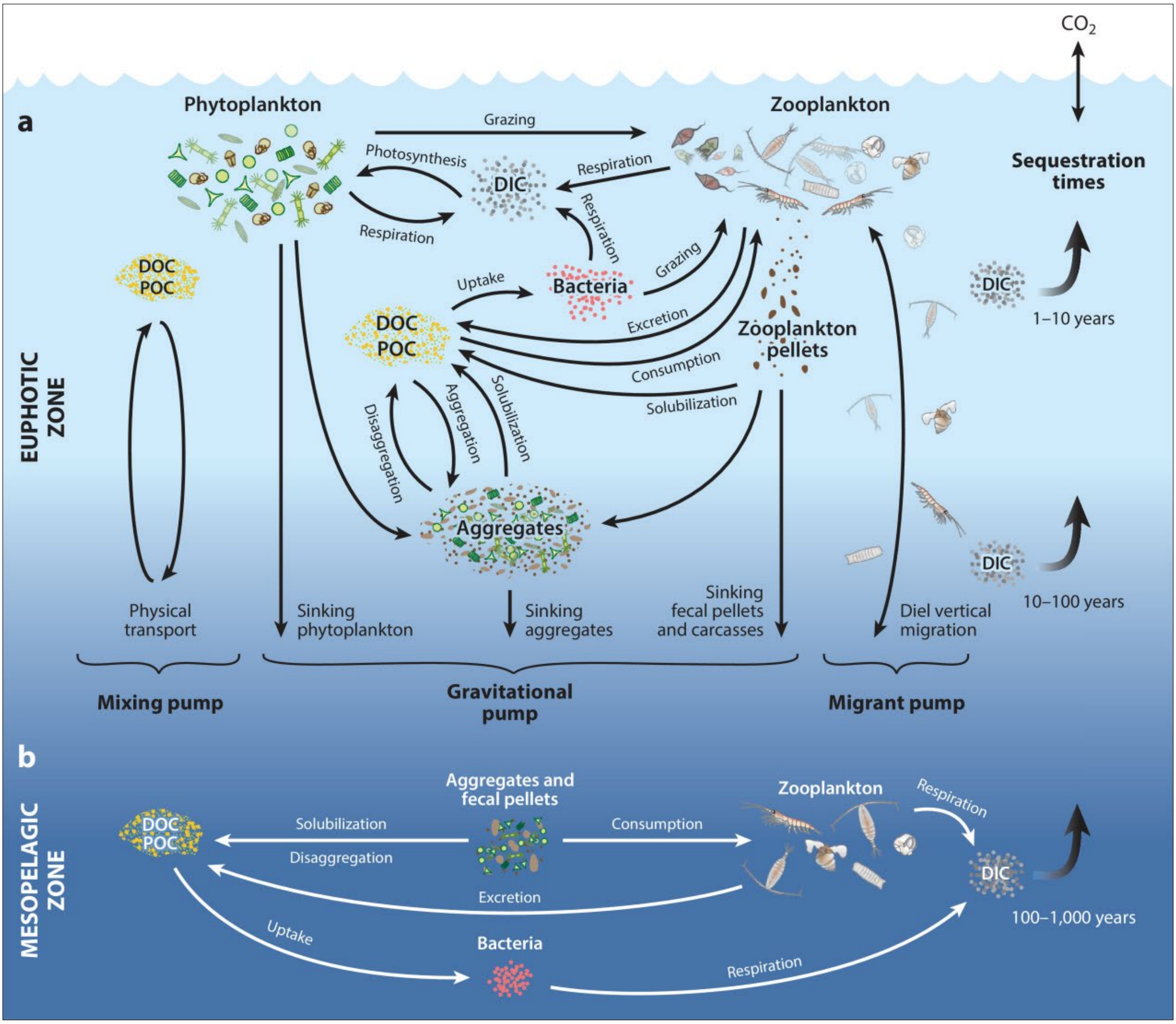


Figure 2.1 Schematic overview of marine carbon dioxide removal (mCDR) methods included in this Future Science Brief.

Credit: Rita Erven, GEOMAR (CC BY 4.0).



Credit: Adapted from Siegel et al. (2023) (CC BY 4.0).

Figure 2.2 Schematic representation of the biological carbon pump in the Ocean, showing how phytoplankton uptake CO_2, and how the subsequent sinking of organic matter transports carbon to depth. The storage times on the right (1–10 years, 10–100 years and 100–1,000 years) illustrate the temporal scales of carbon storage associated with various processes. Abbrevations: DOC (Dissolved Organic Matter); DIC (Dissolved Inorganic Matter); POC (Particulate Organic Matter).

2.1 Biotic mCDR methods

Biotic mCDR methods harness the process of photosynthesis, in which marine organisms, particularly phytoplankton, take up CO_2 and convert it into biomass. When these organisms die, some of their organic matter sinks, carrying the carbon with it. This is a process that removes carbon from the atmosphere and transports it to the Ocean's depths, where it is stored as part of long-term carbon sequestration. This is called the Ocean’s biological carbon pump (Figure 2.2), and its efficiency depends on factors like plankton community structure, nutrient availability, Ocean currents and the rate at which organic matter decomposes in the water column (Siegel et al., 2023). Biotic mCDR methods rely on enhancing elements of this biological carbon pump, such as phytoplankton biomass, and macroalgae and coastal vegetation, to increase CO_2 uptake and long-term storage of organic material. The following sections explore a set of biotic mCDR methods.

2.1.1 Preexisting marine biomass removal

Naturally occurring marine algal biomass can be transferred to the deep Ocean where the biomass and degradation products can be stored out of contact with the atmosphere on climate-relevant timescales (>100 years). A key candidate for this is Sargassum, a genus of free-floating, fast-growing macroalgae, that grows in temperate and tropical seas (Figure 2.3).

Since 2011, Sargassum has increasingly been found to stretch all the way from the west coast of Africa to the Gulf of Mexico and the Caribbean Sea, due to the proliferation of the Great Atlantic Sargassum Belt (Wang et al., 2019). The Great Atlantic Sargassum Belt is thought to have been initiated by a shift in regional wind patterns (Johns et al., 2020) and sustained by Amazon River and West African upwelling nutrient inputs (Wang et al., 2019). Sargassum then accumulates on the beaches of the Caribbean islands (Figure 2.3) and has negative social, economic and ecological consequences (Degia et al., 2024). Some Caribbean nations have begun depositing Sargassum offshore as a management strategy (van den Burg et al., 2024), but it could also be considered as a mCDR method that has a co-benefit of reducing the beaching of these Sargassum rafts. The long-term fate of sunken Sargassum to the deep Ocean is a key knowledge gap. Whether it achieves durable sequestration depends on depth, oxygen conditions, remineralisation rates (i.e. the rates at which organic matter is turned back into nutrients and CO$_2$ by microbes) and circulation. A substantial fraction of the Sargassum carbon may be consumed and remineralised back into Dissolved Inorganic Carbon (DIC) over years to decades, leaving uncertain the proportion that is sequestered in the sediment over the long-term (Peoples et al., 2024).

Some of the potential impacts and challenges of natural biomass removal are the same as for cultivation of marine biomass for either sinking or making products (see Section 2.1.2). For instance, large amounts of biomass introduced to the deep Ocean could disrupt existing deep-sea ecosystems. The decomposition of organic matter will consume oxygen, which may lead to hypoxic conditions detrimental to marine life. Sinking biomass might affect upper Ocean nutrient distribution and cycling, potentially leading to unintended consequences such as algal blooms or shifts in species composition. It is uncertain when the carbon would be re-released to the atmosphere, and this will depend on local conditions. Ensuring that the carbon remains sequestered over desired timescales requires robust understanding of deep-sea carbon system, which is currently limited due to sparse observations.

2.1.2 Marine biomass cultivation

Biomass sinking

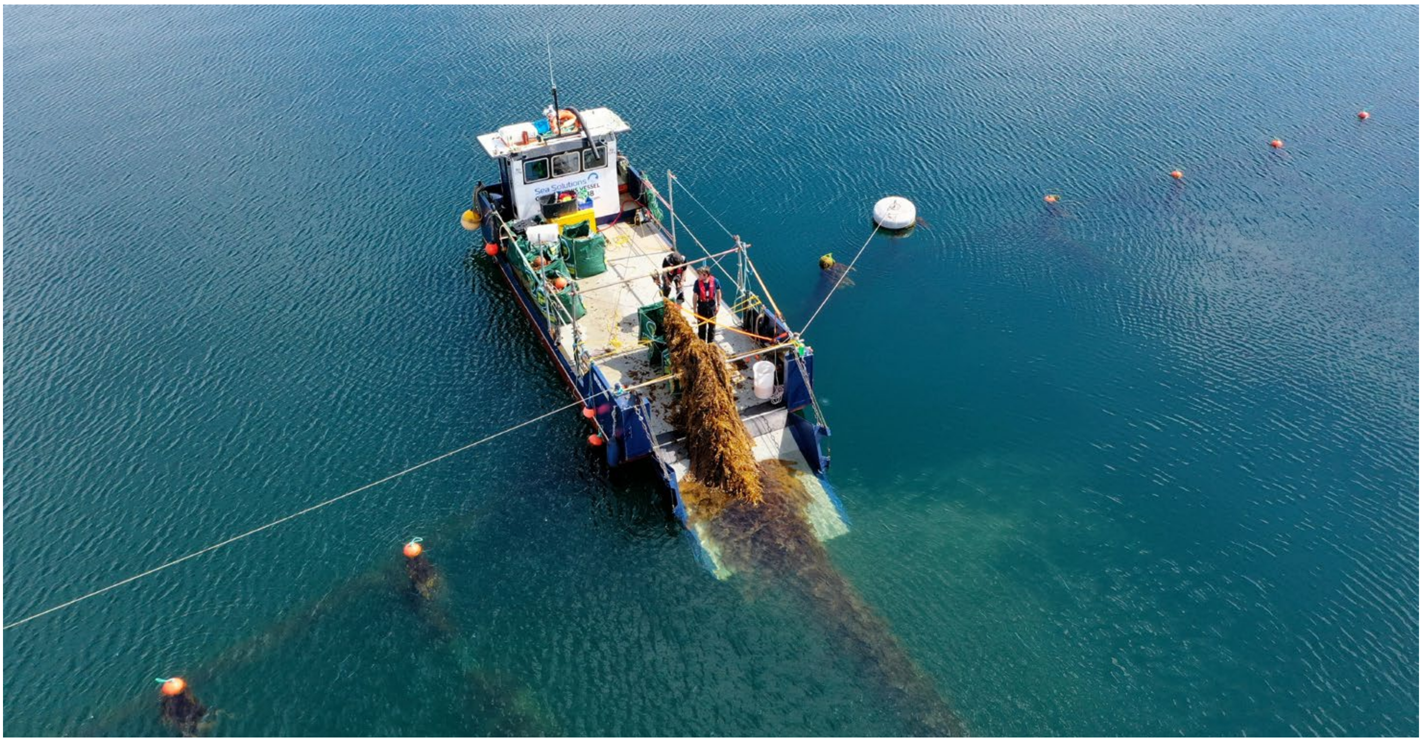
In addition to removing naturally occurring marine biomass, it could also be cultivated, harvested and sunk for the purpose of carbon removal. This process involves intentionally growing marine macroalgae, which take up CO$_2$ through photosynthesis, and then harvesting and sinking it into the deep Ocean to increase CO$_2$ removal from the atmosphere. Carbon is fixed into the macroalgal biomass and some is remineralised to DIC at depth, with a smaller fraction reaching the sediments and being buried. Durability depends on depth, oxygen conditions, remineralisation rates and circulation.

This method should consider biodiversity and marine ecosystems sustainability impacts, e.g. community composition shifts, in the same way as removal of natural marine biomass (see Section 2.1.1). Meaningful carbon storage through biomass sinking could require vast Ocean areas for seaweed cultivation, which may not be practical or environmentally sustainable (Alevizos & Barillé, 2023). Large-scale deployment could disrupt marine ecosystems, affecting biodiversity and altering nutrient dynamics (Chen et al., 2024). Ensuring long-term carbon storage is challenging due to reliance on numerical models and limited observational capabilities, especially in the deep Ocean. Uncertainties remain about permanence and potential for re-release. Monitoring and managing the growing biomass can be complex, requiring advanced technology, though continued advances in

Credit: Valerie Stiger (LEMAR-IUEM-UBO).

Credit: Hazel Oxenford.

Figure 2.3 Sargassum is a key candidate for the mcDR method 'pre-existing marine biomass removal'. **Left:** Close-up of one of the morphotypes of Sargassum underwater. **Right:** Sargassum washing up on Caribbean shores.



Credit: Alasdair O'Dell.

Harvesting of *Saccharina latissima* by the Scottish Association for Marine Science (SAMS) at a research focused seaweed farm in Scotland. Macroalgae cultivation and sinking / using it for durable products are mCDR methods.

aquaculture and biotechnology could increase carbon capture efficiency and reduce operational costs for both deployment and monitoring. While techniques for measuring the carbon uptake are relatively well established, robust methods to determine carbon permanence remain underdeveloped (Rose & Hemery, 2023). Standardised MRV protocols and improved methodologies for quantifying carbon uptake and long-term storage still need to be developed.

Macroalgae cultivation and sinking has been simulated in experiments using Ocean biogeochemical models, with and without extra nutrients being supplied by artificial upwelling (Wu et al., 2023). They demonstrated that while theoretically macroalgae cultivation and sinking has CDR potential, it leads to a large-scale reorganisation of nutrient fields with implications for primary production and the food webs it supports.

Terrestrial biomass sinking, where organic material originating from land is transported and deposited into the deep Ocean for long-term carbon storage, represents a hybrid CDR approach, with removal occurring terrestrially but storage and permanence managed within the marine environment. Terrestrial biomass will mostly not sink unaided and delivery would require active transport and ballasting (or waterlogging) to depths (Chopin et al., 2024). The energy and materials used for collection, processing, offshore transport, and deployment must be included in the life cycle assessment (see Section 3.4) and MRV as operational and embodied emissions and totalled against gross CO_2 removal. Although not strictly considered mCDR, its MRV requirements closely align with those of marine biomass sinking, due to shared challenges around carbon fate and permanence, and ecological impacts.

Marine biomass for durable products and energy with long-term storage

In marine Bioenergy with Carbon Capture and Storage (mBECCS), seaweed is converted to bioenergy with CO_2 captured and stored underground, offering a potential carbon removal pathway. Marine BECCS remains in early development and lags behind its terrestrial counterpart, which faces land and sustainability constraints (Beal et al., 2018; Smith et al., 2016). Carbon can be locked up in long-lived products, where durability corresponds to product lifetime, potentially century-scale for some materials, or as compressed CO_2 stored geologically when bioenergy is paired with Carbon Capture and Storage (CCS), utilising long-term reservoir like saline aquifers or depleted petroleum fields.

Alternatively, seaweed can be turned into long-lived materials such as bioplastics and construction composites, replacing fossil-based products (Nagarajan et al., 2024). Through pyrolysis, i.e. decomposition through high temperature and no oxygen, marine biomass can also be converted into biochar, a black carbon which can improve soil properties like nutrient retention. The carbon in biochar is stabilised in a long-lasting form, preventing it from returning to the atmosphere and effectively sequestering it in the soil for periods of centuries to millennia (Lehmann & Joseph, 2015).

These marine biomass-based methods may offer a dual benefit of reducing atmospheric CO_2 levels and providing alternatives to fossil fuel-based products and energy. However, net removal hinges on the performance and availability of CCS infrastructure. CCS can be resource-demanding (energy, transport, compression), requires suitable storage sites and permitting, and adds monitoring and liability obligations; these factors should be reflected in the MRV and LCA (see Section 3.4). In addition, mechanical harvesting methods disturb marine habitats and lead to bycatch or habitat degradation if not managed responsibly. There are also concerns regarding the scalability, technical limitations, and environmental implications of the removal of nutrients from the Ocean or intensive cultivation practices (see section *Biomass sinking* above).

Credit: Iqbal Farooz, Pexels

Biochar, a charcoal-like material derived from plant biomass, which can be added to soil to improve properties like nutrient retention. The carbon in biochar is stabilised in a long-lasting form, preventing it from returning to the atmosphere and effectively sequestering it for periods of centuries to millennia.

2.1.3 Ocean fertilisation

Ocean fertilisation involves supplying nutrients key to phytoplankton growth, to increase biological CO_2 fixation and thus enhance atmospheric CO_2 uptake by the Ocean. The carbon fixed by fertilisation is expected to be sequestered in the deep Ocean through the export of organic particles and their remineralisation at depth, potentially leading to storage over timescales of decades to centuries. However, as only a fraction of the produced organic carbon sinks deep enough to be stored long-term, the storage depends on sinking and remineralisation rates, to quantify the export efficiency into the deep Ocean.

Fertilisation can occur through the addition of macronutrients, such as nitrogen and phosphorus, and/or micronutrients, such as iron (a process called Ocean iron fertilisation, OIF, or electrochemical Ocean iron fertilisation, eOIF, which uses electrochemical reactions to dissolve iron from inert electrodes directly into seawater), zinc or manganese (Sunda, 2012), or by relocating nutrients already present in the Ocean through artificial upwelling of nutrient-rich deep waters to the Ocean surface (see Section 2.1.4). As almost a third of the global Ocean is iron limited, OIF could be considered to have substantial geographical scope (Williamson et al., 2022).

Successful OIF requires sites that have the right hydrodynamic, biogeochemical and ecological traits, but also carbon accounting technologies that can monitor these sites, e.g. satellite remote sensing and autonomous *in situ* water column monitoring (Williamson et al., 2022). Outdoor field trials of OIF, such as the Southern Ocean Iron RElease Experiment (SOIREE, Boyd & Law, 2001) and the Haida Gwaii project (Xiu et al., 2014), involved adding iron sulphate to specific marine regions, resulting in increased biological productivity. These trials highlighted the potential of Ocean fertilisation to boost carbon capture but were not designed to collect evidence of durable carbon storage (Smetacek & Naqvi, 2008). They also raised concerns about ecological impacts, disruptions to nutrient cycling and the long-term effects on marine ecosystems, such as induced deoxygenation (Yoon et al., 2018). Other unintended consequences, that are yet to be robustly demonstrated, include a decrease in mid-water oxygen due to organic matter decomposition, increased acidification of the Ocean interior, and the production of methane (CH_4) and nitrous oxide (N_2O), which could counteract the effect of CO_2 removal (Yoon et al., 2018).

Compared to OIF, there is less interest in nitrogen and/or phosphorus fertilisation because the quantities of these nutrients needed to stimulate biological CO_2 fixation are substantially greater, leading to significantly higher costs (NASEM, 2022).

Although short-term biological responses to nutrient addition are relatively well understood, there is only moderate confidence in the overall efficacy of Ocean fertilisation as a long-term carbon removal strategy. Key scientific uncertainties remain around the rate and scale of influx of CO_2 from the atmosphere to the Ocean and the durability of carbon storage (Bach et al., 2023), as well as the scale and significance of potential ecological side effects (GESAMP, 2025).

Credit: Stefane Lesbats, Ifremer.

Water sampling to investigate a *Lepidodinium chlorophorum* (non-toxic) phytoplankton bloom in the Bay of Vilaine, France. Ocean fertilisation involves supplying nutrients key to phytoplankton growth, to increase biological CO_2 fixation and thus enhance atmospheric CO_2 uptake by the Ocean.

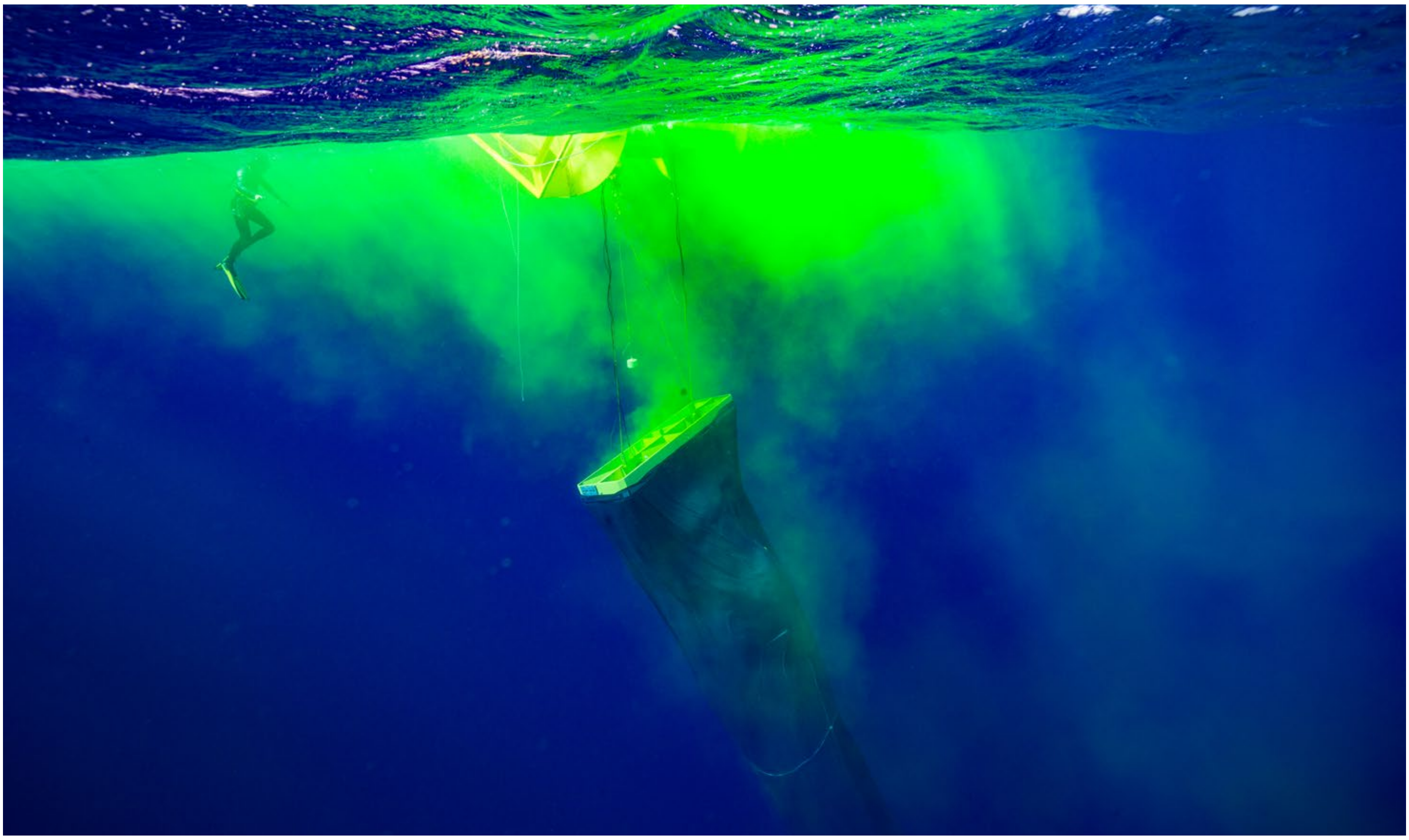
2.1.4 Artificial upwelling

Artificial upwelling (AU) seeks to enhance the Ocean's natural nutrient cycles by pumping cold, nutrient-rich deep waters to the sunlit surface, thereby stimulating phytoplankton growth and amplifying the biological carbon pump to remove atmospheric CO_2. The storage pathway mirrors Ocean fertilisation, where organic carbon is exported to depth with conversion to DIC in the Ocean interior, and with a small, buried fraction. First suggested by Lovelock & Rapley (2007), AU leverages both physical transport and microbial nutrient regeneration in deep waters to fertilise surface ecosystems. AU will require floating pipes or fixed structures to pump nutrient-rich water from 100–300 m depth to the near-surface, which is not technologically feasible yet, so these methods are primarily conceptual for the time being.

To be viable, AU will have to be implemented in low- to mid-latitude regions with nutrient-poor surface waters, particularly in coastal zones where upwelling already occurs. AU has been proposed in the context of macroalgae farming, to provide additional nutrients (Yue et al., 2025). The technical challenges of pumping water up from several tens to a few hundred metres depth are substantial, such as power consumption (Pan et al., 2018), and the few practical field trials could only endure operations for a few days in the challenging marine environment (e.g. White et al., 2010). Engineering research efforts aim to improve efficiency and robustness of AU devices, and test deployments continue, particularly in the context of macroalgae farming (Kimball et al., 2025) or wave energy conversion plants in coastal environments (Zhang et al., 2016). Reported designs span wave-driven pumps (White et al., 2010) to forced systems (Kemper et al., 2022). Energy demand (estimated to be up to 500 kilowatts) rises steeply depending on the density difference between source and discharge layers, and comprehensive LCAs of AU energy use are still lacking.

Modelling studies indicate that any increase in surface Ocean CO_2 uptake (or drawdown) from nutrient supply is partly offset because upwelled water also carries respired DIC, which raises surface CO_2 and limits the net effect (Oschlies et al., 2010a). Jürchott et al. (2023) found that AU's effect on net oceanic CO_2 uptake is strongly scenario-dependent: changes in CO_2 solubility in seawater (the physical solubility pump) and in the efficiency of the biological pump modulate the response. In their simulations, AU would be more effective in some regions when paired with Ocean iron fertilisation, because AU brings macronutrients and DIC to the surface, whereas iron limitation can still cap phytoplankton growth.

AU could have an impact on Ocean stratification, salinity, and temperature, potentially disrupting Ocean circulation, possibly contributing to global warming (Oschlies et al., 2010b) and leading to disruptions of atmospheric dynamics and the hydrological cycle (Kwiatkowski et al., 2015). Additional impacts on marine biota would include the mechanical effects of pumping large volumes of water through industrial-scale structures, and the mixing of diverse ecosystems previously residing at different depths. Conversely, AU would bring cold deep water to the surface, which could cool the lower atmosphere, and this reduced air temperature could slow down soil and plant respiration, thereby increasing the net uptake and retention of CO_2 in terrestrial ecosystems (Oschlies et al., 2010a).



Credit: Michael Sswat, GEOMAR.

Pilot test of a wave-pump for artificial upwelling in the Canary Islands, Spain. The green non-toxic dye was injected to follow the mixing and distribution of the deep water in the surface water. Artificial upwelling seeks to enhance the Ocean's natural nutrient cycles by pumping cold, nutrient-rich deep waters to the sunlit surface, thereby stimulating phytoplankton growth and amplifying the biological carbon pump to remove atmospheric CO_2.

2.1.5 Coastal Blue Carbon management

Carbon is captured and stored by coastal vegetated ecosystems with rooted vegetation, such as mangroves, salt marshes and seagrasses (Figure 2.4) collectively referred to as Blue Carbon ecosystems. Carbon is stored in living biomass (shorter-lived) and as buried organic carbon in sediments, which can persist for centuries to millennia under stable conditions (Piñeiro-Juncal et al., 2025). These coastal vegetated ecosystems may account for half of the organic carbon stored in Ocean sediments (Macreadie et al., 2019), so restoring or creating new coastal ecosystems could increase carbon storage and lock away some atmospheric CO_2 as sedimentary organic carbon, which could be used for issuing carbon credits (see Box 1). However, this coastal sediment reservoir is vulnerable to erosion, drainage, trawling, or sea-level and storm impacts. Coastal wetlands such as mangrove forests, salt marshes or seagrass meadows have lost half of their global area coverage in the last century (Davidson, 2014), due to urban development, pollution and agriculture or aquaculture. Therefore, replanting and restoring these systems could produce organic matter and increase sedimentation. The EMB Policy Brief on Blue Carbon (European Marine Board, 2023) provides additional information on challenges and opportunities of using Blue Carbon to mitigate the climate and biodiversity crises.

Coastal vegetated ecosystems can lock away carbon by trapping and burying calcium carbonate ($CaCO_3$) grains or by promoting the formation of $CaCO_3$, but this process also uses up alkalinity, part of the Ocean's natural acid buffer, thus offsetting some CO_2 removal (Fakhraee et al., 2023b). Conversely, when buried organic matter breaks down, whether by chemical dissolution of carbonates or by oxygen-free microbial decay, alkalinity is released back into seawater, restoring some of the Ocean's buffering capacity (Fakhraee et al., 2023b). There is also the risk of other unintended consequences, such as emission of methane (Rosentreter et al., 2018), whilst environmental co-benefits could be shoreline protection from erosion and floods (Temmerman et al., 2023), and the creation of hotspots for fisheries and biodiversity.

A variation to coastal restoration is planting vegetated ecosystems where there are none, an analogy to terrestrial afforestation. This could have unforeseen consequences to the species that already inhabit those habitats i.e., by disrupting a stable preexisting ecosystem, while simultaneously introducing a new one with potentially higher biodiversity (Sharma et al., 2017), and inappropriate hydrological conditions may hinder the plantation process (Wodehouse & Rayment, 2019). In addition, restoration or new planting of mangroves may encounter land tenure issues, e.g. in abandoned mariculture ponds (Song et al., 2023).

Credit: S. Baez, B. Bernal, J. Lefcheck, adapted from Christianson et al. (2022) (CC BY 4.0).

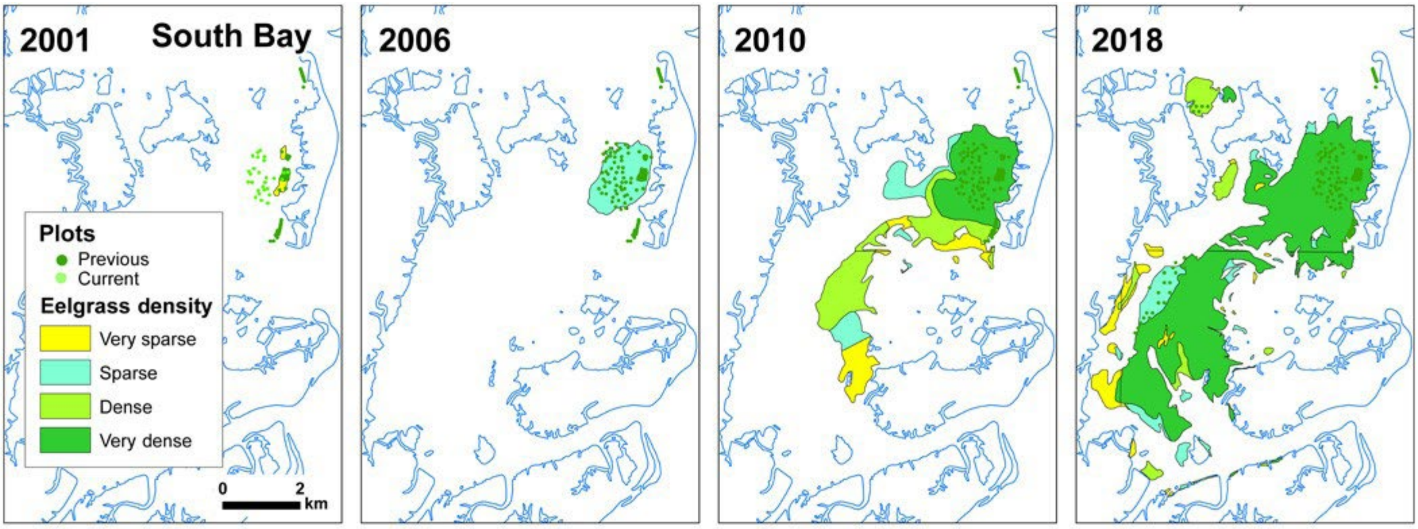
Figure 2.4 Coastal restoration of Blue Carbon habitats is a mCDR method, where the carbon is stored in living biomass or buried organic carbon in sediments can persist for centuries to millennia under stable conditions. Blue Carbon habitats include mangrove forest (left), salt marsh (middle) and seagrass meadows (right).

Box 1. In-depth focus: Restoration of coastal Blue Carbon for carbon credits

Globally Blue Carbon habitats have declined markedly over recent decades (Hilmi et al., 2021), though there are efforts to restore them. While there are large uncertainties, restoration, or even creation of Blue Carbon habitats, has limited contribution to CO_2 removal relative to global emissions (Macreadie et al., 2021; European Marine Board, 2023). However, they may be considered a favourable climate change mitigation approach, as they are generally relatively low-cost, low-regret, with the potential for significant co-benefits, such as biodiversity enhancement, coastal protection and pollution mitigation, as well as enhancing local livelihoods and employment (Friess et al., 2024; European Marine Board, 2023).

There are significant ongoing efforts to map and quantify the coastal Blue Carbon inventory and storage potential in many parts of the world. A number of countries include measures like mangrove restoration in their Nationally Determined Contributions (NDCs) as part of the Paris Agreement (Bonotto, 2024), and this trend will continue in the updated NDCs in 2025. While there is potential to increase Blue Carbon stocks, knowledge gaps include quantifying the carbon removal potential and the significant challenges of monitoring to demonstrate additionality and durability of carbon storage (European Marine Board, 2023). These include difficulties in determination of carbon burial rates, the role of lateral carbon transport, fluxes of other GHGs and short-lived climate forcers like dimethyl sulphide (Szopa et al., 2023), and vulnerability to future climatic and non-climatic change (Williamson & Gattuso, 2022).

As an example of restoration, in the USA, Virginia's coastal seagrass meadows (*Zostera marina*, or eelgrass) disappeared in the 1930s due to a combination of diseases produced by a marine slime mould and the impact of hurricanes. Small patches of natural regrowth were discovered in the 1990s, which led to a 20-year restoration project. Seagrass seedlings have been planted annually, and the project has been monitoring the increasing seagrass cover (Figure 2.5), water quality, carbon and nitrogen levels, as well as marine life such as scallops (Orth et al., 2020). The restored and actively managed meadows have improved water quality, increased marine life populations, and stored 5,000 tonnes of carbon accumulated over twenty years. The long-term monitoring including of the captured carbon has led to this project being issued carbon credits.



Credit: Adapted from Orth et al. 2020 (CC BY-NC 4.0).

Figure 2.5 Seagrass coverage along Virginia's coast between 2001-2018 where green indicates very dense (>70%), and yellow very sparse seagrass coverage (<10%). Virginia's coastal seagrass meadows disappeared in the 1930s due to a combination of diseases and the impact of hurricanes. Since the 1990s, seagrass seedlings have been planted annually. The restored and actively managed meadows have improved water quality, increased marine life populations, and stored 5,000 tonnes of carbon accumulated over twenty years.

2.2 Geochemical mCDR methods

Geochemical mCDR methods capture and store atmospheric CO_2 through non-biologically mediated chemical processes. These methods are inspired by natural carbon cycles and chemical weathering of rocks on land that help regulate Earth's climate over geological timescales. The geochemical capture and storage of CO_2 happens through the following mechanisms: atmospheric CO_2 dissolves naturally in seawater, where it is in equilibrium with the other forms of DIC, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. Dissolved CO_2 represents about 1% of the total DIC in typical surface seawater. Over long timescales, i.e. months to hundreds of years, carbon can be incorporated into carbonate minerals through biologically mediated calcification and eventually contribute to sediment formation (Milliman, 1993). Over longer timescales (10,000–100,000 years), carbonate minerals become buried below the active surface layer of sediments and the carbon they contain enters the geological carbon cycle. The following sections explore a set of geochemical mCDR methods.

2.2.1 Ocean Alkalinity Enhancement

The concept of Ocean Alkalinity Enhancement (OAE) is inspired by natural alkalinity production through the weathering of silicate or carbonate rocks on land that removes atmospheric CO_2 and, on geological timescales (> 100,000 years) compensates for CO_2 emissions from volcanic activity (Oschlies et al., 2025a). OAE uses various methods to enhance the oceanic capacity to take up CO_2 from the atmosphere by increasing the transformation of dissolved CO_2 into HCO_3^- and CO_3^{2-} at the Ocean surface, therefore enabling more atmospheric CO_2 to enter the Ocean. When alkalinity in seawater increases, more of the dissolved CO_2 reacts into HCO_3^- and CO_3^{2-} that remain dissolved for roughly 10,000–100,000 years. This exceptional durability arises when added alkalinity converts reactive CO_2 into stable dissolved forms, which only re-enter the atmosphere once deep-Ocean carbon reservoirs and sedimentary carbonates reach equilibrium over hundreds of millennia. The stability of HCO_3^- and CO_3^{2-} plays a key role in storing carbon over time and is essential for regulating the Ocean's pH and buffering against Ocean acidification. When alkalinity is added to the surface Ocean, the air just above still has higher CO_2, so CO_2 molecules move from air to sea until the difference in partial pressure of CO_2 (pCO_2) shrinks. How fast this "air–sea CO_2 equilibration" happens depends mainly on wind and turbulence (how fast gas crosses the surface), how deep the mixed layer is, and the carbonate chemistry that buffers CO_2 in seawater.

Several ideas have been proposed to increase the alkalinity of Ocean surface waters (Eisaman et al., 2023), such as "Ocean liming", which uses industrially processed hydrated lime (a highly reactive and dissolving quicklime); the use of other alkaline substances such as silicate minerals or alkaline industrial wastes; or electrochemical methods that split seawater into an acid and base, and then removes the acids and leaves the bases behind to boost the Ocean's ability to take up more CO_2.

Eisaman et al. (2023) suggest that OAE would be effective in removing CO_2 from the atmosphere. However, the short- and long-term environmental impacts are of major concern (Bach et al., 2019), especially if OAE were to change the marine system to be outside of its natural variability ranges. Large-scale (e.g. >1 gigatonne per year of finely ground mineral feedstock material added to the Ocean) deployment of OAE could raise suspended particulate matter in the Ocean by an order of magnitude, with potential impacts on filter-feeding organisms (Oschlies et al., 2025a). Furthermore, adding alkaline compounds changes carbonate chemistry in a multifaceted way and requires complex calculations of multiple interacting parameters to determine how much CO_2 is actually removed. Additional impacts can be due to the risk of inclusion of (potentially polluting or toxic) heavy metals from the mineral feedstocks or industrial by-products used to increase seawater alkalinity. Deployment of open-Ocean OAE at scale will require repurposed commercial or dedicated vessels for dispersion (Caserini et al., 2021), which could introduce additional environmental challenges, and the extraction and processing of the minerals that will be required for OAE would also need to be factored into the CO_2 emissions associated with this mCDR method and the LCA that would be required


Credit: Sarah Schumann.

Rhodamine red dye is used in Ocean Alkalinity Enhancement experiments to trace the distribution of added substances.

2.2.2 Artificial downwelling

Artificial downwelling creates a downward flow of upper Ocean waters to enhance the transport of both dissolved and particulate carbon to the Ocean interior, to enhance long-term carbon storage of the biological and solubility pumps (NASEM, 2022). Artificial downwelling has been proposed to tackle eutrophication and hypoxia in coastal regions (Stigebrandt et al., 2015) as the downward flow of water will also transport nutrients, oxygen, salt, heat and other properties (NASEM, 2022). Engineering approaches for artificial downwelling include various pump technologies (wave-powered, airlift and bubble pumps), salt-fountain systems to boost water density, thermohaline strategies using Ocean thermal energy conversion cold-water discharge, renewable-energy-driven pumps, and affecting salinity through controlled brine rejection. Each exploit different physical drivers, such as mechanical force, density inversion, or convective processes, to subduct CO_2-rich water below the mixed layer. All these approaches remain at early development stages with limited field trials (Zhou & Flynn, 2005). They have never been tested in the context of mCDR nor in an open-Ocean environment (NASEM, 2022) but have been tested to oxygenate deep water (Stigebrandt et al., 2015). This method has been considered unreasonably expensive, and therefore not competitive for carbon storage (Zhou & Flynn, 2005).

There is little literature specifically assessing artificial downwelling, therefore its efficacy, impacts and scalability is unknown. Another unknown is whether downwelled buoyant organic material will remain in the Ocean interior (NASEM, 2022), whether the return flow of upwelled waters (which must occur due to mass conservation) will lead to increased outgassing of CO_2 to the atmosphere (Zhou & Flynn, 2005), and whether there will be a net increase in long-term carbon storage (NASEM, 2022). The return flow could also lead to unintended biological fertilisation as upwelled waters will bring nutrients to the euphotic zone. Artificial downwelling would also alter Ocean ecosystem structure and any benefits may cease upon the termination of the approach (NASEM, 2022).

2.2.3 Direct Ocean carbon removal

Direct Ocean carbon removal aims to extract carbon from seawater in a designated facility, e.g. via electrochemistry powered by renewable energy. The CO_2 extracted from seawater is stored underground in geological formations, mineralised into stable carbonates (solid phase), or used in products with a long lifetime (e.g. construction materials). CO_2-depleted seawater is released out of the facility back into the surface Ocean, where it can absorb atmospheric CO_2 via gas exchange through the air-sea interface. However, because Ocean mixing and circulation continually exchange surface waters with deeper layers, the treated water remains in contact with the atmosphere for only days to weeks, preventing CO_2 levels from fully reaching equilibrium, and hence limiting net uptake. If the CO_2 extracted via direct Ocean carbon removal is used for short-lived products (e.g. synthetic fuels), the net result would be an increase in atmospheric CO_2 at the expense of the depletion of the Ocean carbon reservoir. Therefore, long-term storage of the extracted CO_2 is critical, as the Ocean already represents a durable storage system, and direct Ocean carbon removal must not lead to a net reduction in the durability of CO_2 storage. It is important to note that direct Ocean carbon removal itself does not represent a mCDR method; but only the subsequent air-sea flux of CO_2 is climatically relevant

Credit: Captura Corp.

Direct Ocean carbon removal pilot plant in Kona, Hawaii.

and counts as mCDR. This has implications for MRV, particularly for detection and attribution (see Section 3.1).

Technically, direct Ocean carbon removal is based on the same geochemical principle as OAE but flips the sequence: it first acidifies a seawater stream to convert HCO_3^- and CO_3^{2-} into CO_2 gas, which is then vacuum extracted. The acidified water is immediately neutralised with the retained base so that when it's released back to the Ocean, its overall chemistry, aside from the removed CO_2, is unchanged. The electrochemical cells used for extraction consume less energy when operating on higher-salinity water, which is why direct Ocean carbon removal systems are often proposed to be co-located with desalination plants that supply concentrated brine feedstocks.

There have been laboratory, modelling, prototypes and pilot plants for direct Ocean carbon removal (Eisaman, 2024). NASEM (2022) noted that a limitation to the scalability of direct Ocean carbon removal could be the renewable energy requirements. However, in principle, hydrogen could be a by-product from of direct Ocean carbon removal, which could incentivise the development of this mCDR method (Patterson et al., 2019). As for possible side effects of direct Ocean carbon removal, it could pose a range of environmental risks, including shifts in seawater chemistry, unintended ecological disturbances, and by-product releases. Key concerns include acid–base imbalances, nutrient perturbations, energy and brine discharges, toxic by-products and governance gaps (Niffenegger et al., 2023).

3 Key challenges for Monitoring, Reporting and Verification

3.1 CO_2 and other greenhouse gases

Marine CDR methods primarily focus on removing and sequestering CO_2 from the atmosphere. However, they can also lead to the production or mitigation of other greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O). Beyond these non-CO_2 GHGs, short-lived climate forcers such as dimethyl sulphide (DMS) can also be affected by mCDR and should be considered in environmental MRV (eMRV) where relevant (see Section 3.5). Establishing a standard approach to integrate the impacts of CH_4 and N_2O alongside CO_2 emissions is necessary, yet challenging, as it involves sophisticated analytical methods and robust datasets.

CO_2-equivalent (CO_2eq) is often used to compare the climate impact of the different gases by expressing their effects in terms of the equivalent amount of CO_2 over a defined time scale (usually 100 years). Because of the atmospheric lifetimes of the different GHGs (e.g. about 12 years for CH_4, and about 120 years for N_2O), the same CO_2eq can yield very different climate effects. For mCDR, using CO_2eq can provide a more accurate representation of the net climate impact by integrating emissions of CH_4, N_2O and other GHGs, which may offset or complicate the benefits of CO_2 removal. For example, CH_4 has a global warming potential 27 - 30 times higher than CO_2 over a 100-year period (Forster et al., 2023). In the Ocean, CH_4 can be produced through biological processes, particularly under low-oxygen conditions that may arise with certain mCDR methods. N_2O has a global warming potential about 273 times higher than CO_2 over a 100-year period and can be produced by marine microbial processes in low-oxygen, nitrogen-rich environments. Therefore, measuring the full impact of mCDR methods requires precise tracking of various GHGs produced or mitigated by the methods used.

The production of CH_4 and N_2O as by-products of Ocean fertilisation, for example, complicates MRV because of their different global warming potentials and the difficulty in measuring them accurately in marine environments. CH_4 measurement is especially complex due to its potential production in low-oxygen zones, which are difficult to monitor consistently. Accurately measuring N_2O is challenging due to its sensitivity to microbial nitrogen cycling, a process highly sensitive to oxygen levels and influenced by Ocean fertilisation.

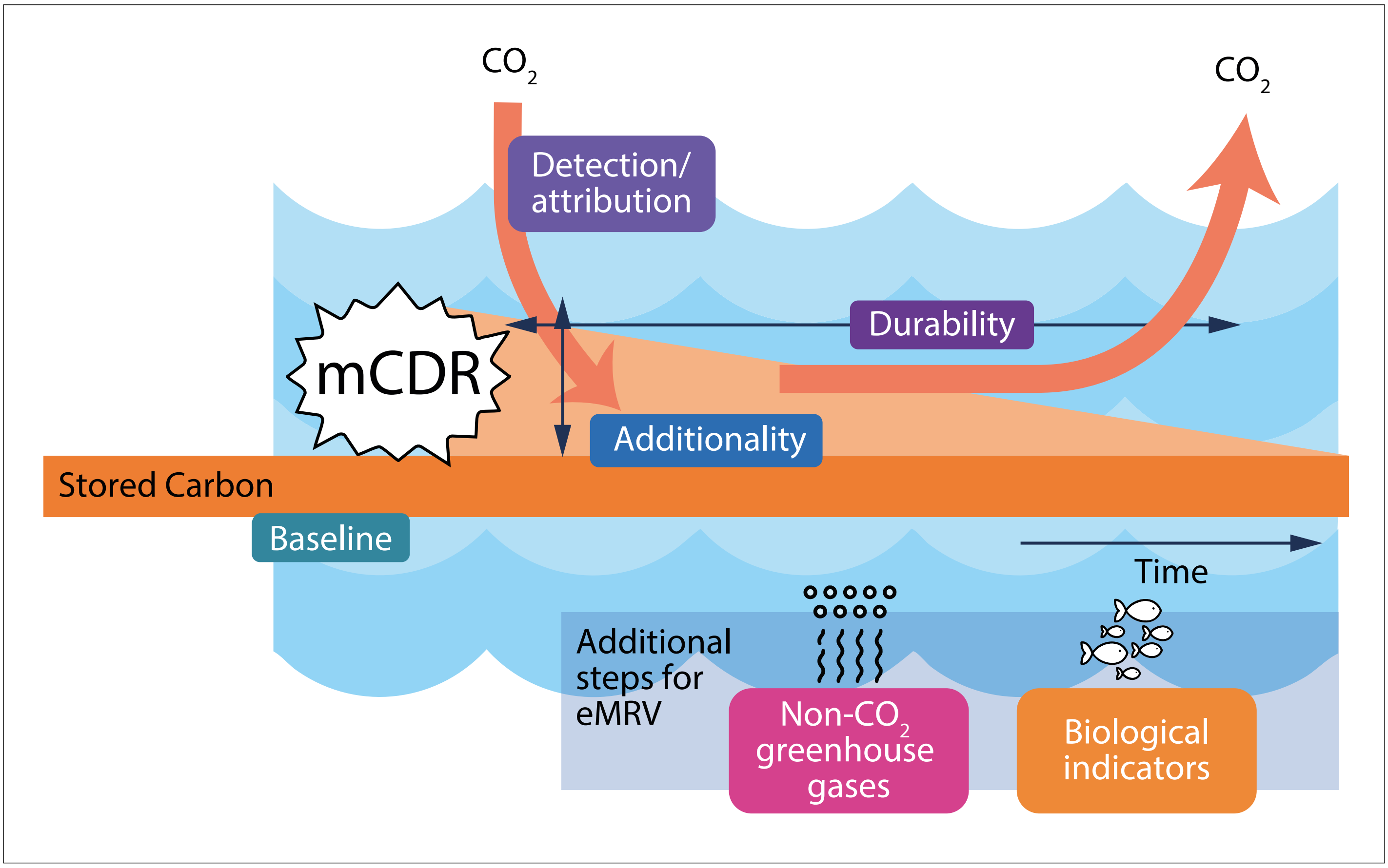
Detection and attribution are established concepts in climate science (Stott et al., 2010). For the purpose of MRV for mCDR (Figure 3.1), detection and attribution mean showing that a measurable change in e.g. air-sea CO_2 flux, other greenhouse gases, Dissolved Inorganic Carbon (DIC), pH or an ecological indicator, occurred due to the implemented mCDR method, i.e., beyond natural variability. Attribution evaluates how much of that change was caused by the mCDR activity versus other drivers, e.g. weather, currents, background trends, and gives the confidence in that assignment. In practice, this requires pre-registered designs (e.g. impact-reference comparisons, before-after-control-impact), adequate sampling power (from Observing System Simulation Experiments or OSSEs, see Section 5.7), and multiple lines of evidence (*in situ* sensors, tracers/isotopes and models). Together, detection and attribution allow MRV to distinguish mCDR effects from background variability and to quantify net atmospheric CO_2 removal with a range of uncertainty around the estimated value.

Marine CDR methods like Ocean fertilisation promote phytoplankton blooms to increase particulate organic carbon (POC) and dissolved organic carbon (DOC) but verifying this production requires deploying sediment traps or optical sensors across vast, often inaccessible Ocean regions, making continuous measurement difficult (Buesseler et al., 2024). Additionally, because only a fraction of produced POC and DOC sinks deep enough to be sequestered long-term, which depends on sinking rates and remineralisation, reports should combine surface biomass increases with observation-derived export efficiency estimates to avoid overestimating net carbon removal. A more detailed discussion on observing systems for MRV is presented in Chapter 4.

3.2 Measuring additionality and establishing baselines

Ensuring additionality is fundamental to regulating mCDR methods. To deliver net carbon removal, mCDR methods must demonstrably remove more carbon than would be removed without it (i.e. additionality, see Figure 3.1). This requires robust calculation of the amount of carbon the Ocean would store without the mCDR method (i.e. baseline stored carbon, see Figure 3.1).

As noted by Visser (2025), imprecise use of ‘sequestration’ risks counting natural biological carbon pump turnover as climate-relevant removal; baselines must explicitly exclude this natural turnover to demonstrate additionality. Baselines for mCDR can be defined at different spatial and conceptual scales, each serving distinct purposes. At the deployment scale, baselines describe the local conditions before the intervention, enabling MRV to demonstrate that additional carbon has been removed and stored. Counterfactuals describe the theoretical baseline conditions, often modelled using pre-intervention data, that would have existed without the intervention. At wider local to regional scales, baselines can capture counterfactual system behaviour to assess potential displacement effects, e.g. whether an Ocean iron fertilisation (OIF) deployment at one location reduces productivity and carbon uptake elsewhere. At the global scale, baselines underpin tracking of changes in the global carbon sink over time, supporting climate science objectives such as the global carbon budget. While not directly linked to mCDR MRV, these global



Credit: EMB based on a concept by Olivier Sulpis.

Figure 3.1 Main components essential for Monitoring, Reporting and Verification (MRV) of mCDR. The different components are explained in this chapter.

reference points provide important context for understanding cumulative changes from both climate change and mitigation interventions. In this document, baselines and counterfactuals are used interchangeably.

In climate mitigation accounting, emission reductions refer to actions that avoid or reduce the release of GHGs into the atmosphere compared to a baseline, whereas CDR refers to human activities that actively remove CO_2 from the atmosphere and store it for a climate-relevant period. Some mCDR methods, such as coastal restoration, can do both: an avoided-emissions component from preventing carbon loss and a removal component from new carbon uptake. Robust MRV must quantify each component separately and apply consistent baselines to ensure transparency and prevent double accounting.

Baseline measurements are hence important for regulators to distinguish between carbon removal and emissions reductions. For example, restoring marine ecosystems within a country's Exclusive Economic Zone (EEZ) might be classified as emissions reduction rather than carbon removal, depending on the baseline applied. If the baseline assumes historical and continued degradation (and associated CO_2 emissions) of those ecosystems, then restoration merely avoids these emissions, classifying it as an emission reduction. By contrast, if the baseline assumes stable, non-degrading ecosystems, then any additional carbon stored through biomass expansion would qualify as a carbon removal. Misclassification could lead to double accounting in national climate inventories, allowing countries to overstate their climate mitigation performance and potentially undermine the credibility of their reported contributions (Mengis et al., 2023), or the sale of carbon removal credits which then become meaningless within the voluntary carbon market.

However, establishing baselines is highly complex due to the dynamic and variable nature of oceanic carbon fluxes, which are influenced by circulation, mixing and spatially decoupled storage processes (Mengis et al., 2023). The impacts on marine ecosystems from historical anthropogenic activities and ongoing climate change further complicate baseline determination. The selection of a reference ecosystem state to guide restoration efforts is key and involves decisions with significant ecological and regulatory implications.

The spatial disconnect between carbon removal and storage (see Section 3.3) raises contentious questions about equity and justice in the allocation of carbon removal credits. This spatial disconnect is two-fold. On the one hand, there is often a geographical difference between where the CO_2 is removed from the atmosphere and where it is ultimately sequestered, due to the dynamic nature of Ocean biogeochemical processes. On the other hand, the entity paying for the removal activity may be spatially disconnected from the activity itself. For example, a high-emission country such as Germany might claim credit for climate mitigation resulting from an intervention whose sequestration benefits are realised in the Global South, raising questions about the equitability of the practice. This highlights the justice and equity dimensions that will have to be taken into consideration when developing national and international MRV for mCDR and corresponding regulatory frameworks (Berger et al., 2024).

Credit: Sanja Matić-Skoko, IZOR.

Sediment and vegetation sampling for carbon sequestration analysis in the Pantan Special Reserve salt marshes (Croatia) in the framework of the Interreg Adriatic-Ionian project Cradles (Creating Resilient Areas to Develop Lifecycles and Ecosystems Services).

Regulation of MRV for mCDR faces an additional political challenge: Some countries resist including coastal ecosystems in their national carbon accounting inventories, as the degradation of these environments has turned them into net carbon sources rather than sinks. Therefore, including coastal ecosystems in their national inventories would fundamentally change these countries' overall climate accounting balance.

In addition, regulating open-Ocean mCDR within a country's EEZ is technically challenging, as carbon fluxes are transboundary and governance frameworks for managing them remain difficult to implement. Consistent inclusion of mCDR in Nationally Determined Contributions (NDCs) would require international agreement under the United Nations Framework Convention on Climate Change (UNFCCC[1]), and the regulation of high-seas carbon credits remains unresolved (Boettcher, 2023).

3.3 Durability - timescales of carbon removal

Establishing how long the carbon removed by a mCDR method will stay out of contact with the atmosphere is a very important component for MRV (Figure 3.1). Durable mCDR carbon storage refers to the sequestration of carbon in a form that remains isolated from the atmosphere for an extended period of time, often for at least 100 years. For some mCDR methods, this durability is proposed to be achieved by sinking organic biomass into the deep Ocean, particularly in low-oxygen deep regions. However, the actual longevity of storage depends on many factors such as the water column depth, the accumulative depth of deposition within the sediment, the nature of the sediment, the local oceanographic conditions, and other human activities, which may lead to either long-term sequestration or re-release of CO_2 (Baker et al., 2022). Ensuring that the stored carbon remains sequestered over climate-relevant timescales (i.e. hundreds to thousands of years) is critical for meeting climate mitigation goals. However, the actual longevity and efficiency of storage depend on multiple factors, including the equilibration times between the Ocean surface and atmosphere, and the efficiency of the biological carbon pump in transporting carbon to depth. These processes are very uncertain, and therefore requires long-term monitoring to verify storage, which represent major challenges for the practical implementation of mCDR methods.

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[1] https://unfccc.int/

Longer-term storage can be achieved when organic carbon reaches the seafloor and is buried and stored over long timescales (Siegel et al., 2023). Carbon transported to the deep Ocean remains isolated from the air-sea interface because of the layering of the Ocean. However, depending on the geographical location it will eventually resurface due to Ocean currents, with storage timescales estimated from decades to thousands of years (Ricour et al., 2023). In shallow water sediments, storage timescales of organic carbon are highly sensitive to human activities. Bottom trawling will re-suspend the carbon into the water column, potentially leading to its re-release into the atmosphere (Porz et al., 2024). Therefore, long-term monitoring strategies are required to ensure long-term storage of carbon in regions vulnerable to human activities. Additionally, climate change and its impact affect the oceanic carbon storage capacity and thus the timescale of carbon removal. Such changes could alter the long-term effectiveness of mCDR methods, emphasising the need for MRV strategies that consider both natural and human-driven impacts on carbon storage durability.

For biotic mCDR methods (see Section 2.1), the form and location of carbon sequestration are crucial to determine the durability of the carbon storage. Consensus on timescales of durable carbon sequestration has not been reached, with estimates ranging from decades to millennia (Brunner et al., 2024), and yet durability is one of the critical factors at the core of robust MRV and a major knowledge gap (Ho & Bopp, 2024). Carbon sequestration timescales are often discussed in the context of climate-relevant timescales, defined within the IPCC assessments as a minimum of 100 years (IPCC, 2007), but durability timescales of less than 1,000 years are argued to be insufficient for net zero climate targets as warming continues when CO_2 is re-released (Brunner et al., 2024). Durability of carbon storage varies considerably between methods, with Ocean iron fertilisation estimated at 10-100 years, artificial upwelling/downwelling at 10-1,000 years, and macroalgae cultivation at 10-100 years but will be highly dependent on sinking location (NASEM, 2022), coastal Blue Carbon at 1,000 years, and Ocean Alkalinity Enhancement (OAE) at up to 20,000 years (Cross et al., 2023).

Durability tiers for mCDR methods (Table 3.1) help set MRV requirements and crediting rules. Methods in the short-term durability tier (years-decades), require higher-frequency monitoring in the near-term to detect rapid reversal risks and to evidence continued storage. Methods in the medium-term tiers need post-deployment observation over decades to centuries to ensure the permanence assumptions hold. Methods in long-term tiers can justify higher confidence credits but require pre-verified storage conditions. Some methods straddle tiers depending on deployment design.

Table 3.1 Durability tiers for mCDR methods and examples of carbon storage reservoirs.

DURABILITY TIER	TYPICAL STORAGE DURATION	RESERVOIR EXAMPLES	CONSIDERATIONS
Short-term	Years to decades (<100 years)	Upper Ocean dissolved inorganic carbon, biomass in living vegetation or plankton.	Vulnerable to rapid re-release due to biological respiration, disturbance or warming; may provide temporary climate benefit if removal is continuous.
Medium-term	Centuries (≈100–1,000 years)	Deep Ocean dissolved inorganic carbon (below thermocline), refractory dissolved organic carbon, buried organic matter in sediments, long-lived products.	Requires stable environmental conditions; storage can be reversed by mixing, trawling, sediment erosion or climate-driven circulation changes.
Long-term	Millennia, tens of millennia (≈1,000–100,000 years)	Geological formations (saline aquifers, depleted oil/gas fields), carbonate minerals (from mineralisation or OAE), dissolved inorganic carbon in seawater.	Very high durability; reversal only from tectonic processes, extreme chemical changes, or long-term geologic cycling.
Permanent	>100,000 years	Deep geological carbonates, subduction into Earth's mantle.	Effectively permanent.

3.4 Life Cycle Assessments

Life Cycle Assessments (LCAs) provide a rigorous, end-to-end framework for quantifying greenhouse-gas (GHG) emissions and environmental impacts across every stage of a process: from upstream activities like raw-material extraction, transportation and production, through on-site operations, to downstream disposal or recycling. For example, OAE (see Section 2.2.1) incurs emissions during mineral quarrying, crushing, shipping and dispersal, which can be quantified by LCAs, and compared against a "business-as-usual" baseline to determine true net carbon removal (Abd Rashid & Yusoff, 2015).

LCAs can model multiple scenarios to address uncertainties in carbon accounting and predict a spectrum of potential long-term carbon storage outcomes. LCAs also assess spatial and temporal variability by examining emissions at each life cycle stage, including seasonal changes like Ocean biological storage cycles or land-use changes for the production of biofuel used by ships. Biofuel production is a useful example that highlights the value of LCA as a tool since biofuel production and any related land-use changes (e.g. deforestation), seasonal uptake variability, and non-CO_2 GHGs emissions such as

CH_4 and N_2O, can offset or even reverse CO_2 savings when compared to fossil fuels. By incorporating CO_2eq metrics (see Section 3.1), LCAs capture the total warming impact of all GHGs, crucial for contrasting emissions from mCDR methods with those from fossil fuels (see Section 7.2).

Moreover, LCAs can help identify the potential for leakage, where carbon savings in one area may inadvertently increase emissions elsewhere and therefore identify indirect effects of mCDR methods. LCAs also define clear system boundaries to model risks of re-emission of GHGs from storage sites and assess long-term carbon sequestration stability.

LCAs critically examine claims of carbon neutrality, for example in the context of biofuel, which, despite its carbon-neutral label, can involve significant emissions. By examining the full life cycle, from origin to end-of-life stages, LCAs provide a complete picture, ensuring a more accurate and transparent assessment of carbon mitigation strategies. While LCAs provide scenario-based estimates across the full life cycle including environmental impacts, eMRV (see Section 3.5) focuses on collecting and verifying real-time operational data to assess actual carbon removal and environmental impacts during project implementation. Combining LCAs with robust eMRV protocols, can therefore enhance the credibility and comparability of mCDR efforts by linking modelled estimates to real-world outcomes.

3.5 Environmental impact

All Ocean interventions, including mCDR, carry inherent environmental risks, many of which remain poorly characterised, particularly in deep-sea environments (Lidström et al., 2024). The nature and severity of environmental risks depend on the specific mCDR method, but also the scale, duration and timing of deployment, as well as the location and sensitivity of species and habitats.

Environmental impact risks are summarised in Table 3.2. The alteration of physical and chemical conditions due to mCDR may cause unintended consequences for ecosystems. Risks include changes to local circulation patterns, stratification (Keller et al., 2014), light penetration and the pH regime, as well as trace metal release (Bach et al., 2019), oxygen depletion (Oschlies et al., 2025b), nutrient robbing (i.e. depletion of essential nutrients that would otherwise support natural CO_2 uptake through photosynthesis elsewhere) and net nitrogen loss. The risk of habitat alteration due to enhancement of noise, entanglement risks and smothering (Loomis et al., 2022) also needs to be considered. Marine CDR methods could shift plankton diversity and abundance (Santos-Bruña et al., 2025) or affect calcifying plankton communities (e.g. coccolithophores), with knock-on effects on ecosystem function and services such as fisheries and aquaculture (Strong et al., 2009).

Marine CDR methods can also produce climate-active gases through complex feedback loops, which may undermine the effectiveness of the method and should therefore be considered in environmental monitoring. In addition, some mCDR methods may stimulate the production of biologically derived aerosols such as dimethyl sulphide (DMS), with the potential to affect cloud formation and regional climate. For instance, site-specific field studies for Ocean fertilisation, showed that DMS levels can increase (Levasseur et al., 2006). Due to DMS's role in aerosol-cloud interactions, and in ozone depletion if it reaches the stratosphere, it should also be included in environmental monitoring. Potential impacts of mCDR may be local or far-field in time and/or space, such as acidification of intermediate or deep waters due to transport of carbon to depth for certain mCDR methods. Implications for MRV include the requirement of baselines/counterfactuals at regional scales (not just at the deployment site), with nutrient and carbon mass balances, tracer particle studies, and coupled observations - models to detect leakage or displacement of climate benefits.

Given these risks, transparent and comprehensive Environmental Impact Assessments (EIAs) must be a prerequisite to permitting the deployment of a mCDR method (see Section 6.1.1). Ongoing modelling and environmental monitoring should track both anticipated and unforeseen effects across physical, chemical and biological parameters (eMRV). However, implementing eMRV presents challenges, including the lack of standardised guidelines, operational and technical limitations in implementing suitable methods to detect and measure impacts, gaps in baselines data, and lack of suitable governance mechanisms. Clear protocols for determining unacceptable ecological side-effects that trigger policy and management responses, such as cessation or temporary suspension of a mCDR deployment, should be established in advance of mCDR deployment to ensure responsible and adaptive management (Boyd et al., 2023).

Box 2. In-depth focus: Challenges for MRV in the open Ocean (Ocean Alkalinity Enhancement and Ocean Iron Fertilisation)

The application of MRV for Ocean Alkalinity Enhancement (OAE), Ocean iron fertilisation (OIF) and other mCDR methods, is challenging as it takes place in natural open-Ocean systems where carbon fluxes are highly variable. The challenges primarily relate to: (a) the spatio-temporal decoupling between these mCDR actions and their effects, meaning that when and where you add alkalinity or nutrients in the open Ocean often do not match the locations and times where the resulting CO_2 uptake actually occurs, making it difficult to directly link the intervention to its carbon- removal effect; (b) the spatially-dependent timescales of carbon removal; (c) the slow, regionally and seasonally varying CO_2 equilibration timescale; (d) the multiple timescales of unintended biogeochemical and ecological impacts; and (e) the insufficient consideration of all environmental impacts to be covered by MRV.

Quantifying the carbon sequestration potential of OAE and OIF requires accurate estimation of the net increase in carbon storage resulting from mCDR (additionality) and the duration for which carbon remains stored in the Ocean (durability). To assess the additionality, it is essential to distinguish carbon storage that already occurs due to natural processes and other human activities, from the storage caused by mCDR methods. This requires the knowledge of a baseline, which is not fixed, as is influenced by significant natural variability and ongoing anthropogenic-driven changes in the Ocean (Gruber et al., 2023). Models that incorporate interactions between the Ocean and atmosphere (see Chapter 5) are required to realistically estimate additionality (Yamamoto et al., 2024). Net carbon removal quantification is further complicated by the slow CO_2 Ocean-atmosphere equilibration process, which can take from several months to a year, depending on mixed layer depth, buffering capacity, wind speed and ice cover (Nowicki et al., 2024), which contribute to significant seasonal and geographical variations (Zhou et al., 2025) that must be taken into account when estimating atmospheric CO_2 drawdown (Bach et al., 2023). Additional challenges include CO_2 fluxes back to the atmosphere caused by decreases in atmospheric CO_2 levels, that can, for instance, result from land responses to global atmospheric CO_2 fluctuations (Keller et al., 2014). For example, when atmospheric CO_2 is taken up by mCDR, but the resulting lower air–sea CO_2 gradient cause some CO_2 to diffuse back from the Ocean into the atmosphere. Similarly, changes in atmospheric CO_2 levels can prompt soils and vegetation on land to release or absorb CO_2 , thus partially offsetting the initial removal. In the Ocean, the durability of biologically-derived carbon storage is heavily influenced by Ocean dynamics, making it difficult to constrain through direct observation, so inverse modelling (DeVries et al., 2012) and/or virtual Lagrangian particle tracking (i.e. simulating the path of particles through space and time) (Baker et al., 2022) is needed to estimate the centennial-scale sequestration (Ricour et al., 2023) required to assess durability (Buesseler et al., 2024).

Developing conceptual models for both OAE and OIF requires not just models that represent the physics but also need to include the chemical and biological processes that unfold over multiple spatial and temporal scales, and impact Ocean biogeochemistry and ecosystem structure. Monitoring these environmental changes requires comprehensive observing systems (see Chapter 4), which need to be complemented by experiments mimicking natural conditions, and carefully conducted field trials.

Mesocosms (Figure 3.2) are commonly used in OAE research (Riebesell et al., 2023). Mesocosms are experimental enclosures filled with seawater and/or sediment with volumes ranging from 1 to 1,000 m^3, meant to act as realistic replicates of natural environments and ecosystems. They provide estimates of the dissolution rates of alkaline minerals, the effects of dissolution on seawater chemistry (Fuhr et al., 2025), and of the response of organisms to OAE, e.g. benthic (Hylén et al., 2023) and planktonic communities (Sánchez et al., 2024). Field deployment of OAE is at an early stage. Early field trials (e.g., an alkalinity-enhanced wastewater discharge) show near-field chemical changes (Kitidis et al., 2024), while tank and mesocosm studies indicate that air-sea CO_2 equilibration can take weeks to months and report limited effects on early fish life stages under tested conditions (Goldenberg et al., 2024). Offshore, ecosystem-scale field confirmation of these patterns is required, but still limited. Field trials also highlight crucial processes altering the efficiency of OAE, such as the precipitation of secondary minerals (Hartmann et al., 2023), as predicted from laboratory experiments (Moras et al., 2022). In OIF applications, *in situ* experiments have been performed since 1990 and report mixed results: while adding iron to iron-limited Ocean regions has indeed stimulated phytoplankton growth, most experiments did not report any significant increase in the carbon export below the Ocean mixed layer (Yoon et al., 2018).

Mesocosm experiments and field trials are often limited in duration, making it difficult to evaluate the long-term effects of OAE and OIF. Continuous, prolonged studies are necessary to understand chronic impacts and the potential for unforeseen ecological shifts over time. Achieving sufficient replication in mesocosm or field studies can be challenging due to logistical and financial constraints, and limited replication may affect the statistical robustness of the findings, especially given the inherent variability in biological responses.

Table 3.2 A summary of key potential environmental impacts for the mCDR methods considered in this document.

MARINE CDR METHOD	DESCRIPTION	POTENTIAL ENVIRONMENTAL IMPACTS
BIOTIC METHODS		
Pre-existing marine biomass removal	Enhanced sinking of naturally occurring biomass (such as Sargassum drifts) to the seafloor to sequester carbon for long timescales.	• Oxygen depletion and acidification in deep-sea zones; • Alteration of deep-sea nutrient cycles; • Risk of carbon re-release upon decomposition; and • Unintended benthic ecosystem shifts.
Marine biomass cultivation and sinking	Enhanced sinking of cultured and harvested biomass to the seafloor to sequester carbon for long timescales.	• Oxygen depletion and acidification in deep-sea zones; • Alteration of deep-sea nutrient cycles; • Risk of carbon re-release upon decomposition; • Unintended benthic ecosystem shifts; and • Large-scale mono-cultivation could alter local pelagic ecosystems.
Marine biomass cultivation for durable products and energy	Cultivation of marine organisms, such as seaweed, which can later be harvested and utilised to make durable products or for generating energy coupled with carbon capture and storage.	• Habitat disturbance and bycatch; • Alteration of nutrient cycles; and • Large-scale mono-cultivation could alter local ecosystems.
Ocean fertilisation	Adding nutrients to the surface waters to enhance phytoplankton growth and increase CO_2 uptake. The sinking of biomass to the seafloor sequestering carbon for long timescales.	• Excessive nutrient input can cause harmful algal blooms, oxygen depletion and acidification, potentially destabilising local ecosystems; • Shifts in food web dynamics; • Release of GHGs (e.g. N_2O, DMS, CH_4); and • Downstream nutrient robbing.
Artificial Upwelling	Using engineered systems to bring nutrient-rich deep waters to the surface, which can enhance phytoplankton growth and increase CO_2 uptake. The sinking of biomass to sequester carbon with short-term durability.	• Disturbance of natural circulation; • Potential nutrient imbalances; • Risk of triggering harmful algal blooms, oxygen depletion and acidification; • Disruption of natural upwelling patterns; and • Risk of release of GHGs, including upwelled CO_2, to the atmosphere.
Coastal Blue Carbon management	Enhance carbon storage by restoring or increasing coastal ecosystems (e.g. mangrove forests, seagrass meadows, salt marshes). Triggering alkalinity release through $CaCO_3$ dissolution and anaerobic organic matter decay, which can neutralise CO_2.	• Potential current habitat disruption, including unintended, possible beneficial, changes in local biodiversity; and • Conflicts with other coastal activities.

MARINE CDR METHOD	DESCRIPTION	POTENTIAL ENVIRONMENTAL IMPACTS
GEOCHEMICAL METHODS		
Ocean Alkalinity Enhancement	Increasing seawater alkalinity to convert dissolved CO_2 into stable HCO_3^- and CO_3^{2-}, thus increasing the drawdown of atmospheric CO_2.	• Altered pH levels and reduction of dissolved CO_2; • Nutrient imbalances; • Ecosystem disturbances, such as reduced light availability from added particulates, or disturbance of benthic ecosystems by sinking of carbonate minerals due to excessive alkalinity; • Rapid changes in local chemistry may stress marine organisms if pH or nutrient levels shift abruptly; and • Release of heavy metals, depending on mineral source.
Artificial downwelling	Using engineered systems to force CO_2-rich surface water into deeper waters, effectively isolating it from the atmosphere.	• Altered local circulation patterns; • Disruption of nutrient distributions and oxygen concentrations; • Possible impacts on deep-sea ecosystems; and • Modified water stratification, and nutrient and oxygen cycles, affecting deep-sea habitats and biota.
Direct Ocean carbon removal	Using chemical and electrochemical systems to extract dissolved CO_2 directly from seawater. This CO_2 is then stored in underground geological formations.	• Generation of chemical by-products; • High energy consumption; • Localised water chemistry alterations; and • Potential toxicity to marine life, with ecosystem consequences.

Credit: Signe Klavsen, Michael Sswat and Uli Kunz.

Figure 3.2 Pelagic mesocosm facilities for Ocean Alkalinity Enhancement (OAE) research. OAE increases seawater alkalinity to convert dissolved CO_2 into stable HCO_3^- and CO_3^{2-}, thus increasing the drawdown of atmospheric CO_2.

3.6 Co-deployment of mCDR methods

The (un)intended co-deployment of mCDR methods is a challenge when undertaking robust MRV for mCDR. Examples of intentional co-deployment include electrochemical iron fertilisation and OAE, which could alleviate Ocean acidification as a co-benefit (Taqieddin et al., 2024), Artificial upwelling (AU) to support scalable open Ocean macroalgae farming (Wu et al., 2023), and the dispersal and subsequent burial of alkaline-coated buoys made from terrestrial biomass with macroalgae seedlings attached to the buoys, a strategy that was trialled by a mCDR start-up called Running Tide that has since ceased operations[2]. An example of unintended co-deployment is OAE via dissolution of silicate rocks, which may have secondary fertilisation effects by releasing iron (Bach et al., 2019).

Co-deployment of mCDR methods will increase the number of confounding factors leading to increased uncertainty around the efficacy and impacts of the methods (Vivian et al., 2024). Measuring the net effect of more than one mCDR method on carbon uptake and storage will require more parameters to be measured over larger spatio-temporal scales, as the timescales of influence are likely to differ for the different methods. For example, for OAE via dissolution of the mineral olivine (a silicate mineral), measurements of seawater carbonate system parameters may be sufficient to quantify net carbon uptake, if supported by modelling and statistical methods (Ho et al., 2023). However, assessing its unintended iron fertilisation effect would need additional biogeochemical monitoring, such as nutrient (nitrate, phosphate) and iron- specific sensors, alongside chlorophyll measurements using both *in situ* samplers and satellite Ocean-colour imagery across meso-scale patches (1,000–10,000 km^2) and over periods of weeks to months (Buesseler et al., 2024).

The combination of a global deployment of AU and OIF may yield great potential, by removing iron-limitation, however it might have negative impacts on the Ocean oxygen and nitrogen content (Jürchott et al., 2024). In addition, the thermal perturbation of the upper Ocean could alter the energy and moisture balance in the atmosphere, leading to changes in terrestrial ecosystems and thus carbon reservoirs (Keller et al., 2014).

If mCDR were to be scaled up, distinct mCDR methods will also likely interact with other uses of Ocean space, such as fisheries and aquaculture. Intentional co-deployments should be limited until MRV protocols for individual methods have been tested and proven to be effective. It is critical to address the knowledge gaps in the assessment of changes in efficacy and the practicality of undertaking robust MRV in co-deployment scenarios prior to any co-deployments.

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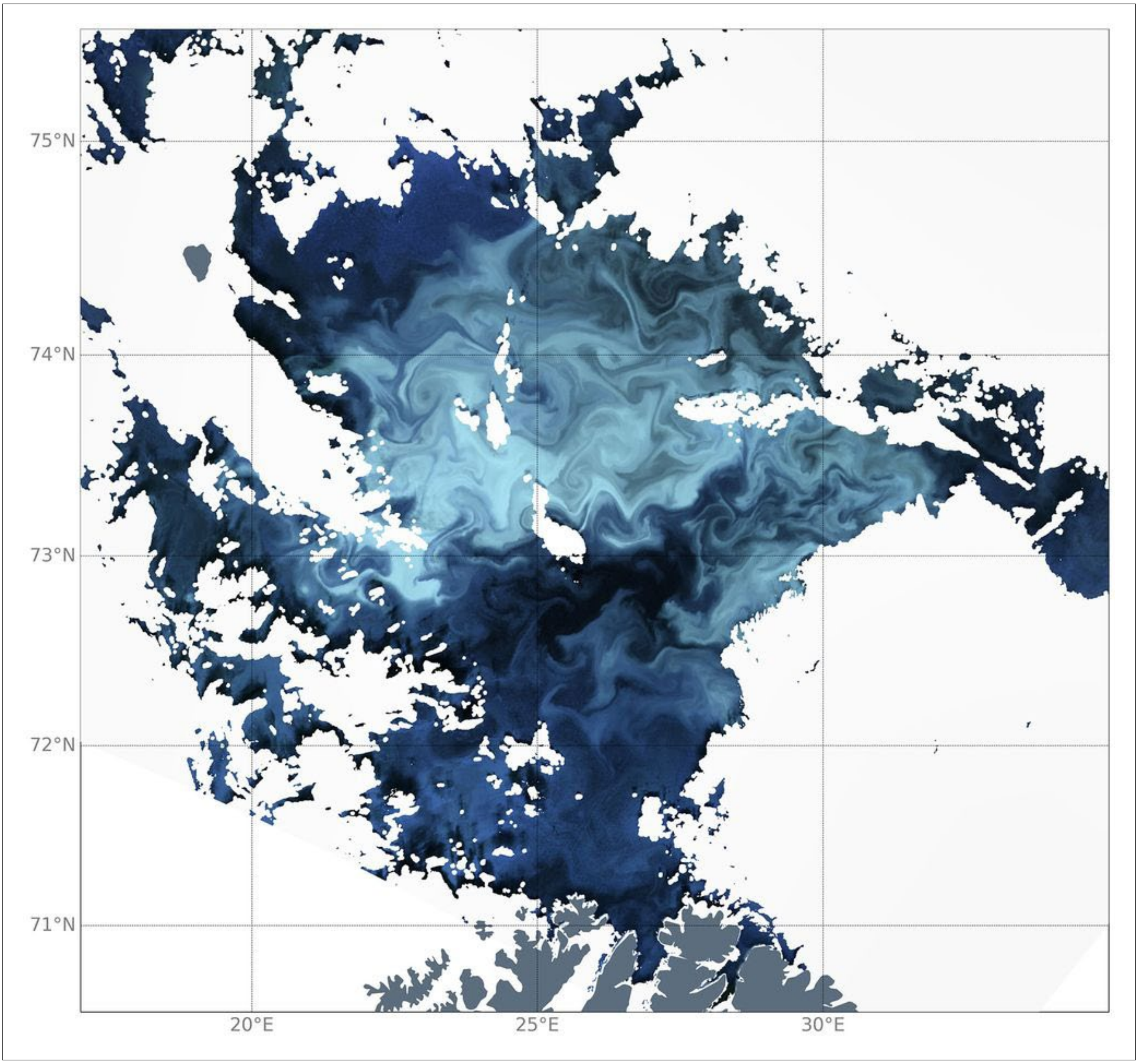
[2] https://19987014.fs1.hubspotusercontent-na1.net/hubfs/19987014/docs.runningtide.com%20files/Quantification%20Methodology%20v1.6.0_vPublic.pdf



Credit: Ben Loveday.

A bloom of coccolithophores in the Barents Sea on 13 July 2022, captured by the Ocean and Land Colour Instrument (OLCI) aboard the Copernicus Sentinel-3B satellite. Marine CDR methods could shift plankton diversity and abundance and affect calcifying plankton communities, such as coccolithophores, with knock-on effects on the ecosystem. Contains modified Copernicus Sentinel-3 data (2022), processed by EUMETSAT.

4 State of the Ocean carbon observing system and data capacities

4.1 Key variables for MRV for mCDR

To support robust MRV for mCDR, including the assessment of additionality and durability, it is essential to monitor key variables that help establish a baseline and attribute observed changes to mCDR methods. The selection of observational variables and design of monitoring strategies must be tailored to the specific mCDR method, deployment context, location and monitoring objectives.

The sea surface concentration or partial pressure of CO_2 ($p\mathrm{CO}_2$) is an essential variable that drives the direction of air-sea CO_2 exchange. When the $p\mathrm{CO}_2$ in seawater is lower than that in the overlying atmosphere, it creates a concentration or pressure gradient that promotes the uptake of CO_2 by the Ocean. The Ocean's ability to buffer carbon in its inorganic form is governed by the concentration of dissolved CO_2 products (total dissolved inorganic carbon or DIC, i.e., dissolved CO_2, HCO_3^- and CO_3^{2-}), seawater pH, and the total alkalinity (TA). These four variables of the seawater carbonate system are therefore essential for monitoring the Ocean's long-term CO_2 storage capacity for inorganic carbon. At least two of these four variables ($p\mathrm{CO}_2$, pH, DIC, TA) must be measured to fully characterise the seawater carbonate system; measuring only one is insufficient (Zeebe, 2012). Furthermore, measurements of CH_4 and $\mathrm{N}_2\mathrm{O}$ complete the observing system for the most important greenhouse gases (GHGs).

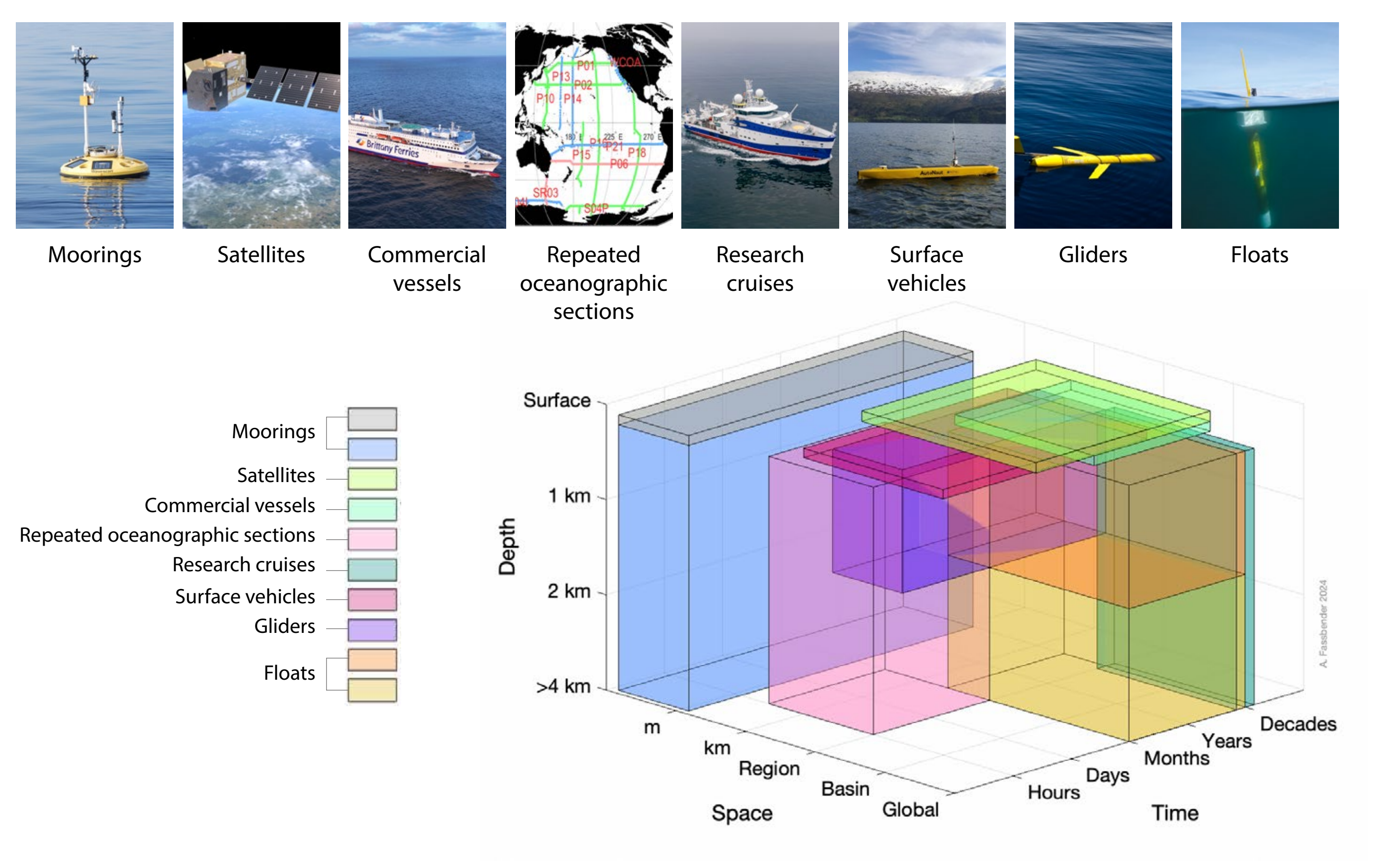
Monitoring additional variables, such as dissolved organic carbon (DOC) and particulate organic carbon (POC), is required to determine baselines and assess environmental and ecological impacts. POC plays a crucial role in carbon export from the euphotic zone—the upper layer of the Ocean with enough sunlight for photosynthesis—to the Ocean floor. For both DOC and POC, understanding bioavailability and recycling rates is key, as CO_2 can be rapidly respired back into dissolved components.

Dissolved inorganic nutrient concentrations, oxygen levels and trace metals should also be monitored to assess environmental and ecological consequences of mCDR (i.e. for eMRV). Where relevant, eMRV should include monitoring of short-lived climate forcers (e.g. DMS) and non-CO_2 GHGs, such as CH_4 and $\mathrm{N}_2\mathrm{O}$, and their sea-air fluxes to capture responses of short-lived climate forcers (see Section 3.5). Finally, remote estimates of biomass and primary productivity should be used to assess large-scale ecological effects of mCDR as well as to monitor shifting ecological baselines. Monitoring these variables helps detect unintended environmental side effects, informs adaptive management strategies, and ensures that mCDR methods do not undermine Ocean health or ecosystem services.

While some variables, such as sea surface $p\mathrm{CO}_2$ and air-sea CO_2 flux, are broadly relevant across methods, others are approach-specific. For example, full seawater carbonate system parameters may be essential for Ocean Alkalinity Enhancement (OAE) but may be less critical for macroalgal sinking, where monitoring may instead focus on biomass quantification, fate tracking and carbon durability. However, understanding of the air-sea CO_2 fluxes in this case may be needed to confirm the additional removal of CO_2 from the atmosphere, and to measure any unexpected cascading feedbacks affecting additionality (Bach et al., 2021). Similarly, in Ocean fertilisation, monitoring deep Ocean carbon fluxes and air-sea exchange may be more relevant than DOC/POC measurements in the surface layer. Therefore, MRV design should begin with a clear articulation of the carbon removal mechanism and associated risks, followed by a fit-for-purpose observation strategy that supports additionality, durability and environmental safeguards. See Annex 2 for a suggestion on the minimum metrics, study designs and reporting elements needed to build up and support robust MRV for mCDR.

4.2 Observing platforms and the state of the technology

There are multiple ways of observing the Ocean (Figure 4.1). *In situ* measurements are key to monitoring changes in seawater chemistry and identifying the drivers behind these changes. However, the spatio-temporal heterogeneity of the Ocean requires multiple monitoring strategies. Discrete measurements taken during repeated oceanographic sections or transects on research or commercial vessels can provide insights from annual to decadal scales across Ocean basins. Continuous time-series measurements at fixed locations, e.g. on moorings, capture monthly to interannual variability in specific regions. High-frequency continuous measurements using sensors on platforms, such as gliders, floats, and surface and subsurface robotic vehicles, offer finer resolution and better spatial coverage, which could allow the capture of episodic events that impact seasonal and interannual variability that might be missed with discrete measurements. It is crucial to build upon these established methods while embracing innovation and new technology to improve efficiency and coverage. New sensor technology and platforms are continuously being developed to fill the current measurement gaps at various timescales.



Adapted from Andrea Fassbender (NOAA PMEL), with images from Poseidon System, HCMR; ESA/Mlabspace; Brittany Ferries; Carter et al. (2019); IEO-CSIC; Alberto Dallolio, NTNU; Balearic Islands Coastal Observing and Forecasting System (SOCIB); Olivier Dugornay/Ifremer.

Figure 4.1 Visualisation of how different observing systems contribute to the multi-scale monitoring required for MRV for mCDR, adapted from Andrea Fassbender (NOAA PMEL). Ocean carbon monitoring platforms (top row) each have their own respective observational coverage across spatial (metres to global scale), temporal (hours to decades), and depth (surface to >4 km) dimensions (bottom 3D graph).

Emerging sensors, autonomous platforms and data integration tools have the potential to enhance long-term monitoring, reduce operational costs and capture processes at higher spatio-temporal resolution. Such developments complement existing observation strategies and are essential for sustaining standardised, cost-effective and long-term monitoring efforts.

In addition to *in situ* measurements, satellite and autonomous sampling methods are also important. While the variables of the seawater carbonate system ($p\text{CO}_2$, pH, DIC, and TA) cannot be detected remotely, satellites can provide valuable sea surface chlorophyll concentration, temperature, salt content and Ocean circulation data, which help in understanding the distribution of carbon in the Ocean.

4.3 Observing programs

To observe the testing and potential future deployment of mCDR, we still lack globally coordinated and sustained observing programs tailored to the needs of this new and emerging field. The pursuit to understand the Ocean as a carbon sink has led to the foundation of global observing programs and coordination efforts that can serve as best practice for future mCDR observing programs.

The Global Ocean Observing System[3] (GOOS), established by the Intergovernmental Oceanographic Commission (IOC) of UNESCO[4], plays a pivotal role in coordinating global Ocean observation efforts. GOOS aims to address global needs for better climate change forecasting, efficient management of marine resources, disaster mitigation and the sustainable use of coastal and oceanic zones. It also supports the monitoring of Essential Ocean Variables[5] (EOVs), such as inorganic carbon, using innovative technologies like biogeochemical sensors and autonomous profiling floats. By coordinating international efforts, GOOS enhances our ability to collect and share high-quality data, providing key insights into Ocean health and guiding effective marine resource management decision-making.

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[3] https://goosocean.org/

[4] https://www.ioc.unesco.org/

[5] https://goosocean.org/what-we-do/framework/essential-ocean-variables/

Ocean observing networks within GOOS include ARGO[6], Voluntary Observing Ships[7], GO-SHIP[8], OceanSITES[9], Ocean Gliders[10], and others. In addition to *in situ* efforts, satellite missions, such as GOSAT[11], SENTINEL[12] and PACE[13] provide essential, free and publicly open marine data covering the surface of the global Ocean. Historical observing programs offer invaluable insight for MRV for mCDR, as they provide crucial data on measurement quality, uncertainty, and best practice guidelines (Dickson et al., 2007). Several long-term observing programs, such as Voluntary Observing Ships, GO-SHIP, and ARGO, have received significant funding and support from the USA. Ensuring the continued support for such long-term observing programs, via international cooperation, and across successive administrations, is essential for mCDR and MRV.

At the European level, the Integrated Carbon Observation System[14] (ICOS) is a research infrastructure that supports climate science and policy by monitoring GHGs, including carbon in the Ocean. With 28 stations in eight countries, using commercial ships, buoys and research vessels, ICOS data includes the four key seawater carbonate system variables: $p\mathrm{CO}_2$, pH, TA and DIC, though coverage varies by site and platform (see Section 4.1).

While global observing systems such as GOOS are foundational for understanding long-term Ocean trends, supporting climate models, and informing global carbon budgets, they are not sufficient on their own to support MRV for mCDR at the scale of individual deployments or pilot projects. Robust MRV at the project scale requires high-resolution, site-specific observations that capture localised changes in carbon fluxes, ecosystem responses and water mass movement. This requires targeted deployments of autonomous vehicles, sensor arrays, moorings and/or ship-based sampling in the vicinity of the mCDR deployments. These local observational strategies must be designed to measure changes relative to a pre-defined baseline, detect signals from the intervention amid natural variability and verify modelled storage outcomes. In this sense, global observing programs provide the necessary context, long-term stability and best practice guidelines, while local and regional observing systems must be developed (and adapted if possible) to directly support MRV efforts as mCDR methods are tested and deployed.

4.4 Public databases, accessibility and usability

Community-driven efforts to promote open data systems have led to significant advancements in understanding climate change and marine carbon dynamics. Measurements obtained through different observing programs have been collected and unified in public databases, such as the Global Ocean Data Analysis Project[15] (GLODAP) for interior Ocean biogeochemical observations of seawater carbonate system variables, such as DIC and TA, the Surface Ocean CO_2 Atlas[16] (SOCAT) for surface Ocean $p\mathrm{CO}_2$, and the GEOMAR Memento database[17] for interior Ocean CH_4 and NO_2 measurements. These databases provide a foundation for studying the natural carbon cycle and its variability over time, thus enabling scientists to build background or baseline concentrations of the essential monitoring variables. The combination of these databases allows the marine carbon cycle community to study and track changes, which is critical for assessing the ongoing impacts of climate change (Friedlingstein et al., 2025).

For MRV, measurements need to be of a high standard, must be traceable and undergo routine intercomparisons and audits. For seawater carbonate variables, the JPI Oceans Ocean Carbon Capacities roadmap recommends: (i) establishing a European Hub for certified reference materials for measurements of the seawater carbonate system to reduce the current single-supplier risk (García-Ibáñez et al., 2025); (ii) implementing regular audits of Europe's surface-Ocean CO_2 observing system with clear assessment tools; and (iii) making better use of research and commercial vessels to reverse recent declines in surface CO_2 observations and ensure consistent delivery to SOCAT and the Global Carbon Budget[18]. These actions would strengthen data reliability and improve MRV traceability for mCDR.

As mCDR progresses toward deployment and regulation, Findable, Accessible, Interoperable and Reuseable (FAIR) data should be mandatory for project approval and inclusion in national or international carbon inventories. Data collected for the purpose of MRV should be made publicly available in standardised, interoperable formats and deposited in accessible repositories such as the community-accepted databases above. This approach will enable independent verification and quality control, best practice guidance, support cumulative learning across projects, and foster public and stakeholder trust in reported carbon removals. As mCDR methods scale up, adherence to FAIR data principles will be essential to enable coordinated international oversight and avoid fragmented or proprietary reporting that could undermine the credibility of carbon accounting.

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[6] https://argo.ucsd.edu/

[7] https://community.wmo.int/en/voluntary-observing-ship-vos-scheme

[8] http://www.go-ship.org

[9] https://www.ocean-ops.org/oceansites/

[10] https://www.oceangliders.org/

[11] https://earth.esa.int/eogateway/missions/gosat

[12] https://sentinels.copernicus.eu/

[13] https://pace.gsfc.nasa.gov/

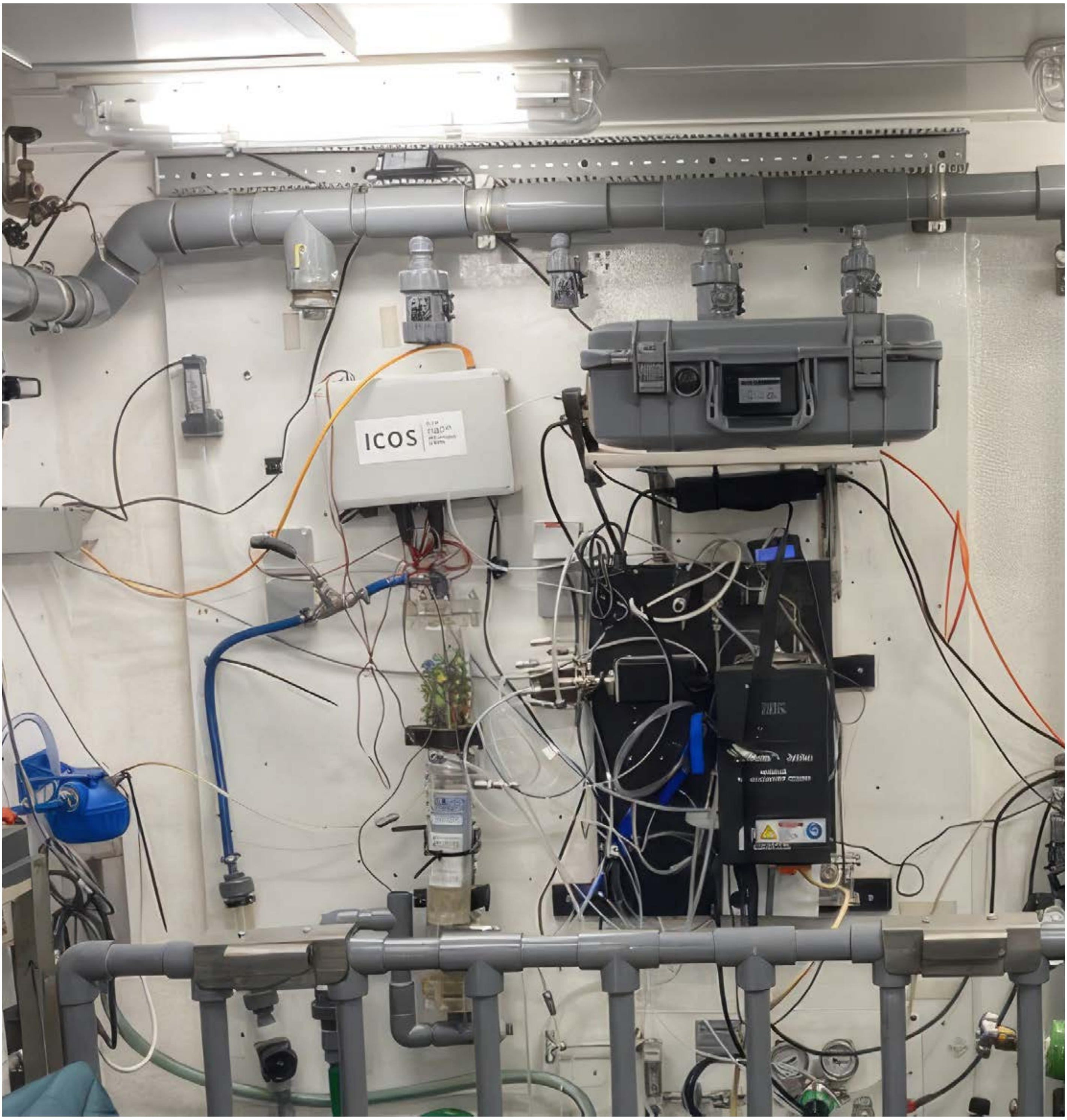
[14] https://www.icos-cp.eu/

[15] https://glodap.info/

[16] https://socat.info/

[17] https://memento.geomar.de/

[18] https://globalcarbonbudget.org/



The VLIZ underway system installed on the research vessel R/V Simon Stevin, measuring the concentration of the greenhouse gases CO_2, nitrous oxide (N_2O) and methane (CH_4) and Total Alkalinity in seawater.

Credit: VLIZ, ICOS Group.

5 State of modelling capabilities

5.1 Modelling to inform monitoring, reporting and verification

A model is a simplified representation of a natural system that helps understand, predict and analyse complex (environmental) processes. Models can be used to support the quantification of the Ocean's role in the global carbon budget and can provide insights into processes relevant to mCDR. Models can help evaluate the efficacy, scalability potential and storage durability of different mCDR methods, and are particularly useful for identifying and understanding potential (un) intended environment impacts, co-benefits and cascading feedbacks. In this chapter, only numerical models are covered, but physical models used to better understand mCDR methods, such mesocosms, are briefly described in Box 2.

Different modelling tools and approaches are used to address various facets of MRV for mCDR. They can range from very localised, high-resolution models (on the order of micrometres to millimetres) to global-scale Earth System Models (ESMs), which include representations of the Ocean, land, atmosphere and cryosphere (i.e. the Earth's frozen water, including snow, ice, glaciers, permafrost and sea ice). Higher-resolution, small-scale models tend to describe processes mechanistically, meaning that they explicitly represent the underlying physical, chemical or biological principles governing a process. Conversely, lower-resolution, large-scale models tend to be empirical or statistical, and hence they rely on established relationships between predicted variables and observed data. This diversity of scales and modelling tools is required to support different aspects of MRV, including: (i) predicting alkalinity generation, biomass growth and mineral dissolution relevant to MRV at immediate intervention sites; (ii) assessing atmospheric CO_2 removal efficiency relevant to MRV across local-regional scales and beyond deployment locations; and (iii) evaluating local and non-local ecological and environmental impacts spanning a broad spatio-temporal range. An overview of the current state of modelling approaches relevant for mCDR and MRV is provided below, ranging from process-level models to global ESMs (see also Figure 5.1).

5.2 Small-scale, mechanistic models

Models that focus on fine-scale physical, chemical, and biological processes are relevant to mineral dissolution, alkalinity enhancement and biomass growth for mCDR. For Ocean Alkalinity Enhancement (OAE), it is useful to predict the process of alkalinity generation itself, often through mineral dissolution, because it is not instantaneous and is associated with biogeochemical feedbacks at a microscopic scale. The most simplistic of these models are shrinking-core models, able to predict the dissolution of spherical grains of a known initial diameter (Lindman & Simonsson, 1979), assuming that the dissolved by-products mix in the surrounding water. For more complex shapes, more computationally costly 3D models can be used, which can simulate hydrodynamic effects, chemical reactions across heterogeneous grain surfaces and transport limitations (Sulpis et al., 2022a). Mineral dissolution immediately alters water chemistry around the dissolving grains, which may induce the precipitation of authigenic mineral phases (i.e. minerals that precipitate or recrystallise *in situ* within sediments, forming directly where they are found rather than being transported there), the clogging of sediment pores, or fuel microbial activity (Fuhr et al., 2022). These effects may enhance or reduce the net alkalinity release from mineral dissolution (Moras et al., 2022) and need to be resolved to predict how much alkalinity is being released in seawater.

For OAE methods where mineral dissolution happens in the seabed, diagenetic sediment models can be used (i.e. models that describe what happens to the sediment after it settles on the seafloor) (Sulpis et al., 2022b). Such models predict how freshly deposited sediments chemically and physically transform over time as they become buried, through reactions like mineral dissolution, cementation, compaction and microbial breakdown. For methods where dissolution takes place when minerals are suspended or settling through the water column, particle-settling models are used. The models simulate the deployment of minerals at the Ocean surface for OAE purposes, and the subsequent dissolution, settling through the water column, (dis)aggregation, and effects on grazing and organic matter consumption (Fakhraee et al., 2023a). They do not predict mCDR but provide a quantitative basis for the alkalinity generation rates of OAE methods, considering the immediate feedback mechanisms that alter OAE efficiency.

For biotic mCDR methods, small-scale models of macroalgae cultivation and phytoplankton productivity are critical for understanding carbon uptake efficiency, nutrient interactions, and physical constraints. Macroalgal growth models, such as the Floating Macroalgal Growth and Drift Model (FMGDMv1.0) (Zhou et al., 2021), simulate macroalgae productivity based on light-dependent photosynthesis, temperature-dependent enzymatic processes and nutrient uptake, and they also take into account light penetration, self-shading and water mixing, which can affect photosynthetic activity (Hurd, 2000). Finally, particle-based biomass settling models track the behaviour of detached macroalgal fragments as they sink and degrade in the deep Ocean, playing a crucial role in assessing the

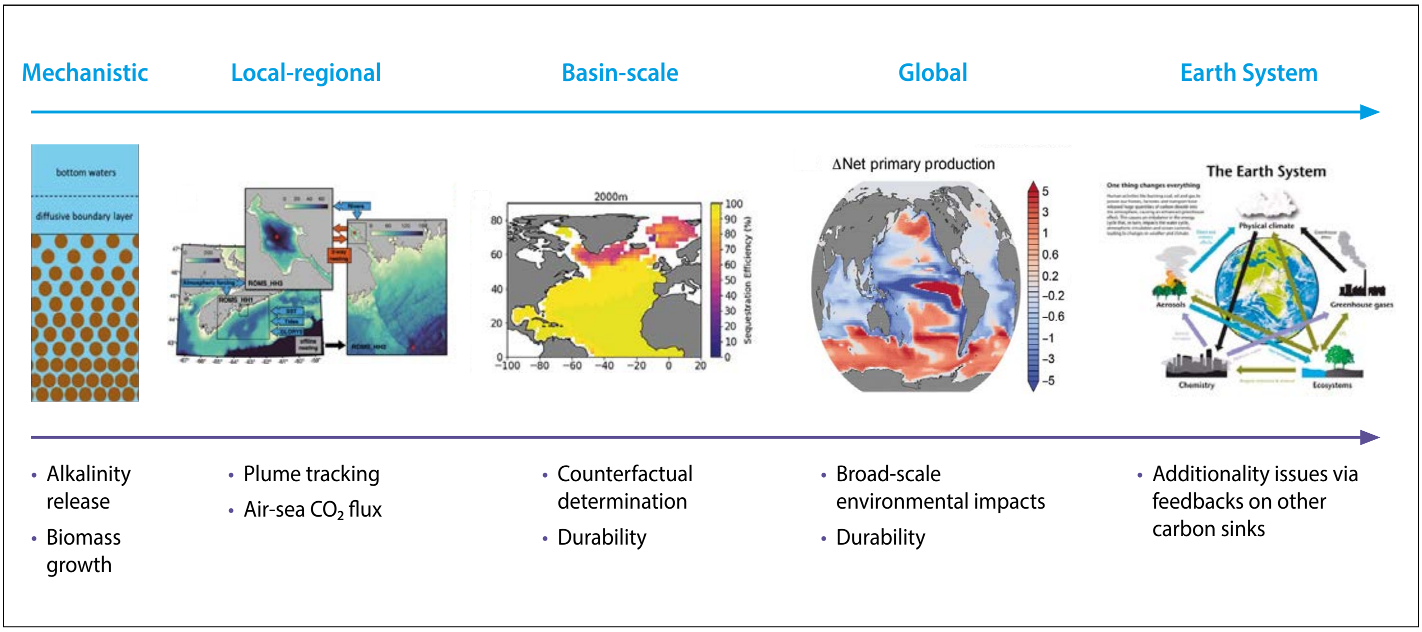


Figure 5.1 Graphic illustrating examples of how modelling can be used for MRV from mechanistic to Earth System scale models (blue arrow), with some examples of model outputs relevant to MRV (purple arrow). Figures modified from Sulpis et al. (2022), Wang et al. (2025), Baker et al. (2022), Tagliabue et al. (2023), Met Office (2013) Reprinted with permission © Crown Copyright 2013, data supplied by the Met Office.

Credit: EMB based on a concept by Chelsey Baker.

long-term storage potential of macroalgae-based mCDR strategies. Wu et al. (2023) used such models to simulate macroalgae cultivation and sinking, highlighting the redistribution of nutrients and potential large-scale ecological impacts.

Thus, for MRV, models on scales from micrometres to metres are useful for predicting realistic alkalinity release rates from mineral dissolution, biomass growth rate and carbon export in the context of coastal restoration, offshore macroalgal cultures and Ocean fertilisation. Micrometre- to metre-scale process models simulate the dissolution of specific minerals (e.g. olivine, calcite) under varying temperature, pH and flow conditions to predict real time alkalinity release rates, guiding the placement and frequency of *in situ* water chemistry sensors needed for accurate monitoring. They also model local biomass growth and particulate organic carbon (POC) production for coastal restoration or macroalgal farms, informing the design of sediment traps and optical sensors to quantify export fluxes with sufficient spatial resolution (Ho et al., 2023). To predict induced air-sea CO_2 fluxes, and environmental and ecological repercussions, larger-scale models are needed (see sections below).

5.3 Marine ecosystem and food web models

Marine ecosystem and food web models are relevant to any mCDR methods that may alter or interact with marine biota. They can represent biotic life from phytoplankton to fish, to marine mammals and birds, and can range in geospatial scale from specific locations, such as a kelp forest in the California current region (Vilalta-Navas et al., 2018) to global-scale explorations of phytoplankton diversity (Dutkiewicz et al., 2020). These models vary in complexity and can represent different characteristics, behaviours and processes including, but not limited to, marine biodiversity, adaptive responses and acclimation of marine organisms, population dynamics, physiological traits and responses to anthropogenic drivers, as highlighted in the EMB Future Science Brief on marine ecosystem modelling (Heymans et al., 2018).

There are a diverse range of marine ecosystem models that could be applicable to mCDR, particularly in terms of understanding the impacts of mCDR perturbations and how they may cascade through the food web. Marine ecosystem models could provide a useful testbed to understand how the ecosystem may respond to mCDR perturbations. For example, kelp forest models can simulate responses to different growth and seabed deposition quantities. For instance, modelled changes in kelp supply to the Arctic seafloor were found to have altered deep-sea food web structure and biodiversity (Vilas et al., 2020); and modelling of large-scale harvesting of beach kelp suggested negative impacts on ecosystem functioning, as beach kelp provides essential food and shelter for coastal fauna (Orr, 2013). In terms of their application to MRV, any cascading impacts that lead to changes in the natural uptake and storage of CO_2 because of a mCDR perturbation (e.g. changes to calcifying plankton communities), should be modelled and may need to be included in carbon budget calculations to ensure additional carbon has been removed and stored compared to the counterfactual state. As small-scale field mCDR trials progress, thorough monitoring to capture any ecosystem feedback will be crucial to ensure these models can be further developed, parameterised, calibrated and validated, to capture critical processes and interactions between organisms and their environment and to inform MRV.

5.4 Regional scale models

Regional Ocean models, such as the Regional Oceanic Modelling System (ROMS, Shchepetkin & McWilliams, 2005), can be used to simulate Ocean dynamics and changes over time, especially in coastal areas. These models can simulate currents, mixing of water layers, and how substances such as nutrients, tracers or pollutants, spread. Regional models use a special type of grid that follows the shape of the Ocean floor, and can provide results in high resolution (typically from a few kilometres down to hundreds of metres in very localised domains). They can also be connected to larger models, and coupled with other models that simulate Ocean chemistry and ecosystems (Zhang et al., 2024). Thanks to these features, regional Ocean models can capture local and regional Ocean changes that bigger, global models may not be able to simulate. Regional models can also be used to simulate (future) mCDR scenarios.

In the context of mCDR, regional models are already used to explicitly simulate OAE deployments, design observing strategies via Observing System Simulation Experiments (OSSEs, see Section 5.7), and compare modelled signals to targeted measurements for attribution (see Section 3.1), which are core MRV tasks (Fennel et al., 2023). Recent studies, building on broader demonstrations of the ability to model coastal conditions (Laurent et al., 2021), include simulations of OAE to mitigate local acidification at the Great Barrier Reef (Mongin et al., 2021), and a coupled ice-circulation biogeochemical model that quantified local CO_2 uptake and dispersion to assess OAE efficiency in the Bering Sea (Wang et al., 2023). In addition, regional models have been used to assess localised dispersion, carbon storage and ecosystem impacts of OAE in coastal areas, highlighting potential risks like pH spikes in nearshore environments (Anderson et al., 2025). High-resolution nested ROMS models, where a fine-scale grid is embedded inside a coarser grid, have also been used to study effects of alkalinity addition on the Scotian Shelf, revealing enhanced CO_2 drawdown in productive shelf waters (Laurent et al., 2025). Furthermore, regional models can inform OAE site selection with passive tracer simulations to identify optimal deployment locations and timings, taking into account seasonal circulation patterns (Guo et al., 2025).

Regional Ocean models can be used to model plume tracking, transport pathways, to support the elaboration of footprint maps, and to provide guidance for experimental design for MRV. However, uncertainties in boundary-conditions and atmospheric forcing, process parameterisation, imperfect inclusion of biogeochemistry, and limited reach to model multi-decadal durability are limitations, that means that these regional models must be comprehensively validated with observations and linked to larger-scale global models given the spatial decoupling of uptake and storage. Incorporating regional modelling frameworks alongside global assessments (see Section 5.5) could therefore strengthen MRV by bridging the gap between local observations and system-scale carbon accounting.

5.5 Global-scale and Earth System Models

Global Ocean and Earth system models (ESMs) are widely used to investigate processes relevant to all Ocean-based mCDR methods. These low-resolution global simulations, also used extensively by the IPCC (IPCC, 2021), represent how different components of the Earth System interact and respond under various climate conditions and future scenarios. They are particularly valuable for capturing complex feedbacks and for assessing the net removal of atmospheric CO_2, essential for evaluating the overall efficacy of mCDR methods (Keller et al., 2018). Such models can also project long-term impacts across Earth's carbon reservoirs, such as changes in terrestrial soil respiration over centuries (Zickfeld et al., 2021). However, computational constraints mean that global models often simplify key processes, which contributes to significant uncertainties. For instance, projections of future biological carbon storage in the Ocean can diverge widely (Henson et al., 2024), with implications for simulations of mCDR methods that perturb the biological pump or alter Ocean alkalinity.

Global-scale, Ocean-only models, not coupled to other parts of the Earth system (i.e., atmosphere or land) can be used to investigate physical, biogeochemical and ecological processes at various spatial resolutions (from >100 km grid cells to <10 km grid cells) and span a range of complexity in terms of the structure and parameterisations of biogeochemistry components (Kwiatkowski et al., 2023). While these models help elucidate mechanisms and sensitivities, they cannot on their own demonstrate net CO_2 withdrawal from the atmosphere. Models of higher geospatial resolution are better at representing fine-scale physical, biogeochemical and ecological processes by explicitly resolving smaller spatial and temporal dynamics.

Global Ocean models parameterised to describe the formation and propagation of eddies, and the production and settling of biomass, have been used to study natural Ocean processes and to assess the efficacy, scalability and impacts of different mCDR methods through simulations. For example, Ocean models have been used to simulate the potential for global macroalgal cultivation within all EEZs and the subsequent negative impacts on phytoplankton primary production (Berger et al., 2023), how OIF may amplify climate change pressure on marine biomass (Tagliabue et al., 2023), and where near-coast OAE (Palmiéri & Yool, 2024) or offshore OAE (Hauck et al., 2016) is likely to be most effective. One common finding from these studies is that there are significant non-local effects on the carbon system, as well as non-local environmental and ecological impacts, which will have implications for MRV.

The scalability, efficacy, co-benefits and impacts of mCDR geochemical and biotic methods have been explored using idealised ESM simulations, for global OAE (Lenton et al., 2018), coastal OAE (Palmiéri & Yool, 2024), Artificial upwelling (AU) (Jürchott et al., 2023), large-scale OIF (Tagliabue et al., 2023), and a combination of OIF and AU (Jürchott et al., 2024). These studies demonstrate that OAE can have meaningful climate mitigation potential when considering CO_2 removal but will create large-scale perturbations in Ocean biogeochemistry and unclear ecological consequences (Feng (冯玉铭) et al., 2016); high regional variability in impacts and amelioration of Ocean acidification (Lenton et al., 2018); and it may weaken the terrestrial carbon sink (Palmiéri & Yool, 2024). Any CO_2 uptake potential from AU without the combination with Ocean iron fertilisation (OIF) is considered to be low due to iron limitation of biological production (Jürchott et al., 2024) and the upwelling of CO_2-rich-cold deep waters, which would potentially lead to CO_2 outgassing under low or net-zero emissions scenarios (Jürchott et al., 2023).

Long-term simulations can also investigate the response of deep-sea ecosystems, which are still poorly understood and observed, to mCDR methods (Levin et al., 2023). Overall, global-scale models are unsuitable for short-term MRV applications due to their coarse resolution, but they can be useful to predict environmental consequences and identify long-term feedbacks. They can also demonstrate some of the challenges facing robust MRV, such as that more than half of the CO_2 uptake takes place away from the OAE addition locations (Palmiéri & Yool, 2024).

5.6 Model intercomparison projects

The Coupled Model Intercomparison Project[19] (CMIP) is an international modelling initiative that uses ESM simulations to aid in understanding the past, present and future climatic changes in the Earth system due to natural variability and anthropogenic drivers. CMIP coordinates efforts to answer key climate-related research questions by designing comparable experimental ESM simulations that provide climate relevant information for national and international reports such as the IPCC reports (Dunne et al., 2024). The CMIP-endorsed Carbon Dioxide Removal Model Intercomparison Project[20] (CDRMIP; Keller et al., 2018), included mCDR in CMIP version 6 (Eyring et al., 2016), and developed an experimental protocol to test the climate system response to a deliberately large, idealised perturbation of global OAE. This unrealistic scale was chosen to isolate and understand theoretical system responses, rather than to represent any feasible deployment.

Regardless of the scale of focus of a given model, model intercomparison is essential for quantifying uncertainty and variability in mCDR estimates (Keller et al., 2018). Furthermore, the data sharing infrastructure, coordination and support provided by the CMIP framework provide useful inspiration for future coordination of mCDR and MRV modelling activities. These currently tend to rely on single models but should include community-led assessments of model ensembles (multiple models performing the same experiment), to allow for biases and variability to be identified, and for uncertainty to be quantified.

5.7 Modelling applications for monitoring, reporting and verification

Models can help to better design observing tools for MRV. For instance, Observing System Simulation Experiments (OSSEs) are used to design effective observation systems and optimise data assimilation strategies (Fennel et al., 2023). Boyd et al. (2023) showed that OSSEs can be used to evaluate the effectiveness of different observational strategies. This emphasises their role in refining MRV protocols by reducing uncertainty and improving the attribution of carbon flux changes to specific mCDR methods. In the context of OAE research, OSSEs can be used to help optimise observations, including where trade-offs exist between observational platforms. To do so, models can be run in data-unconstrained (free historical) mode or with data assimilation (reanalysis hindcasts) to test the value of alternative sampling designs. A hindcast is a model simulation of past conditions, using historical forcing and sometimes partial observational data, which can then be compared with independent observations. Hindcasts are widely used to validate models, improve parameterisations, and refine predictions for future scenarios.

OSSEs can help to detect, attribute and assess the impacts of mCDR by integrating high-resolution Ocean models with observing networks (Figure 5.2). This helps to identify the most effective observation strategies for monitoring mCDR while minimising uncertainties and potential unintended environmental consequences. Such modelling efforts are essential to ensure robust regulatory oversight of mCDR methods.

Models can also support MRV by helping to quantify carbon removal, storage and durability. To date, two modelling approaches have been used in the context of assessing storage timescales and efficiency. Data-constrained Ocean Circulation Inverse Models (OCIMs) determine the storage timescales by mimicking mCDR carbon storage via direct “injection” of CO_2 into the deep Ocean (Siegel et al., 2021) and study the storage timescales of the biological carbon pump (DeVries et al., 2012). These models are parameterised with nutrient data (DeVries et al., 2012), mean circulation and end-of-winter mixed layer depths (DeVries & Primeau, 2011), since the winter maximum depth largely determines how long surface waters and associated carbon remain isolated from the atmosphere. OCIMs do not account for how any future changes in Ocean circulation or mixed layer depths may impact storage timescales.

The second approach uses virtual particle tracking to follow water parcels over climate-relevant timescales to estimate the storage efficiency of that parcel of water (Baker et al., 2022). This approach could assess the impact of climate change on sequestration efficiency by using future-projected current fields and mixed layer depths under different climate scenarios. This approach is more computationally expensive than OCIMs and therefore better for estimating sequestration efficiency at targeted deployment locations rather than at the basin scale.

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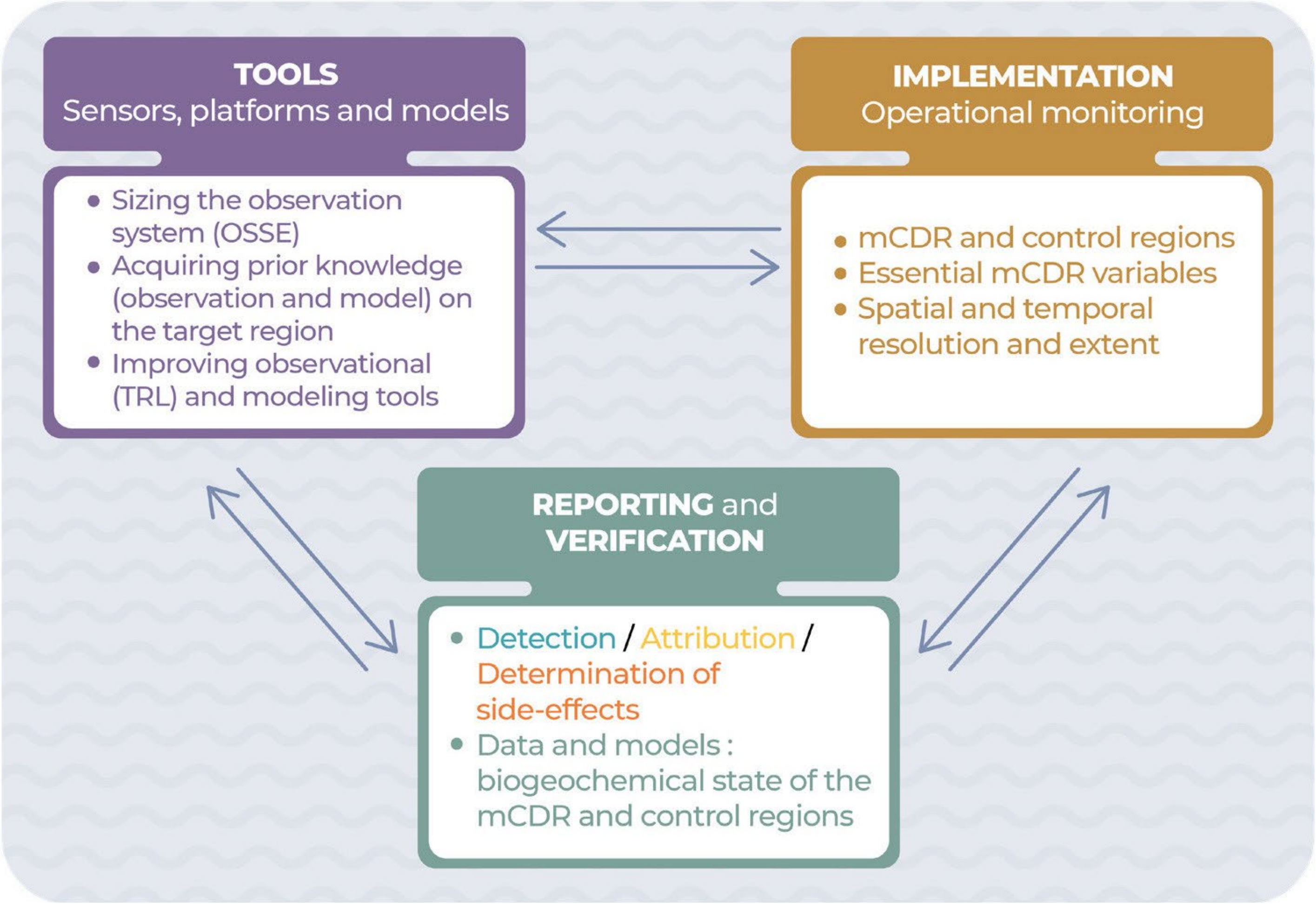
[19] https://wcrp-cmip.org/

[20] https://www.geomar.de/cdrmip



Credit: modified from Boyd et al. (2023) (CC BY 4.0).

Figure 5.2 Illustration of the interconnected components of MRV: (1) Tools used to determine the scale needed for the observing system (i.e. sizing the observing system), enhance the technological readiness level (TRL) of the observing system and modelling capacity; (2) Implementation involving real-time monitoring of mCDR and control regions across spatial and temporal scales; and (3) Reporting and Verification, ensuring the detection, attribution and assessment of side-effects using data and models.

6 Status of MRV regulations and governance

International law lacks specific MRV obligations for mCDR despite its importance for ensuring the efficacy and transparency of mCDR. This chapter outlines the general obligations under international law that are applicable to MRV for mCDR, with particular focus on Environmental Impact Assessments (EIAs), as well as cooperation and monitoring duties established under various international treaties and customary international law (obligations that develop over time from consistent practice which bind the whole international community and are accepted as legally binding). It also examines the role of national greenhouse gas inventories developed under international climate law, specifically the United Nations Framework Convention on Climate Change (UNFCCC, 1992), the Kyoto Protocol (Kyoto Protocol, 1997), and the Paris Agreement (Paris Agreement, 2015), as foundational mechanisms that could support the integration of mCDR into broader climate monitoring and accountability frameworks. European Union (EU) regulatory efforts concerning voluntary certification systems and private project-based certifications are also discussed (see Section 8.2 for a summary of the regulatory and governance framework).

The slow regulatory pace can be attributed to the growing trend towards deferring activities other than legitimate scientific research, which is governed under the International Law of the Sea. This trend reflects widespread concerns about the potential for mCDR to cause serious and irreversible environmental harm. Additionally, it is argued that mCDR could undermine efforts to reduce greenhouse gas emissions and entrench reliance on fossil fuels. As Sands & Cook (2021) observed, it is arguable that the deployment of such technologies run counter to the objectives of the UNFCCC and the Paris Agreement.

The future regulation on mCDR could also be influenced by the International Tribunal on the Law of the Sea's (ITLOS) advisory opinion on climate change (ITLOS, 2024). The opinion confirmed that greenhouse gas emissions into the atmosphere constitute pollution of the marine environment (paragraph 179) and UN Member States have a legal obligation to reduce these emissions and to protect the marine environment from climate change impacts (paragraphs 223 and 400).

ITLOS also noted that States have discretion to determine the measures necessary to reduce these emissions and protect the Ocean from the effects of climate change (paragraphs 206-207). One may argue that States may consider mCDR methods as measures to counterbalance their residual greenhouse gas emissions and protect the marine environment from the impacts of climate change (Webb, 2024). Yet, the Tribunal argued that:

"Article 195 of the Convention requires States, in taking measures to prevent, reduce and control pollution of the marine environment, not to transfer, directly or indirectly, damage or hazards from one area to another or transform one type of pollution into another. In this context, some participants raised the issue of marine geoengineering. Marine geoengineering would be contrary to article 195 if it has the consequence of transforming one type of pollution into another. It may further be subject to article 196 of the Convention which requires States, inter alia, to take all measures necessary to prevent, reduce and control marine pollution resulting from the use of technologies under their jurisdiction or control. The Tribunal is aware that marine geoengineering has been the subject of discussions and regulations in various fora, including the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters 1972 and its 1996 Protocol, and the CBD (paragraph 231)."

It appears that ITLOS only considered marine geoengineering as a source of potential pollution, but did not discuss its potential to counterbalance greenhouse gas emissions and consequently protect the marine environment. It is unfortunate that marine geoengineering (both solar radiation and mCDR) are treated indistinctively, without acknowledging how diverse these methods are.

6.1 General obligations for MRV for mCDR

6.1.1 Environmental Impact Assessments (EIAs)

Environmental Impact Assessments and Life Cycle Assessments (EIAs and LCAs, respectively; see Section 3.4) are both important in supporting MRV for mCDR. EIA is a regulatory process required for the initiation of specific human activities in many jurisdictions before project approval. It identifies, predicts and evaluates the likely environmental impacts of a proposed activity, and proposes mitigation measures. EIAs integrate scientific evidence, stakeholder input and legal requirements to inform decision-makers. For mCDR, EIAs would evaluate potential local and transboundary impacts, such as altered ecosystem services before any activity is authorised. EIAs focus on assessing the local environmental impacts of a proposed activity at the site of deployment, while LCAs expand this evaluation by analysing the entire life cycle of the activity, from material sourcing and implementation to decommissioning, thereby capturing its broader environmental footprint (see Section 7.2). While traditional EIAs evaluate the likely impact of a proposed activity on the environment, Article 31(1)(b) of the Agreement on Biodiversity Beyond National Jurisdiction (BBNJ Agreement, 2023) prescribes that EIAs include any associated impacts, such as economic, social, cultural and human health impacts, including potential cumulative impacts.

EIA obligations are established in numerous binding global (Ocean) treaties, as they evaluate the impact of a proposed activity on the

Table 6.1 Summary of Environmental Impact Assessments (EIAs) obligations under UNCLOS, CBD and the BBNJ Agreement.

LEGAL INSTRUMENT	EIA OBLIGATION	DETAILS
United Nations Convention on the Law of the Sea (UNCLOS, 1982)	Article 206 includes an obligation to conduct EIAs, as far as possible, if a planned activity *"may cause substantial pollution of or significant and harmful changes to the marine environment."*	While the obligation to conduct an EIA is well established, how States should implement this obligation remains unclear (Craik & Gu, 2023). Neither UNCLOS nor customary international law establish a process for conducting an EIA (Tanaka, 2024).
Convention on Biological Diversity (CBD, 1992)	Article 14(1)(a) obliges States to conduct, as far as possible and as appropriate, EIAs of projects *"likely to have significant adverse effects on biological diversity."*	As for UNCLOS, this obligation is similarly weak and lacks detailed procedural guidance.
Agreement on Biodiversity Beyond National Jurisdiction (BBNJ Agreement, 2023)	Articles 28(1) and 28(2) require prior EIAs for planned activities in Areas Beyond National Jurisdiction or under the jurisdiction of a State that *"may cause substantial pollution of or significant and harmful changes"* to such areas.	Article 28(2)(a) includes a step-by-step mapping of the BBNJ EIA process, highlighting the role the new Clearing House Mechanism (CHM) could play in governing the monitoring of mCDR (Boettcher & Brent, 2024). Unlike obligations established in UNCLOS or the CBD, Part IV Article 27(a) of the BBNJ Agreement seeks to provide *"processes, thresholds and other requirements for conducting and reporting"* EIAs (Bodansky, 2024). The CHM plays a key role at all seven EIA stages laid out by the BBNJ Agreement (Boettcher & Brent, 2024).

environment. It has also become a customary law obligation[21], universally requiring that all States conduct EIAs, independent of treaty commitments. Table 6.1 summarises the existing EIAs obligations. ITLOS, in its advisory opinion on climate change and international law, noted that the obligation to conduct EIAs *"encompasses the duty of vigilance and prevention"* (paragraph 356) that must be undertaken prior to the implementation of an activity and the content of EIAs could embrace cumulative impacts, including socio-economic impacts of the activities concerned (paragraphs 358, 365).

Only activities that may cause significant or substantial damage are subject to EIAs; those that may cause minor or transitory damage are exempt. The exact meaning of *"significant and substantial damage"* remains unclear, but legal literature consistently confirms that mCDR methods must be subject to EIAs (Burns, 2023; Du, 2017). In 2023, the parties to the London Convention (London Convention, 1972) and the London Protocol (London Protocol, 1996) (see Section 6.2.1) issued a statement emphasising that mCDR, including Ocean Alkalinity Enhancement (OAE) and biomass cultivation for carbon removal, *"has the potential for deleterious effects that are widespread, long-lasting or severe"* (LC45/LP18). The International Law Commission (ILC) clarified in its draft articles on the Prevention of Transboundary Harm from Hazardous Activities (ILC, 2001) that significant damage entails serious consequences and detrimental effects on the environment, human health or industries. These detrimental effects *"must be susceptible to being measured by factual and objective standards"*.

EIAs and Baselines

Table 6.1 illustrates that both UNCLOS (UNCLOS, 1982) and the CBD (CBD, 1992) contain relatively limited obligations regarding EIAs. In contrast, the BBNJ Agreement establishes a more detailed framework for conducting and reporting EIAs in areas beyond national jurisdiction. However, as clarified in ITLOS' advisory opinion on climate change and international law, the obligation to carry out EIAs under UNCLOS allows States a degree of flexibility to define the content and procedures of such assessments within their national legal systems[22]. This should be seen as an opportunity to determine mCDR baselines. EIAs for mCDR are a good way to define a baseline scenario against which mCDR removals are measured. This is because EIAs offer a reference point that allows comparison after deployment. As monitoring will need to be carried out through the mCDR method's lifespan, the removal of carbon dioxide can therefore be measured against the baseline scenario, and the information gathered in the EIAs should be the basis to develop further MRV protocols.

Within an MRV for mCDR context, a Clearing House Mechanism should host agreed-upon variable lists, sampling protocols, calibration references, data templates, project inventories and contact networks, improving comparability and uptake without acting as a crediting system.

In the EU, the implementation and monitoring of mCDR initiatives should align with the requirements of key existing environmental legislation to ensure environmental integrity and regulatory

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[21] The status of EIA as a customary law rule is found in Case Concerning Pulp Mills on the River Uruguay (*Argentina v Uruguay*) Judgment on the merits, ICGJ 425 (ICJ 2010), 20th April 2010, para. 204. https://www.icj-cij.org/case/135

[22] Pulp Mills on the River Uruguay (*Argentina v Uruguay*) Case, ICGJ 425 (ICJ 2010), 20th April 2010, para. 205. https://www.icj-cij.org/case/135. In this case the ICJ observed that international law does not *"specify the scope and content of an environmental impact assessment… Consequently, it is the view of the Court that it is for each State to determine in its domestic legislation or in the authorization process for the project, the specific content of the environmental impact assessment required in each case".*

compliance. For example, the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC, 2008) requires EU Member States to achieve or maintain Good Environmental Status of marine waters. Marine CDR methods should then be evaluated for their impact on indicators such as biodiversity, eutrophication and sea-floor integrity. Coordinated monitoring programs are essential to assess these impacts. The Marine Spatial Planning Directive (Directive 2014/89/EU, 2014) provides a framework for the spatial planning of maritime activities to promote sustainable development and use of marine resources. Projects discharging to, or operating in, coastal waters influenced by agricultural runoff should evidence compliance with the Nitrates Directive (Directive 91/676/EEC, 1991), its Nitrate Vulnerable Zones Action Programmes and include nitrate/oxygen/Harmful Algal Bloom limits, thresholds or safety checks in MRV. For mCDR deployment sites within, or with potential impacts on, Natura 2000 areas or those covered by the Nature Restoration Regulation (NRR, Regulation (EU) 2024/1991, 2024), MRV systems should incorporate method-specific eMRV indicators and thresholds that align with local conservation objectives. This includes using baselines and monitoring protocols consistent with the Birds Directive (Directive 2009/147/EC, 2009) and Habitats Directive (Directive 92/43/EEC, 1992), and applying Appropriate Assessment outcomes to ensure no deterioration of protected habitats or species, while also documenting any co-benefits for ecosystem restoration. Marine CDR should furthermore be integrated into maritime spatial plans to ensure that these activities consider, and are considered by, other Ocean uses and environmental protection objectives. Aligning mCDR methods with these European Directives, including the upcoming 2027 EU Ocean Act, may help ensure that any mCDR conducted is environmentally sustainable, legally compliant and well-integrated into marine management strategies and priorities.

6.1.2 Cooperation in monitoring and assessment

Fragmentation and inconsistent MRV standards are significant obstacles in regulating mCDR. The collection and reporting of information across diverse regulatory fora are essential. States are obliged to submit information, but to be useful, the data should be consistent and comparable (see Section 4.4), fostering greater transparency and cooperation.

Binding obligations to cooperate in monitoring, assessment and information exchange are found, for example, in Article 204 of UNCLOS, where States, acting individually or through competent international organisations, must monitor the effects of pollution (including mCDR methods) in the marine environment, both within and beyond national jurisdiction. Monitoring is defined as comprehensive, encompassing *“acts of observance, measurement, evaluation and analysis”* (Blitza, 2017) and constitutes a continuous obligation. The collected and analysed information must be reported and made available to all States as prescribed in Article 205 of UNCLOS. However, the Convention does not specify which types of information must be included. This can lead to inconsistent and incomparable data and consequently to inconsistent and non-comparable mCDR MRV standards.

Credit: NIOZ.

The sharing and open access to research infrastructure, such as laboratories, enhance dissemination of scientific knowledge and international collaboration on monitoring. Cooperation in monitoring, assessment and information exchange is a binding obligation in international legislation, such as UNCLOS.

Articles 35, 36 and 37 of the BBNJ Agreement impose stricter monitoring obligations applicable to mCDR MRV in Areas Beyond National Jurisdiction, i.e., parts of the Ocean more than 200 nautical miles (370 km) from the nearest coast. First, the BBNJ Agreement establishes a continuous obligation to monitor the impacts of projects that the Agreement parties authorise or participate in. Second, monitoring obligations include the impacts that may occur in areas under national jurisdiction. Parties must monitor the impacts of the activity using *"the best available science and scientific information and, where available, the relevant traditional knowledge of Indigenous Peoples and local communities"* (Article 35). They must prepare periodic reports and make them publicly available through the Clearing House Mechanism (CHM, Article 36). If the State authorising or implementing the project identifies significant adverse impacts, either unforeseen or due to a breach of the conditions of approval, they must review their decision to allow the activity to proceed, and *"notify the Conference of the Parties, other Parties and the public, including through the [CHM]"* (Article 37(2)).

6.2. Specific obligations

6.2.1 London Protocol

The Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter (London Protocol, 1996) is the only international agreement that specifically regulates mCDR. It governs the disposal of land-generated waste at sea via ships, artificial structures and aircraft. In 2013, an amendment (Resolution LP.4(8), 2013), introduced provisions for marine geoengineering:

The London Protocol defines marine geoengineering as *"a deliberate intervention in the marine environment [...] to counteract anthropogenic climate change [...] and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting, or severe."* It also prohibits placing matter into the sea *"from vessels, aircraft, platforms or other man-made structures at sea for marine geoengineering"*. The Protocol includes a list of mCDR methods subject to regulation, which currently contains only Ocean fertilisation, and this may be authorised only if conducted for legitimate scientific research. Such legitimacy must be assessed according to the criteria established in Annex 5 of Resolution LP.4(8). The Protocol also provides an assessment framework relevant for MRV, which requires a proposed activity to demonstrate: (i) how the mCDR method fulfils the purpose of carbon sequestration other than the mere disposal at sea of wastes, and (ii) the goals, methods, scale, timings, location(s), benefits and risks of the research, including potential effects on human health, on marine ecosystems structure, amenities and other legitimate uses of the sea.

As the amendment on geoengineering has not been ratified by two-thirds of the parties to the London Protocol, it has not yet entered into force. However, London Protocol parties issued a statement emphasising that mCDR, including OAE and biomass cultivation for carbon removal, *"has the potential for deleterious effects that are widespread, long-lasting or severe"* (LC45/LP18, 2023). Additionally, considering the growing interests in marine geoengineering, the parties are also considering including OAE and biomass cultivation for carbon removal as part of the protocol.

Overall, the regulation of mCDR and the approach to MRV under the London Protocol closely align with the precautionary principle, which states that when there is a risk of serious or irreversible damage, measures to prevent environmental degradation must be taken, even if there is scientific uncertainty on the effects of the activity (Chapter 2.4. in Du (2017)).

6.2.2 Convention on Biological Diversity (CBD)

While not explicit, the CBD also applies to mCDR methods. In 2010, the Conference of the Parties (COP) urged against deploying marine geoengineering techniques that may affect biodiversity until there is *"an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts"* (Convention on Biological Diversity, Decision X/33, para. w 2010).

6.2.3 Climate Law

Although international climate law (e.g. the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Paris Agreement) does not regulate mCDR, the following obligations are pertinent to the development of further MRV standards. It requires States to harmonise their methodologies to ensure that the available data is comparable. The obligations are typically differentiated according to the category of the country, as explained in the table 6.2.

Table 6.2 Categorical differentiation of Parties under the UNFCCC and the Kyoto Protocol, which tailor their obligations.

ANNEX I PARTIES[23]	ANNEX II PARTIES	NON-ANNEX I PARTIES
Understood as developed countries including economies in transition (EIT parties).	Understood as developed countries. Economies in transition (EIT parties) are excluded.	Understood as developing countries. Special consideration to least developing countries.

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[23] https://unfccc.int/process/parties-non-party-stakeholders/parties-convention-and-observer-states?field_national_communications_target_id%5B515%5D=515

Conversely, the Paris Agreement does not follow the specific categories of the UNFCCC or the Kyoto Protocol nor does it impose differentiated obligations based on these categories. MRV obligations are based on criteria established in its Article 13, including self-differentiation as developed, developing and least developing countries (Rajamani, 2016). In addition, the obligations in the Paris Agreement are qualified by the legal expressions *"different capacities"* and *"special circumstances"*, providing flexibility for States in meeting their obligations. *"Different capacities"* refers to the varying levels of ability among States to implement their obligations. For example, differences in financial resources, technical expertise and institutional strength. *"Special circumstances"*, by contrast, addresses context-specific factors that may justify additional flexibility or exceptions for certain States, such as Small Island Developing States (SIDS) or nations particularly vulnerable to climate impacts. It allows consideration of unique national situations beyond general capacity levels.

National greenhouse gas inventories

Marine CDR methods fall under the scope of national greenhouse gas inventories established within the UNFCCC, the Kyoto Protocol and the Paris Agreement. These inventories are a fundamental component of MRV. While MRV refers to the overall system for tracking climate-related information, greenhouse gas inventories focus specifically on quantifying and reporting a country's emissions and removals. These inventories are the main data source underpinning MRV processes.

The UNFCCC obliges all parties to develop *"national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases [...]"*, and to report these to the COP. Additionally, it requires Annex I parties to report on mitigation policies and estimate the effects such measures *"will have on anthropogenic emissions by its sources and removals by its sinks"*. The COP primarily assesses these reports in accordance with Article 7.2(e) of the UNFCCC.

COP13 in 2007 introduced the MRV principle in the Bali Action Plan (Bali Action Plan, 2013-2017) and the COP has subsequently developed an MRV framework, with detailed guidelines to Annex I parties. Special attention has been given to developing states (non-Annex I parties), many of which took longer to file their national communications about the Convention implementation (Bodansky et al., 2017). Accordingly, non-Annex I parties are required to submit their national communications every four years and are *"encouraged"* to use the methodology in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Non-Annex I parties are also obliged to submit Biennial Update Reports (BURs) that include: greenhouse gas inventory reports, mitigation measures and information on national MRV systems. Such reports undergo a process of International Consultation and Analysis (ICA). Annex I parties submit Biennial Reports (BR) instead of Biennial Update Reports (BURs), and they and are subject to an International Assessment and Review (IAR) to increase the comparability of data between developed States, instead of undergoing the process of International Consultation and Analysis. Both the process of International Consultation and Analysis and International Assessment and Reviews are conducted under the Subsidiary Body for Implementation[24] (SBI).

The Kyoto Protocol has a more comprehensive reporting obligation, which requires Annex I parties to implement *"a national system for the estimation of anthropogenic emissions by sources, and removals by sinks of all greenhouse gases"*. These reports must also include information verifying compliance with their quantified emission limitation and reduction commitments. To ensure consistency and compatibility of data across parties, the use of methodologies developed by the IPCC are mandated. The reports are reviewed by Expert Review Teams[25] (ERTs) that assess the individual performance of States, although this process has been criticised for being very politicised (Huggins, 2015).

The MRV process established under the Paris Agreement, known as the Enhanced Transparency Framework[26] (ETF) replaced the framework developed under the UNFCCC and the Kyoto Protocol on 31 December 2024, when the Biennial Transparency Report (BTR) were submitted by the parties, although Small Island Developing States and Least Developed Countries have discretion to submit their BTRs after this date[27]. With the Paris Agreement, MRV is moving towards uniformity between the parties (Mayer, 2019), but some flexibility is allowed based on parties' differing capacities (Shapovalova, 2024). For Annex I parties, the Enhanced Transparency Framework will supersede the Biennial Reports (BRs) and International Assessment and Review, whilst for non-Annex I parties, the Enhanced Transparency Framework will replace the Biennial Update Reports (BURs) and International Consultation and Analysis. BRs and BURs are replaced by the Biennial Transparency Report.

The Paris Agreement requires parties to submit a *"national inventory report of anthropogenic emissions by sources and removals by sinks"*, along with information on their progress towards achieving their Nationally Determined Contributions (NDCs), following the IPCC Guidelines for National Greenhouse Gas Inventories. However, as Schulte et al. (2024) explain, the IPCC Methodology Report on Carbon Dioxide Removal, set to be produced during the seventh IPCC assessment cycle in 2027, will provide more concrete guidance for reporting anthropogenic emission by sources and removals by sinks.

Technical expert reviews[28] (TERs) under the Paris Agreement assess the comparability and consistency of the reported information, evaluate the implementation and achievement of the parties' NDCs, and identify areas for improvement. Once these reports are published and made publicly available, a Facilitative Multilateral Consideration of Progress allows parties to share their perspectives on the assessments, to pose questions and engage in discussions (Shapovalova, 2024). Finally, the Paris Agreement includes a global stocktake[29] to collectively assess NDCs.

The Paris Agreement Crediting Mechanism (PACM) governs the voluntary cooperation between States to reach their climate targets by transferring carbon credits earned from the reduction or removal of greenhouse gas emissions to other countries to help meet their climate targets. In October 2024, the Article 6.4 Supervisory Body adopted the *"Standard: Requirements for activities involving removals under the Article 6.4 mechanism"* (A6.4-SBM014-A06) (UNFCCC, 2024),

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[24] https://unfccc.int/process/bodies/subsidiary-bodies/sbi
[25] https://unfccc.int/topics/mitigation/workstreams/measurement--reporting-and-verification/reporting--accounting-and-review-under-the-kyoto-protocol
[26] https://unfccc.int/node/9097
[27] The submissions can be found at https://unfccc.int/first-biennial-transparency-reports
[28] https://unfccc.int/technical-expert-review
[29] https://unfccc.int/topics/global-stocktake

which sets monitoring, reporting, uncertainty and reversal provisions for removals. The standard also includes requirements for reversal and avoidance of leakage and of *"other negative environmental and social impacts and respecting human rights and the rights of Indigenous Peoples"* (UNFCCC, 2024). PACM defines removals as *"the outcomes of processes by which greenhouse gases are removed from the atmosphere as a result of deliberate human activities and are either destroyed or durably stored through anthropogenic activities"* (UNFCCC, 2024), making them relevant for mCDR.

The Paris Agreement Crediting Mechanism standard requirements for removal activities mandates the monitoring to be based on reliable data from measurements, sampling, remote sensing, third-party sources and published literature, and that the data must be statistically representative, conservative and account appropriately for uncertainties (UNFCCC, 2024). Quality control measures must also be implemented, including cross-checking monitoring results with external data sources or published literature, and regularly calibrating measurement equipment. Methodologies must include monitoring and mitigation of identified risks, such as reversal risks and risks to the broader United Nations Sustainable Development Goals, as outlined in the sustainable development tool of the UNFCCC[30]. This includes ensuring the free, prior and informed consent of Indigenous Peoples directly or indirectly affected by the activity. Participants must also submit a comprehensive monitoring plan as part of the project design document when registering the activity, and this plan must be updated at the beginning of each renewed crediting period, to ensure continuous alignment with improved MRV capacities and standards.

The Paris Agreement Article 6.4 requirements also explicitly outline reporting standards and stipulate that those undertaking removals are required to prepare comprehensive monitoring reports. These reports must be based on the above-mentioned pre-approved monitoring plan outlined in the registered project design document and include details of the monitoring methods used, estimated net removals during the period, including estimated uncertainties, and any collected data. They should also provide records of any observed greenhouse gas release events that could lead to reversals and must explain how reversal risks and any negative environmental or social impacts were assessed and mitigated, in line with the measures in the project design document.

Although the reports can be submitted at least once every five years, depending on the activity type, risk of reversals and other relevant factors, monitoring must be continuous. In addition to this regular reporting, an immediate report needs to be submitted if an event occurs that could cause a greenhouse gas release and potential reversal. Failure to submit a report by the due date every five years will result in suspension of operations, including issuance, transfer or cancellation of credits (UNFCCC, 2024). And finally, monitoring must continue after the end of the last active crediting period of the activity to detect and quantify any reversals and/or verify ongoing greenhouse gas storage. This post-crediting monitoring can only stop if transparent and verifiable information that shows that the stored greenhouse gases are at a negligible risk of reversal, or if potential future reversals are remediated (UNFCCC, 2024).

6.3. Project-based certifications

Apart from the binding obligations described in Sections 6.1 and 6.2, MRV is also based on independent crediting programmes that support voluntary carbon markets. Some of these programmes are shown in Figure 6.1, however, only a small subset of these apply to mCDR. For instance, only Isometric has a certified protocol for OAE projects (IEAGHG, 2024). The non-binding nature of these programmes means that such certifications cannot be counted towards countries' NDCs (Van Dam et al., 2024), and the verification process only looks at the compliance of the programme and not the net removal of carbon from the atmosphere, which is the outcome of the mCDR method (Schulte et al., 2024).

Figure 6.1 Examples of different independent crediting programs.

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[30] https://unfccc.int/documents/632490

6.4. EU voluntary certification system

In November 2024, the European Parliament and the Council of the European Union agreed to establish a voluntary EU certification framework for permanent carbon removals, carbon farming and carbon storage in products (Regulation (EU) 2024/3012, 2024). According to this regulation a voluntary scheme was chosen to facilitate and encourage the uptake of high-quality carbon removals and soil emission reductions. Additionally, the *"voluntary nature of the Union certification framework means that existing and new public and private certification schemes will be able to apply for recognition by the Commission under this Regulation but will not be obliged to do so in order to operate in the Union"*.

The Regulation's definition of carbon removal and carbon farming is broad enough to include mCDR. Carbon removal is defined as *"anthropogenic removal of carbon from the atmosphere and its durable storage in geological, terrestrial or Ocean reservoirs, or in long-lasting products"*, and carbon farming means *"any practice or process carried out over an activity period of at least five years, related to the management of a terrestrial or coastal environment and resulting in the capture and temporary storage of atmospheric or biogenic carbon"*.

The Regulation distinguishes between permanent removals and carbon farming (Article 2(9)–(10)). Operators must demonstrate that carbon will be stored permanently, with permanent defined as *"a duration of several centuries"*. By contrast, carbon farming refers to *"a practice or process carried out over an activity period of at least five years, related to the management of a terrestrial or coastal environment and resulting in the capture and temporary storage of atmospheric or biogenic carbon in biogenic carbon pools, or in the reduction of soil emissions"*. The Regulation prescribes that operators are subject to monitoring obligations that combine on-site measures with remote sensing or modelling. Operators are also liable to address and mitigate identified risks of reversal. Additionally, certification requires operators to submit detailed information on quantification, additionality, storage, monitoring plans and sustainability objectives, all of which will be subject to verification by an accredited certification body. It is the responsibility of Member States to appoint certification bodies. The European Commission will supplement the Regulation with further certification methodologies. Currently, methodologies for OAE are on the regulatory agenda of the EU[31].

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[31] https://climate.ec.europa.eu/citizens-stakeholders/events/workshop-carbon-removals-through-enhanced-rock-weathering-and-ocean-alkalinity-enhancement-2025-09-25_en

7 Existing MRV protocols and LCAs for mCDR and current knowledge gaps

7.1 Existing MRV protocols for mCDR

MRV protocols are being developed by commercial mCDR entities (e.g. Captura[32], Planetary Technologies[33], Ebb Carbon[34], Running Tide [ceased operations]), by carbon registries (e.g. Isometric[35]) or by companies undertaking MRV tool development (e.g. Hourglass Climate[36], [C]Worthy[37]). The TraceCDR tool[38] developed by the Grantham Research Institute provides an overview of MRV protocols, including mCDR, and details how many carbon credits have been issued using these protocols. It highlights that as of October 2024, MRV protocols for mCDR had only been developed and applied for Ocean Alkalinity Enhancement (OAE), marine biomass sinking, terrestrial biomass sinking in the marine environment and direct Ocean carbon removal. The MRV protocols for mCDR are generally international in scope and have only been applied in the context of voluntary markets, as mCDR is not included in current international compliance markets (Mercer & Burke, 2023).

Currently MRV protocols are being developed for specific mCDR deployment strategies to account for the intricacies and complexities of each method, and they are likely only being applied in one specific location as commercial mCDR entities are yet to scale. Whilst the protocols vary in technical detail and specific approach, many of them refer to the International Organization for Standardization[39] (ISO), e.g. ISO 14064 is a greenhouse gas (GHG) accounting/verification standard, ISO 14040/14044 is a cradle-to-grave LCA methodology, and ISO 14067 is a method to quantify and report the carbon footprint of a product. Some protocols had a short public consultation period prior to ratification while others provided contact details and invited further feedback, considering the protocol a ‘living document’. Open access sharing of well-documented MRV protocols, in line with FAIR principles, is crucial to ensure comprehensive, reproducible, and transparent MRV and to drive innovation (Ho et al., 2023). Although mCDR innovators and market leaders largely appear to be adhering to such FAIR principles, the MRV protocols ideally need to be tested *in situ* and independently validated.

7.2 Integrating Life Cycle Assessments (LCAs) into MRV protocols

Life Cycle Assessments (LCAs) can support the MRV for mCDR by providing a comprehensive, transparent framework to quantify and account for both the direct and indirect emissions associated with mCDR methods over their entire life cycle (see Section 3.4). LCAs are typically conducted before deployment or periodically updated to optimise design, compare options and assess net carbon removal potential under different assumptions. It helps to clearly define what constitutes carbon removal by establishing standardised system boundaries and functional units (e.g. per tonne of CO_2 removed and permanently stored). This standardisation is crucial for consistent MRV reporting and for comparing different mCDR methods. By accounting for energy inputs, materials and emissions from construction, operation, maintenance and decommissioning, LCA reveals the full carbon footprint of a mCDR method (including non-CO_2 greenhouse gases). This detailed inventory is key for verifying that the net removal is genuine and not offset by indirect emissions (e.g. from energy use or downstream impacts).

LCA methodologies quantify uncertainty in process emissions, which must be combined with MRV uncertainty on measured removals, and can be propagated within MRV systems to report confidence intervals on net CO_2 removal. This helps decision-makers understand the uncertainty (confidence intervals) around reported carbon removals and could inform adjustments in management strategies if required. The CarbonPlan CDR Verification Framework interactive tool[40] maps key uncertainties (and confidence levels) associated with quantifying net carbon removal and storage durability for different CDR methods, essential for proper MRV protocols. If enough information is available, LCA frameworks can also highlight where the environmental impact is highest during the mCDR process, which can indicate where more precise monitoring is needed. Additionally, LCA may reveal trade-offs or potential co-benefits such as improvements in water quality or ecosystem health, which are valuable for comprehensive MRV.

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[32] https://capturacorp.com/

[33] https://www.planetarytech.com/

[34] https://www.ebbcarbon.com/

[35] https://isometric.com/

[36] https://hourglassclimate.org/

[37] https://www.cworthy.org/

[38] https://www.lse.ac.uk/granthaminstitute/tracecdr/

[39] https://www.iso.org/standard/66454.html

[40] https://carbonplan.org/research/cdr-verification

LCAs quantify cradle-to-grave emissions and resource flows, while Environmental Impact Assessments (EAIs) evaluate likely impacts in a specific location and regulatory context, and eMRV measures the environmental impacts during and after implementation of mCDR. LCA can thus inform project design and alternative selection, EIA can ensure regulatory compliance and mitigation planning, and MRV, including eMRV, can verify whether predicted and permitted environmental and carbon outcomes are achieved in practice. Together these tools can form an integrated framework for rigorously evaluating and governing marine CDR initiatives.

However, LCA is a complex method, and it is difficult to capture high-resolution and reliable data to build data inventories for the LCA of mCDR methods. The four main challenges are: (1) The definition of boundaries: LCA requires clear boundaries for different processes, whereas mCDR methods involve complex interactions between marine ecosystems, the environment and industrial activities. For example, an LCA of OAE would require an EIA of alkalinity enhancement to account for emissions from mining, transportation and application of minerals. (2) Data availability and quality: obtaining reliable data on methods such as Ocean fertilisation or direct Ocean carbon removal, is very difficult because there are very few pilot projects, and they exist within large natural variability. For instance, the amount of CO_2 removed versus unwanted CH_4 or N_2O emissions would have to be estimated from high-resolution monitoring data that are often unavailable. (3) Temporal and spatial variability: impacts specific to mCDR, such as the carbon sequestration potential of kelp farming, can be highly site- and time-dependent as it may be influenced by seasonal biological growth or changing Ocean currents. (4) Systemic consequences and trade-offs: mCDR may bring non-intended impacts, such as alteration of marine biodiversity or biogeochemical cycling.

As the long-term durability of additional carbon sequestration by mCDR methods (see Section 3.3) cannot be measured and needs to be quantified to allow for credits to be issued within carbon markets, we must rely on theoretical understanding and modelling approaches for these durability estimates, and they must be appropriately factored into LCAs. Further research is required to understand and advance different approaches to quantifying durability and the associated uncertainties with these estimates.

7.3 Knowledge required for MRV for mCDR

MRV for mCDR is needed to determine the amount of additional CO_2 removed from the atmosphere as well as the durability of this removal (Ho et al., 2023). Ideally air-sea CO_2 exchange would be continuously measured and compared against the air-sea CO_2 exchange in a control site without the mCDR deployed. Gas exchange of CO_2 across the sea surface is relatively slow and it takes months to years for the Ocean surface mixed layer to reach equilibrium with the atmosphere (Jones et al., 2014). This implies that even short deployments of mCDR will require long-term monitoring.

Currently, anthropogenic CO_2 in the Ocean is taken up at a rate of about 10.5 gigatonnes of CO_2 per year. This is larger than what is envisaged for even large-scale mCDR deployments. Being able to detect the impacts of mCDR methods will rely on accurate knowledge of the baseline, i.e. the rate of uptake the Ocean would have reached without the proposed mCDR method. Monitoring systems based on current global observing systems may provide a good basis but need to be refined specifically for the measurement of biogeochemical variables and ecological parameters and tailored to specific deployment locations (see Chapter 4).

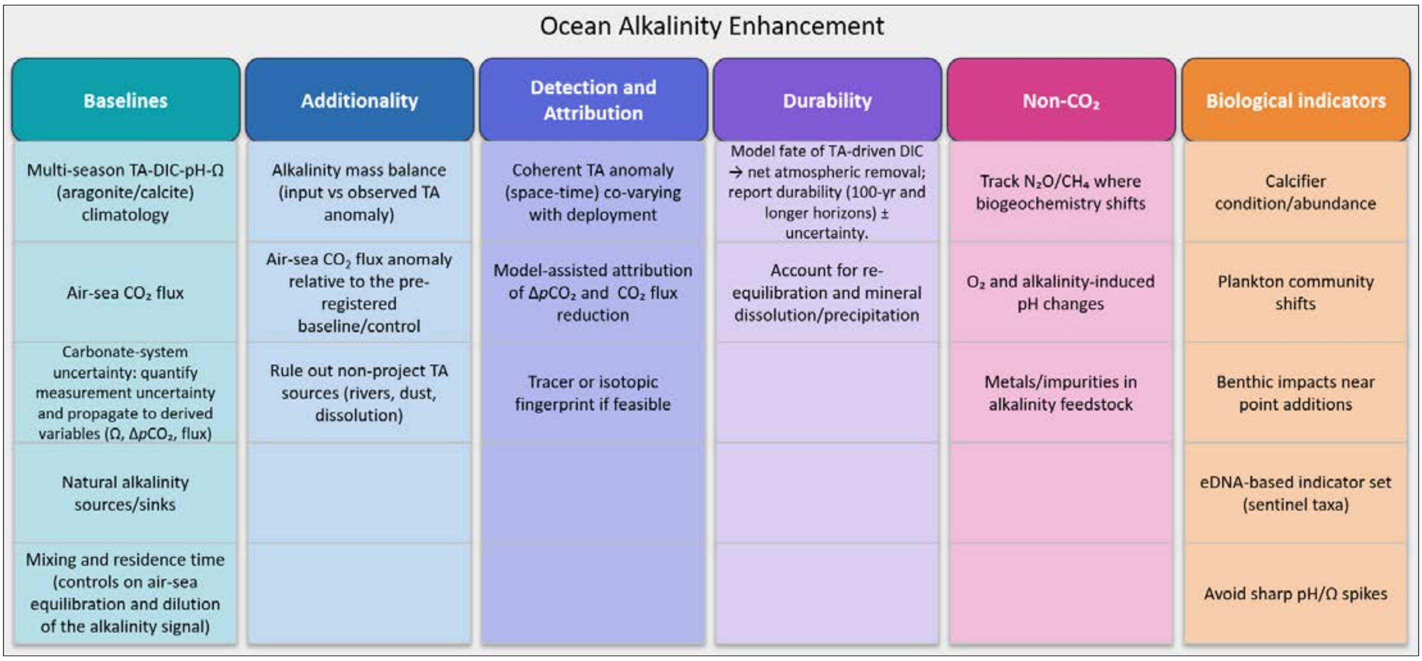
Parameters required to describe the state of the Ocean carbon pool, such as primary production, biomass and alkalinity are relatively straightforward to measure but are not sufficient to quantify air-sea CO_2 flux. Numerical models will therefore be important for future MRV schemes (see Chapter 5). Maximising information and quantifying uncertainties will require the combination of observational data and numerical models via data assimilation approaches. These will need to include not only physics, as already applied in a few weather centres and universities across Europe, but also biogeochemistry and biological observations and models. These model-data combinations will need to be expanded and all environmental impacts will need to be covered using eMRV.

Table 7.1 summarises the current state of perceived MRV-readiness at the pilot-scale for the different mCDR methods considered in this document. This includes, whether field-deployable methods, traceable data streams, Quality Assurance/ Quality Control, uncertainty treatment, and independent verification exist to: (i) set a credible counterfactual baseline, (ii) quantify and verify durability of stored carbon over relevant timescales, (iii) account for non-CO_2 climate forcers (e.g. CH_4, N_2O; where relevant, short-lived species), and (iv) assess eMRV impacts. The ratings reflect MRV capability only, not technology efficacy, scale-up potential, costs or permitting, and they are site-, project- and design-dependent. They should be interpreted as a guide to where MRV elements are ready at pilot-stage today, and where targeted MRV development and validation are still needed. They should be revisited as evidence evolves.

Table 7.1 Pilot-scale MRV-readiness for mCDR methods across four MRV dimensions. Colours indicate whether, at the scale of controlled pilots, they are sufficiently mature: 🟩 ready (feasible with established protocols and traceability), ▲ partially ready (key gaps remain, e.g. uncertainty treatment, integration or independent verification), 🔴 not ready (foundational methods/validation missing).

mCDR METHOD	BASELINE	DURABILITY	NON-CO_2 ACCOUNTING	eMRV
Preexisting marine biomass removal	🟩	▲	▲	▲
Marine biomass cultivation	▲	▲	▲	▲
Ocean Fertilisation	▲	▲	▲	🔴
Artificial Upwelling	🔴	🔴	▲	🔴
Coastal Blue Carbon management	🟩	▲	▲	🟩
Ocean Alkalinity Enhancement	🟩	▲	▲	▲
Artificial Downwelling	🔴	🔴	▲	🔴
Direct Ocean Carbon Removal	🟩	🟩	▲	▲

To build up and support robust MRV for mCDR, a six-pillar framework is proposed, focusing on Baselines, Additionality, Detection and Attribution, Durability, Non-CO_2, and Biodiversity. Each pillar illustrates the minimum metrics, study designs and reporting elements needed to show that observed signals exceed natural variability, can be attributed to the intervention, and translate into net atmospheric CO_2 removal with quantified uncertainty, while safeguarding ecosystems and monitoring non-CO_2 climate forcers. Here, we illustrate this approach with OAE as a worked example (Figure 7.1), while the method-specific pillars for each of the mCDR methods presented in this document are provided in Appendix 2. These frameworks are templates, not exhaustive prescriptions. Each project must develop a site- and method-specific, pre-registered MRV plan aligned with applicable regulations and permits.



Ocean Alkalinity Enhancement

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Multi-season TA-DIC-pH-Ω (aragonite/calcite) climatology	Alkalinity mass balance (input vs observed TA anomaly)	Coherent TA anomaly (space-time) co-varying with deployment	Model fate of TA-driven DIC → net atmospheric removal; report durability (100-yr and longer horizons) ± uncertainty.	Track N_2O/CH_4 where biogeochemistry shifts	Calcifier condition/abundance
Air-sea CO_2 flux	Air-sea CO_2 flux anomaly relative to the pre-registered baseline/control	Model-assisted attribution of ΔpCO_2 and CO_2 flux reduction	Account for re-equilibration and mineral dissolution/precipitation	O_2 and alkalinity-induced pH changes	Plankton community shifts
Carbonate-system uncertainty: quantify measurement uncertainty and propagate to derived variables (Ω, ΔpCO_2, flux)	Rule out non-project TA sources (rivers, dust, dissolution)	Tracer or isotopic fingerprint if feasible		Metals/impurities in alkalinity feedstock	Benthic impacts near point additions
Natural alkalinity sources/sinks					eDNA-based indicator set (sentinel taxa)
Mixing and residence time (controls on air-sea equilibration and dilution of the alkalinity signal)					Avoid sharp pH/Ω spikes

Figure 7.1 The six pillars supporting robust MRV for mCDR, illustrated for Ocean Alkalinity Enhancement (OAE) as an example. Similar figures for the other mCDR methods are presented in Annex 2. This framework includes example metrics and checks to show how project signals exceed natural variability, can be attributed to the intervention, and translate into net atmospheric CO_2 removal (with uncertainty) while safeguarding ecosystems. Abbreviations include: TA = total alkalinity; DIC = total dissolved inorganic carbon; pCO_2 = partial pressure of CO_2; Ω = carbonate-mineral saturation state; O_2 = dissolved oxygen; N_2O = nitrous oxide; CH_4 = methane; eDNA = environmental DNA.

8 Overarching challenges and uncertainties for future MRV

8.1 Technical challenges and spatial-temporal variability: detection, measurements and models

Chapters 4 and 5 identified the central challenge of MRV for mCDR: the difficulty of detecting and attributing changes in Ocean carbon to mCDR methods due to the inherent variability and complexity of Ocean systems. Natural fluctuations in CO_2 uptake, circulation and biological processes, combined with uneven and often limited observational coverage complicate efforts to establish carbon baselines and detect additional removal due to mCDR methods.

As shown in Chapter 4, current observing systems, while critical for understanding large-scale Ocean carbon dynamics, lack the spatio-temporal resolution to reliably monitor small-scale or short-term changes associated with mCDR. For example, Figure 8.1 illustrates overall declining trends in sub-surface DIC and surface air-sea CO_2 observations since 2015, which underscores persistent coverage gaps in dynamic and remote environments, such as coastal zones and the Southern Ocean.

Chapter 4 further emphasise that accurate and credible MRV requires fit-for-purpose monitoring systems, adapted to the characteristics of the specific mCDR method and deployment scales. While a comprehensive global Ocean observing network is unlikely to be achieved in the near term, localised strategies using targeted sensors and platforms can support robust MRV for small-scale trials and early deployments.

As mCDR scales, critical uncertainties about long-term carbon fate and storage durability must be addressed. This will increasingly require integrating improved observational coverage with enhanced modelling frameworks (see Chapter 5). Although models are essential tools for estimating additionality and forecasting outcomes, many existing Ocean models are limited by coarse resolution, missing process representation and lack of data for validation (especially for the deep Ocean) (Figure 8.1).

New modelling frameworks that integrate machine learning and process-based models could improve predictability and reduce uncertainty, but they too require validation through real-word data. Controlled field trials and experiments remain essential to refine these tools for each mCDR method (Sánchez et al., 2024). Ocean Visions has built a database[41] of all known mCDR-relevant field trials currently operating or concluded.

Beyond carbon quantification, Chapters 4 and 5 also highlight the need to understand and monitor the ecological effects of mCDR, including shifts in productivity, biodiversity, dissolved oxygen and Ocean acidification, which are poorly understood (Table 3.2). Effective monitoring will require protocols for integrating carbon flux data with biogeochemistry indicators (e.g. pH, dissolved oxygen, dissolved inorganic nutrients) and to include the range of seawater biogeochemical conditions in which a certain marine environment should be maintained. Adaptation of the MSFD 'Good Environmental Status' (GES) to mCDR will be needed, by adding explicit indicators, thresholds and reporting requirements. Controlled field trials are needed to build, test and refine the MRV systems required for different mCDR methods, either in isolation or when co-deployed. This is especially true for the ecosystem effects of mCDR that will require eMRV to recreate realistic environmental conditions, with realistic exposure and accounting for complex behaviours, to identify and monitor indicator species (which still need to be identified). MRV for mCDR should leverage evidence on biological responses not only to Ocean acidification, but also to deoxygenation, nutrient perturbations, and productivity shifts, to anticipate and detect ecological responses to mCDR, and need to select indicator species and thresholds for adaptive management (Bednaršek et al., 2025). The large uncertainties in possible ecological and biogeochemical shifts require careful implementation of MRV for mCDR until the safe operational temporal and spatial scales are identified (see Section 8.2).

In summary, technical limitations in observations and models, and the Ocean's dynamic nature, pose significant barriers to mCDR and its MRV. However, many of these can be overcome through targeted monitoring, strategic modelling and systematic field validation tailored to each mCDR method.

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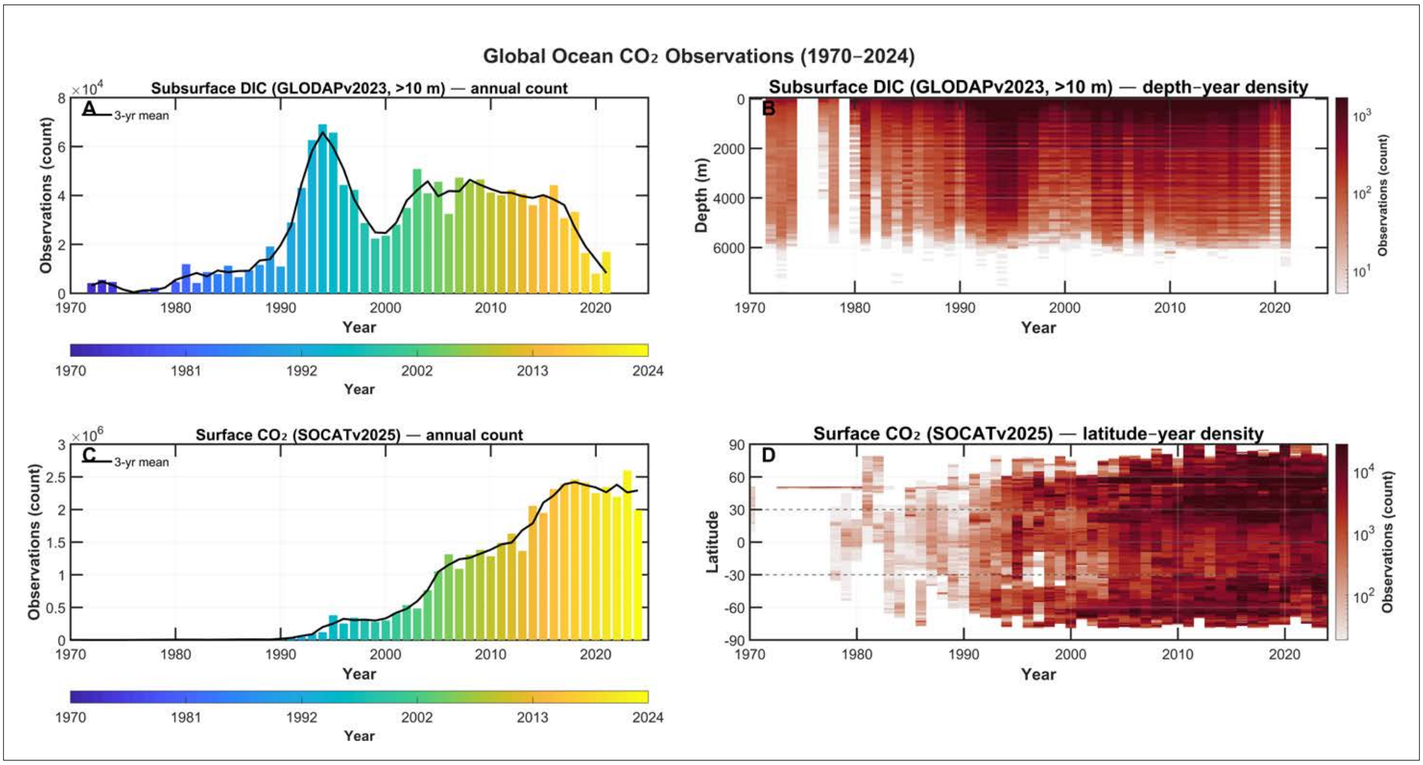
[41] https://oceanvisions.org/mcdr-field-trials/



Credit: Alizée Roobaert.

Figure 8.1 Global Ocean CO_2 observations for the period 1970-2024. (A) Number of sub-surface (> 10m) total dissolved inorganic carbon (DIC) measurements, and (B) their depth distribution over time from the GLODAP database (Source: Lauvset et al., 2024). (C) Surface Ocean CO_2 measurements, and (D) their latitudinal distribution from the SOCAT database (Source: Bakker et al., 2016). Colourbars show the observation year, and 3-year mean in black line in (A) and (C). For (B) and (D), the colouring indicates the observation count.

8.2 Regulatory and governance gaps

There is no overarching international or EU regulatory framework specifically for MRV for mCDR (see Chapter 6). Current MRV obligations lack clear guidelines for continuous monitoring and data-sharing, leading to inconsistent reporting. The lack of MRV standardisation results in inconsistent and non-comparable data, which hinders transparency and accountability. While UNCLOS and the BBNJ Agreement require ongoing monitoring, they do not specify the types of data to be collected. The voluntary nature of many existing MRV initiatives (e.g. EU certification framework and private standards in voluntary carbon markets, see Sections 6.3 and 6.4) further complicates transparency and accountability. Internationally, there is a general trend towards deferring activities other than legitimate scientific research on mCDR. The pending addition of a wider range of mCDR methods to Annex 4 of the London Protocol could provide a framework for permitting legitimate mCDR research, and thus the development of fit-for-purpose MRV.

The Paris Agreement's MRV framework, including the Enhanced Transparency Framework, requires countries to report on emission reductions and carbon removals through their NDCs (see Section 6.2.3). However, there is no clear methodology for incorporating mCDR methods into NDCs. In addition, there are no standardised methods to quantify, verify and report mCDR's carbon sequestration potential, making it difficult to integrate these methods into national climate targets.

The Paris Agreement's carbon crediting mechanisms (PACM) allow States to trade carbon removals (see Section 6.2.3). While Article 6 establishes general requirements for removals (monitoring plans, uncertainty, reversals, safeguards), there are currently no mCDR-specific methodologies defining how to quantify permanence, leakage or environmental impacts for mCDR, nor agreed accounting treatments for integrating mCDR into national inventories. This means it is unclear whether removals would be double-counted or excluded from national inventories (see Chapter 6).

8.3 Summary of uncertainties and challenges

At present, no mCDR method has a mature, independently verifiable, end-to-end MRV system (i.e. the six pillars of MRV: baselines and additionality through detection and attribution, durability, non-CO_2 gases and biodiversity, see Figure 7.1 and Annex 2) suitable for large-scale deployment. Robust, open-Ocean baselines, attribution of additionality and demonstrable durability remain unattainable for all open-Ocean methods. Therefore, only tightly bounded, independently monitored pilot trials with accessible data and pre-defined stop criteria are warranted at this time. This reflects: (i) the high spatio-temporal variability of the Ocean carbon sink, complicating baseline and additionality estimates, and (ii) the need to quantify non-CO_2 greenhouse gases (GHG) and ecological side-effects alongside CO_2 fluxes (eMRV).

For site-specific pilots, partial MRV is feasible today (including carbonate system variables, targeted physical/biogeochemical monitoring, model-data combinations). However, for credit-grade, scalable MRV, key gaps persist including: detection and attribution against shifting baselines, slow air-sea equilibration and spatial decoupling of effects, durability quantification on decadal to centennial horizons, and standardised non-CO$_2$ GHG protocols.

To overcome some MRV challenges, independent oversight, open data in community repositories, pre-registration of project assumptions and MRV plans, and ecological safeguards aligned with existing Ocean governance, are required. Until individual MRV protocols are proven to detect, attribute and verify net removals while accounting for uncertainties in a manner suitable for policy/market use, mCDR methods should not be scaled up or co-deployed.

Table 8.1 summarises the mCDR methods considered in this document, giving a comparison of their attributes, key uncertainties and MRV challenges. It also describes the Technology Readiness Level[42] (TRL), deployment cost considerations, key uncertainties related to efficacy and environmental impact, and the specific MRV challenges associated with each method. The table underscores the significant knowledge gaps and technological hurdles that currently limit the reliable implementation and MRV of various mCDR methods, leading to the key recommendations in Chapter 9.

Table 8.1 A synthesis of the different mCDR methods and their attributes covered in this document. Specifics can vary significantly, depending on implementation scale, site conditions, and regulatory context. Durability entries are indicative and should be interpreted alongside the durability tiers in Table 3.1 (short/medium/long-term), which set MRV implications by storage reservoir. Abbreviations: Particulate Organic Matter (POC); Microalgae-based Bioenergy with Carbon Capture and Storage (mBECCS); and Greenhouse Gases (GHGs).

MCDR METHOD	DESCRIPTION	TECHNOLOGY READINESS LEVEL (TRL)	DEPLOYMENT COST CONSIDERATIONS	KEY UNCERTAINTIES	MRV CHALLENGES	DURABILITY
BIOTIC METHODS						
Preexisting marine biomass removal	Enhanced sinking of naturally occurring marine biomass to the Ocean interior and seafloor.	4-6 (early to mid-development)	• Costs of preexisting seaweed harvesting.	Uncertainty around ecosystem and environmental effects at the seafloor; and the long-term viability of carbon sequestration.	Logistic challenges in monitoring growth rates and effective biomass utilisation across diverse environments.	>100 – >1,000 years, if POC exported to deep Ocean.
Marine biomass cultivation and sinking	Enhanced sinking of cultured and harvested biomass to the Ocean interior and seafloor.	4-6 (early to mid-development)	• Infrastructure and deployment costs (building and maintaining seaweed offshore farms).	Uncertainty around the scalability of cultivation methods, ecosystem impacts, and the long-term viability of carbon sequestration.	Logistic challenges in monitoring growth rates and effective biomass utilisation across diverse environments.	10 – 100 years likely. >100 – 1,000 years, if large fraction of POC exported to deep Ocean.
Marine biomass cultivation for durable products and energy	Using Cultivation of marine organisms to capture CO$_2$, which can be utilised for various durable products or energy generation, including bioenergy with carbon capture and storage (mBECCS).	3-6 (early to mid-development)	• Requires substantial upfront infrastructure investment; • Scalability challenges due to cultivation technology dependencies; • Costs linked to biomass processing; and • Carbon Capture and Storage demands (e.g. energy, transport, compression), and long-term carbon storage.	Uncertainty around the scalability of cultivation methods, life cycle carbon emissions, ecosystem impacts, and the long-term viability of carbon sequestration (durable products).	Logistic challenges in monitoring growth rates and effective biomass utilisation across diverse environments. Tracking life cycle emissions accurately.	>10 – 100 years, dependent on storage medium / product. >1,000 years, if using geological storage.

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[42] https://tracker.carbongap.org/glossary/trl/

MCDR METHOD	DESCRIPTION	TECHNOLOGY READINESS LEVEL (TRL)	DEPLOYMENT COST CONSIDERATIONS	KEY UNCERTAINTIES	MRV CHALLENGES	DURABILITY
BIOTIC METHODS						
Ocean Fertilisation	Adding dissolved inorganic nutrients like iron to increase phytoplankton growth and enhance CO_2 uptake, increasing the sinking of biomass to the Ocean interior and seafloor.	3-5 (experimental)	• High uncertainty in environmental impacts; • Significant site selection risks; and • Operational costs depend on nutrient availability.	Uncertainty in environmental impacts due to variable ecological responses and potential negative effects like eutrophication and associated deoxygenation, and methane release.	Measuring the net effect of nutrient addition on different GHGs complicates monitoring.	10 – 100 years, location dependent. >100 years, if carbon reaches deep Ocean.
Artificial Upwelling	Uses engineered systems to bring nutrient-rich deep waters to the surface, which can enhance phytoplankton growth and increase CO_2 uptake, increasing the sinking of biomass to the Ocean interior and seafloor.	1-3 (conceptual)	• Conceptual stage; • High potential costs; • May pose ecological disruption risks; and • Largely untested in open Ocean.	Lack of empirical data on efficacy and potential consequences on deep-sea ecosystems.	Uncertainties in measuring upwelled materials' fate and potential ecological impacts complicate monitoring.	>100 – >1,000 years, if POC exported to deep Ocean.
Coastal Blue Carbon Management	Enhance carbon storage by restoring or generating new coastal ecosystems (e.g. mangrove forests, seagrass meadows, salt marshes), which also triggers alkalinity release, restoring some of the Ocean's buffering capacity.	5-7 (established, developing)	• Restoration efforts involve ongoing investment; and • Economic viability relies on successful ecosystem rehabilitation.	Variability in sediment carbon storage and long-term ecological stability post-restoration.	Establishing reliable baselines for carbon storage in restored ecosystems is challenging.	10 – 100 years for biomass. 100 – >1000 years for sediments (site- and disturbance-dependent).

MCDR METHOD	DESCRIPTION	TECHNOLOGY READINESS LEVEL (TRL)	DEPLOYMENT COST CONSIDERATIONS	KEY UNCERTAINTIES	MRV CHALLENGES	DURABILITY
GEOCHEMICAL METHODS						
Ocean Alkalinity Enhancement	Increases seawater alkalinity to convert dissolved CO_2 into stable bicarbonate and carbonate ions, thus increasing the drawdown of CO_2 from atmosphere.	2-7 (conceptual to prototype level)	• Energy-intensive; • Involves mining and processing costs; and • Potential ecological risks require thorough assessment.	Efficacy of alkalinity enhancement over time and its ecological implications remain uncertain.	Precise tracking of alkalinity changes and attributing carbon storage is difficult.	>1,000 years.
Artificial Downwelling	Uses engineered systems to force CO_2-rich surface water into deeper waters, effectively isolating it from the atmosphere.	2-3 (conceptual stage)	• Investment in equipment designed to withstand deep - Ocean pressures; and • Comparable costs to upwelling, with additional expenses tied to deep-Ocean challenges.	Efficiency of forced downwelling in achieving long-term CO_2 isolation; potential disruptions to deep-Ocean nutrient cycles; and impacts on marine ecosystems.	Precise measurement of CO_2 transfer to deep Ocean, verifying the permanence, uncertainties related to deep-Ocean biogeochemical processes.	>100 – >1,000 years, if carbon exported to deep Ocean.
Direct Ocean carbon removal	Uses chemical and electrochemical systems to extract dissolved CO_2 from seawater for storage in underground geological formations.	2-5 (conceptual to early development)	• High energy and operational costs; • Requires effective management of CO_2 storage durability; and • Depends on renewable energy.	Uncertainty regarding long-term CO_2 storage and ecological impacts post-extraction.	Difficulty in consistently measuring CO_2 removal efficacy and potential secondary gas emissions.	>100 years, depending on where the extracted carbon is stored.

9 Recommendations

This document does not take a position on whether mCDR should be pursued. However, the development of robust, method-specific MRV protocols, demonstrated to detect, attribute, and verify net removals while transparently accounting for uncertainties in a manner suitable for policy and market use, is vital if mCDR approaches are to be scaled up or deployed alongside other methods. CDR is not a substitute for reducing emissions, but it may serve as a supplementary measure to help achieve the goals of the Paris Agreement.

We recommend that rapid reductions in CO_2 emissions remain the top priority in efforts to reach these goals.

Further to this, we recommend:

Recommendations for policymakers and regulators:

(1) Develop a standardised, comprehensive, regulatory framework for MRV, to overcome the fragmentation, inconsistencies and lack of global governance of existing MRV systems;

(2) Standardise the collection and reporting of mCDR MRV information across diverse regulatory fora, rather than relying on non-binding standards from private initiatives;

(3) Develop regulations for baseline monitoring that cover both carbon and ecology (water chemistry, biodiversity, habitat). Use these baselines to establish additionality for MRV and to detect/attribute ecological effects, with pre-defined indicators and adaptive triggers;

(4) Develop cost-effective, standardised and sustained long-term monitoring and observing systems for carbonate system variables that verify durability and net CO_2 removal of mCDR, and complement these with modelling and machine learning when high-frequency or long-term measurements are not feasible;

(5) Limit scaling and co-deployment of mCDR methods until MRV protocols for individual methods have been proven and assess changes in efficacy and the practicalities of undertaking robust MRV in co-deployment scenarios; and

(6) Consider the requirements of key legislation, such as the Water Framework Directive, the Marine Strategy Framework Directive, the Nature Directive (Birds and Habitats Directives), the Nature Restoration Regulation, the Nitrates Directive and the Maritime Spatial Planning Directive, for the implementation and monitoring of mCDR methods in the European Union.

Recommendations for national, European and philanthropic science funders:

(7) Fund projects to establish baseline carbon fluxes and sinks, particularly those that support development of instruments allowing high-frequency, long-term, *in situ* carbonate system measurements. These baselines are essential for MRV, as accurate long-term data enhances the assessment of how different mCDR methods contribute to carbon storage;

(8) Fund projects that produce observational data for the purpose of validating and refining models, particularly on deep-Ocean processes. Such projects will help fill critical gaps in our understanding of deep-Ocean dynamics, thereby enhancing the accuracy of models used for MRV for mCDR. This is essential for developing better strategies for possible deployment and understanding the potential impacts on marine environments;

(9) Fund projects to investigate how biological processes respond to environmental change as part of MRV assessments, to ensure the direction and magnitude of these changes are acceptable and do not comprise Ocean health. Accurately assessing how biological processes adapt to environmental shifts will directly impact both the effectiveness and the sustainability of various mCDR methods;

(10) Fund projects to close knowledge gaps on the long-term efficacy, environmental impacts and scalability of mCDR methods. This includes projects aimed at understanding the dynamics and fate of organic carbon and total alkalinity, providing insight into the effectiveness of mCDR methods in carbon storage and their impacts on overall carbon cycling;

(11) Require transparent data-sharing policies, as well as open-access publications and project outcomes in all funded projects related to MRV and mCDR;

(12) Support practical applications of real-world MRV for mCDR, to complement the fundamental research behind mCDR methods; and

(13) Support multidisciplinary and trans-disciplinary MRV research projects that scope and map the regulatory landscape, while actively engaging stakeholders and local communities. These projects should involve a broad range of experts, promote collaboration and facilitate community involvement so that MRV projects benefit both society and the environment.

Recommendations for MRV scientists, practitioners and project planners:

(14) Establish robust local-, regional-, and large-scale baselines in terms of carbon fluxes and sinks to support quantification of additional carbon removal;

(15) Quantify uncertainties in MRV protocols for CO_2 removal across different scales, including instrumental precision, measurement accuracy, temporal and spatial variability, and model prediction fidelity;

(16) Determine thresholds for unacceptable ecological and environmental side effects that would trigger policy or management response, such as the cessation or temporary suspension of a mCDR deployment. These thresholds should be set independently of method performance and should be integrated into broader cost-benefit or life-cycle assessments that weigh ecological risks against potential carbon removal benefits;

(17) Quantify the durability of the CO_2 removal, in addition to its magnitude, as part of MRV for mCDR methods. This involves assessing how long the captured CO_2 will remain stored, quantifying uncertainty of such estimates, and the potential for any future release back into the atmosphere;

(18) Establish how interactions between various mCDR methods being co-deployed may be credited within MRV and carbon removal accounting frameworks;

(19) Conduct rigorous Life Cycle Assessments (LCAs) to quantify the net carbon removal effects through mCDR methods. This analysis should consider all stages, from production to long-term storage of carbon, to understand the carbon footprint and impacts of the mCDR methods employed;

(20) Develop standardised environmental MRV (eMRV) guidance and baselines, including protocols, methods, Quality Assurance/Quality Control, and data standards for detecting and attributing ecological impacts and non-CO_2 forcers;

(21) Describe environmental and ecological risks in MRV assessments, at least qualitatively. Any potential risks to ecosystems and biodiversity should be considered alongside the benefits of carbon removal efforts and should be quantified where possible; and

(22) Follow ethical principles and codes of conduct for research and prioritise funding from transparent sources. Scientists and practitioners should commit to being transparent (in terms of data - ensuring FAIR data stewardship, approaches and funding), be independent of funding bodies, and seek financial support from sources where the origin and purpose of the funds are clear, e.g. from the European Commission or national research councils.

Credit: Alasdair O'Dell

Rapid CO_2 emissions reduction is the top priority. CDR is not a substitute for emissions reductions. However, (marine) CDR can be considered as a potential supplementary measure intended to support the goals of the Paris Agreement after substantial emission reduction.

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List of abbreviations and acronyms

ARGO	International programme comprising a network of oceanography floats
AU	Artificial Upwelling
BBNJ	Biodiversity Beyond National Jurisdiction
BR	Biennial Reports
BTR	Biennial Transparency Report
BUR	Biennial Update Reports
$CaCO_3$	Calcium Carbonate
CAPEX	Capital expenditure
CBD	Convention on Biological Diversity
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CH_4	Methane
CHM	Clearing House Mechanism
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
CO_3^{2-}	Carbonate ion
COP	Conference of the Parties
DIC	Total Dissolved Inorganic Carbon
DMS	Dimethyl Sulphide
DOC	Dissolved Organic Carbon
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
eMRV	Environmental Monitoring Reporting and Verification
EOV	Essential Ocean Variable
ERT	Expert Review Team
ESM	Earth System Model
ETF	Enhanced Transparency Framework
EU	European Union
FAIR	Findable, Accessible, Interoperable and Reusable
FMGDM	Floating Macroalgal Growth and Drift Model
GEOMAR	Helmholtz Centre for Ocean Research Kiel
GES	Good Environmental Status
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
GLODAP	Global Ocean Data Analysis Project
GOOS	Global Ocean Observing System
GOSAT	Greenhouse gases Observing SATellite
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program

HCO_3^-	Bicarbonate ion
IAR	International Assessment and Review
ICA	International Consultation and Analysis
ICOS	Integrated Carbon Observation System
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
ILC	International Law Commission
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
mBECCS	Marine Bioenergy with Carbon Capture and Storage
mCDR	Marine Carbon Dioxide Removal
MRV	Monitoring, Reporting and Verification
MSFD	Marine Strategy Framework Directive
N_2O	Nitrous Oxide
NASEM	National Academies of Sciences, Engineering, and Medicine
NDC	Nationally Determined Contributions
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OAE	Ocean Alkalinity Enhancement
OCIM	Ocean Circulation Inverse Models
OIF	Ocean Iron Fertilisation
OPEX	Operational Expenditure
OSSE	Observing System Simulation Experiments
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PACM	Paris Agreement Crediting Mechanism
$p\mathrm{CO}_2$	Partial pressure of Carbon Dioxide
pH	potentia hydrogenii - expression of hydrogen ion concentration in water
POC	Particulate Organic Carbon
ROMS	Regional Oceanic Modelling System
SENTINEL	Earth observation mission from the European Union Copernicus Programme
SIDS	Small Island Developing States
SOCAT	Surface Ocean CO_2 Atlas
SOIREE	Southern Ocean Iron RElease Experiment
SRM	Solar Radiation Modification
TA	Total Alkalinity
TER	Technical expert reviews
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WFD	Water Framework Directive

Glossary

Additionality -The carbon dioxide removal that would not have been removed in the absence of a CDR activity. Additionality tests in carbon credit programs check the legitimacy of carbon removal relative to a counterfactual baseline.

Artificial Downwelling - A method designed to transport surface water, and the carbon that it contains, into deeper Ocean layers, thereby isolating the carbon from the atmosphere for longer periods.

Artificial Upwelling (AU) - A method that brings nutrient-rich deep water to the surface, stimulating biological activity (e.g. phytoplankton blooms), which in turn can enhance CO_2 uptake by the Ocean.

Attribution - *See Detection and Attribution.*

Authigenic - Minerals that precipitate or recrystallise *in situ* within sediments, forming directly where they are found rather than being transported there.

Biochar - A stable, carbon-rich material produced by heating biomass in an oxygen-limited environment (pyrolysis). Biochar can be applied to soils to enhance soil functions, reduce greenhouse-gas emissions from soils and biomass, and store carbon over long timescales

Bioenergy with Carbon Capture and Storage (BECCS) - Technologies that generate an energy service (electricity, hydrogen, biogas, heat) from biomass feedstocks, and capture and store the resulting CO_2 emissions in geological formations. If the biomass is sustainably sourced, a BECCS system results in carbon dioxide removal.

Buffering capacity - Seawater’s ability to neutralise added CO_2, reflected in its total alkalinity, which determines how much carbon the water can uptake before its pH changes significantly.

Carbon credit - A tradeable certificate representing one tonne of CO_2 or carbon dioxide equivalent (CO_2eq) that has been removed, avoided or reduced.

Carbon Dioxide Equivalent (CO_2eq or CO_2e) - CO_2-equivalent is a standardised unit used to express the warming impact of different greenhouse gases as if they were all CO_2. It allows for comparing the climate impact of various gases by converting them to a common unit based on their global warming potential. Often expressed in terms of a timescale, e.g. commonly 100 years.

Carbon Dioxide Removal (CDR) - The process by which CO_2 is taken out of the atmosphere through human activities and store it in a reservoir for a climate-relevant period of time. CDR increases the net flux of CO_2 from the atmosphere into storage and is intended to reduce the concentration of atmospheric CO_2.

Carbon fluxes - The amount of carbon exchanged between Earth's carbon pools, i.e. the Ocean, atmosphere, land and living organisms.

Carbon sequestration - The process of storing carbon in a stable form and location so that it is effectively isolated from the atmosphere, for a specified duration of more than 100 years. Sequestration can occur in biological reservoirs (e.g. forests, soils, marine biomass), geological formations (e.g. depleted oil/gas fields, saline aquifers), or as stable chemical compounds (e.g. bicarbonates and carbonate ions in seawater, carbonate minerals on land or in sediments).

Carbon storage - The process of storing carbon in a stable form and location, so that it is isolated from the atmosphere, regardless of how long it is stored for.

Clearing House Mechanism - A platform that aims to support and facilitate the sharing and exchange of information and data, and serve as (digital) intermediary between different data generators, providers, and users. Used in the context of multilateral agreements such as the BBNJ Agreement.

Counterfactual - A baseline estimate of what would have happened without the intervention, often modelled using pre-intervention data, used after the project has been implemented to assess additionality.

Cryosphere - The components of the Earth System at and below the land and Ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground.

Data assimilation - The process of combining observations with model simulations to enhance the accuracy of state estimates and predictions.

Detection and Attribution - Detection refers to demonstrating that a measurable change has occurred in carbon fluxes, carbonate chemistry, or ecological indicators at a statistically significant level, beyond what would be expected from natural variability alone. Attribution is the subsequent step of assessing the relative contributions of different drivers, such as the mCDR intervention versus natural variability or other human influences, to the observed change, and reporting this with an appropriate level of confidence. Together, detection and attribution are essential for verifying that observed outcomes can be linked to a specific mCDR activity, rather than background variability.

Diagenetic - Diagenesis is the set of post-depositional processes that affect sediments after deposition on the seafloor and before metamorphism. These processes include physical, chemical, and biological changes such as compaction, cementation, dissolution, mineral replacement, and microbial activity.

(Total) Dissolved Inorganic Carbon (DIC) - The total concentration of inorganic carbon species in water, including CO_2(aq), bicarbonate (HCO_3^-), and carbonate ions (CO_3^{2-}). DIC is a key parameter in understanding Ocean carbonate chemistry and its capacity to store CO_2.

Dissolved Organic Carbon (DOC) - The organic carbon compounds dissolved in water which pass through a filter with a pore size of between 0.2 - 0.7 micrometres.

Direct Ocean carbon removal - An approach that extracts CO_2 directly from seawater, often through electrochemical processes, and stores it in a durable form, ensuring that the removal leads to long-term storage. The associated air-sea flux is what yields atmospheric CO_2 removal.

Durability - The time that carbon is stored over a certain amount of time (years to millennia) without rereleasing the carbon to the atmosphere. Tiers are defined in Table 3.1.

Earth System Model (ESM) - A comprehensive model that simulates the interactions between the atmosphere, Ocean, land and cryosphere. ESMs are used to project the long-term impacts of climate change and evaluate the effectiveness of mitigation strategies such as mCDR.

Eddy - A rotating water mass that moves independently of the main flow. Eddies can range from a few to hundreds of kilometres in scale, and transport heat, salt, nutrients, and other properties, important in mixing and redistributing water masses in the Ocean.

Emission reductions - Actions that avoid or reduce the release of greenhouse gases into the atmosphere compared to a defined baseline. Emission reductions lower the *rate of accumulation* of greenhouse gases in the atmosphere but do not remove gases already present.

Environmental Impact Assessment (EIA) - A formal, often regulatory, process used to evaluate the likely environmental impacts of a proposed project or activity in a specific location or regulatory context, before it is carried out. In the context of mCDR, EIAs assess adverse impacts on marine ecosystems, and conditions for proceeding.

Environmental Monitoring, Reporting and Verification (eMRV) - Measurements of key environmental and ecological indicators, e.g. biodiversity, nutrient levels, dissolved oxygen and pH, during and after project implementation of mCDR.

Equilibration - The process of achieving chemical balance between two phases, such as the Ocean and atmosphere.

Euphotic zone - The region where light is sufficient for the growth of plants. It generally extends from the surface to a maximum of about 150 m in the clearest oceanic water.

Eutrophication - The process of nutrient enrichment in aquatic ecosystems causing the productivity of the system to cease to be limited by the availability of nutrients. This stimulates the growth of algae, ultimately resulting in depletion of oxygen. Nutrients can originate from agriculture, riverine input, municipal wastewaters, aquaculture or airborne loading.

Fate (of carbon) - Set of pathways, forms, locations and timescales that carbon atoms follow after an mCDR intervention, from initial capture to their ultimate disposition, including any routes back to the atmosphere.

Land tenure - The relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land rights and responsibilities.

Lagrangian particle tracking - A numerical technique used to simulate how individual "particles" (like water parcels, plankton, sediment grains, or air parcels) move through the Ocean through space and time.

Life Cycle Assessment (LCA) - A model framework for assessing the potential environmental impacts, including greenhouse gas emissions, associated with all stages of a product or project's life, from resource extraction through production, use and disposal.

Marine biomass sinking - Sinking of marine biomass such as macroalgae (seaweed) in the Ocean. The biomass must reach the deep Ocean where the carbon can be stored durably to be considered CDR.

Marine Carbon Dioxide Removal (mCDR) - A suite of methods that use marine processes or engineered interventions to remove CO_2 from the atmosphere and store it out of interaction with the atmosphere.

Mechanistic model - A knowledge-based description of a system that helps observers understand how the system works and predict its behaviour, often used in process design, scale-up and technology transfer.

Mineral feedstock - Raw mineral material, e.g. olivine, basalt or lime; or industrial by-products, e.g. steel slag, used as inputs for mCDR methods such as Ocean alkalinity enhancement, where their dissolution increases alkalinity and promotes CO_2 storage.

Model prediction fidelity - The degree to which a model represents reality.

Monitoring, Reporting and Verification (MRV) - A framework for tracking the performance, impacts and effectiveness of carbon removal or emissions reduction activities. MRV is essential for ensuring transparency, accuracy, and accountability in climate mitigation efforts.

Nationally Determined Contributions (NDC) - A country's self-defined climate plan under the Paris Agreement, setting targets and measures for greenhouse-gas mitigation (and, where relevant, adaptation and support). NDCs are submitted on a five-year cycle and must reflect progression and the country's highest possible ambition, informing tracking and the Global Stocktake.

Nutrient robbing - A mCDR displacement effect in which mCDR enhances primary production at or near the deployment site by consuming limiting nutrients (e.g. Nitrogen, Phosphorous, Silica, Iron), thereby reducing the downstream availability of those nutrients. This can depress productivity and carbon uptake elsewhere, yielding little or no net regional-to-basin carbon-removal gain despite local increases.

Ocean Alkalinity Enhancement (OAE) - An approach aimed at increasing the Ocean's capacity to absorb CO_2 by adding alkaline substances. This process shifts the chemical equilibrium in seawater, converting CO_2 into bicarbonate and carbonate ions for long-term storage.

Ocean Carbon Observing System - A network of observational tools, including satellites, floats and sensors, designed to monitor changes in Ocean carbonate chemistry and track the distribution and storage of carbon in marine environments.

Ocean (Iron) Fertilisation - A technique that involves the addition of nutrients (such as iron) to Ocean waters to stimulate phytoplankton growth, thereby enhancing the natural uptake of CO_2 from the atmosphere.

Olivine - Green iron-magnesium silicate with the chemical formula $(Mg, Fe)_2SiO_4$. When it weathers in nature, CO_2 is removed from the atmosphere.

Parameterisation - Parameterisations are the formulas or simplified representations used to describe complex processes that a model cannot explicitly resolve, e.g., cloud formation, turbulence, or biogeochemical remineralisation.

Particulate Organic Carbon (POC) - The organic compounds and particles dissolved in water that are retained on filters with a pore size of 0.7 micrometres or less. POC in the Ocean can consist of living cells or detritus such as marine snow, faecal pellets or mucus webs.

Pyrolysis - A thermochemical process that decomposes organic materials at high temperatures in the absence of oxygen.

Remineralisation - The process by which dead organic material is turned back into nutrients and CO_2 by microbes.

Short-lived climate forcers - Atmospheric compounds with short atmospheric lifetimes that cause rapid warming or cooling of the climate. They include aerosols (e.g. mineral dust, sea spray) and chemically reactive gases (e.g. ozone, some halogenated compounds, carbon monoxide).

Solubility pump - The physical component of the Ocean carbon cycle whereby air-sea gas exchange and circulation transfer atmospheric CO_2 into the Ocean interior as dissolved inorganic carbon.

Annex 1

Members of the European Marine Board Working Group on marine Carbon Dioxide Removal

NAME	AFFILIATION	COUNTRY
Working Group Chairs		
Helene Muri	NILU, and Norwegian University of Science and Technology (NTNU)	Norway
Olivier Sulpis	CEREGE - Aix-Marseille University, CNRS, IRD	France
Working Group Members		
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Chelsey A. Baker	National Oceanography Centre (NOC)	UK
Miranda Böttcher	Utrecht University & German Institute for International and Security Affairs (SWP)	The Netherlands & Germany
Maribel I. García-Ibáñez	Spanish Institute of Oceanography (IEO-CSIC)	Spain
Karol Kuliński	Institute of Oceanology Polish Academy of Sciences (IO PAN)	Poland
Angela Landolfi	Institute of Marine Sciences (CNR-ISMAR)	Italy
Peter Landschützer	Flanders Marine Institute (VLIZ)	Belgium
Evin McGovern	Marine Institute	Ireland
Živana Ninčević Gladan	Institute of Oceanography and Fisheries (IOF)	Croatia
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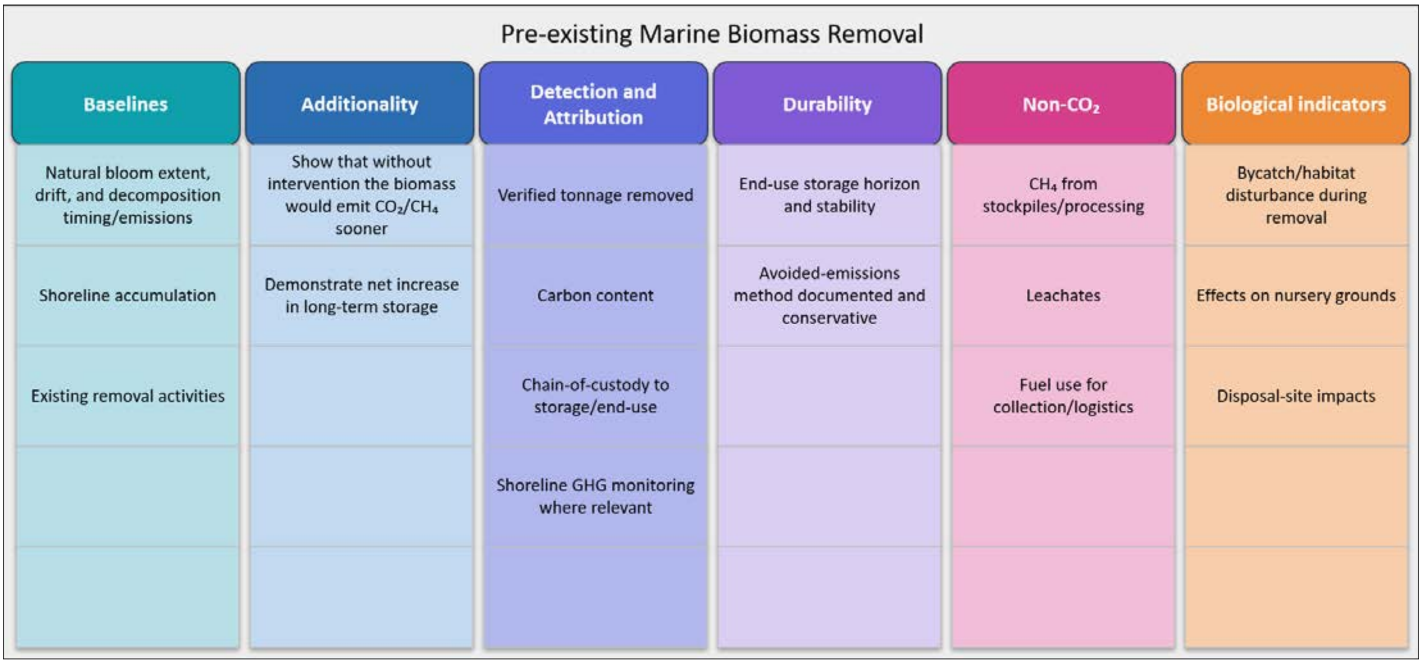
Annex 2. Pillars of MRV for mCDR

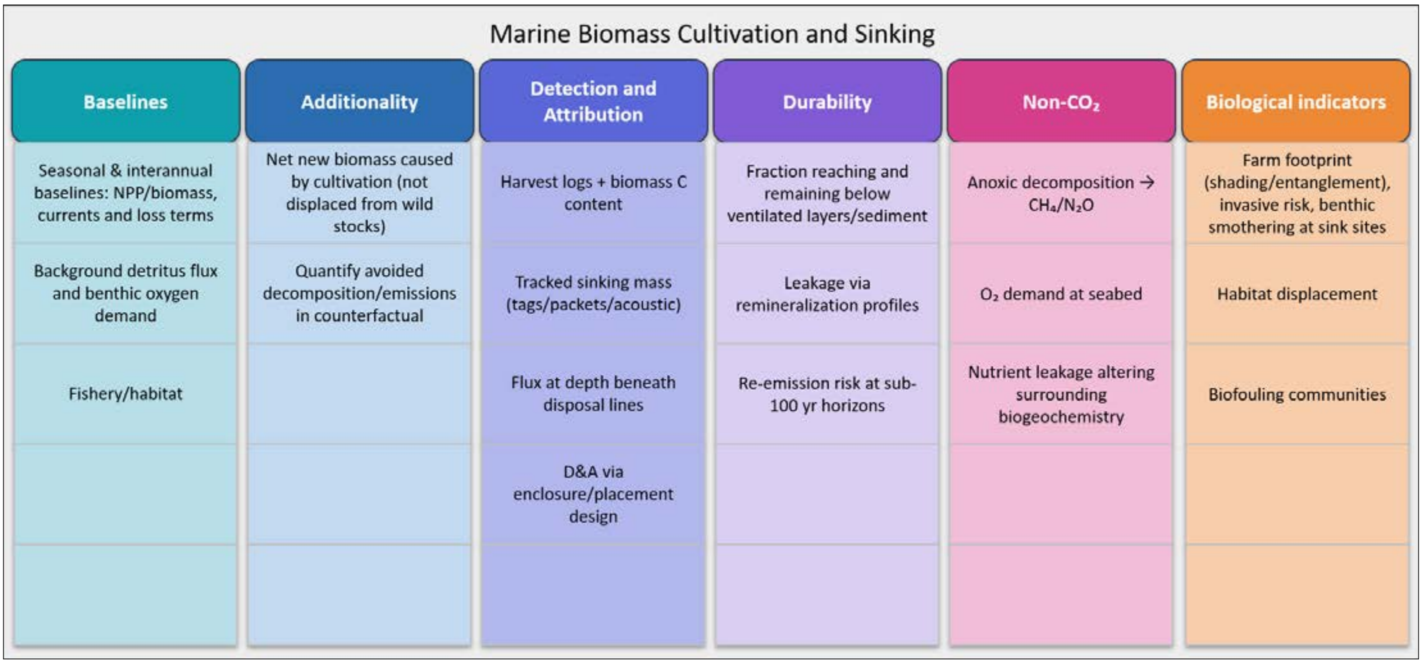
This appendix provides one MRV pillar checklist for each mCDR method considered in the report, expanding on the framework introduced in Section 7.3. The 6 pillars of support for MRV are Baselines, Additionality, Detection and Attribution, Durability, Non-CO_2 gases and Biodiversity. Each pillar is populated with concrete metrics or criteria to be monitored, reported and verified. The checklist highlights method-specific requirements while ensuring comparability across approaches. The pillar-figures presented here are templates, not exhaustive prescriptions: each project must translate them into a site- and method-specific, pre-registered MRV plan that reflects local conditions, deployment design, and applicable regulations and permits. Where appropriate, these templates can be paired with OSSEs and power analyses to set sampling density and minimum detectable change, and report uncertainty for both carbon and environmental indicators.

Abbreviations used in the figures: Chl-a = Chlorophyll-a, D&A = Detection & Attribution, DIC = Total Dissolved Inorganic Carbon, DMS = Dimethyl Sulfide, eDNA = Environmental DNA, MLD = Mixed Layer Depth, NPP = Net Primary Production, O_2 = Oxygen, Ω (omega) = Aragonite, saturation state, pCO_2 = Partial Pressure of CO_2, PP = Primary Production, TA = Total Alkalinity, δ^{13}C-DIC = Stable carbon isotope ratio of total dissolved inorganic carbon, ^{234}Th = Thorium-234 tracer, Δ = change relative to baseline/control.



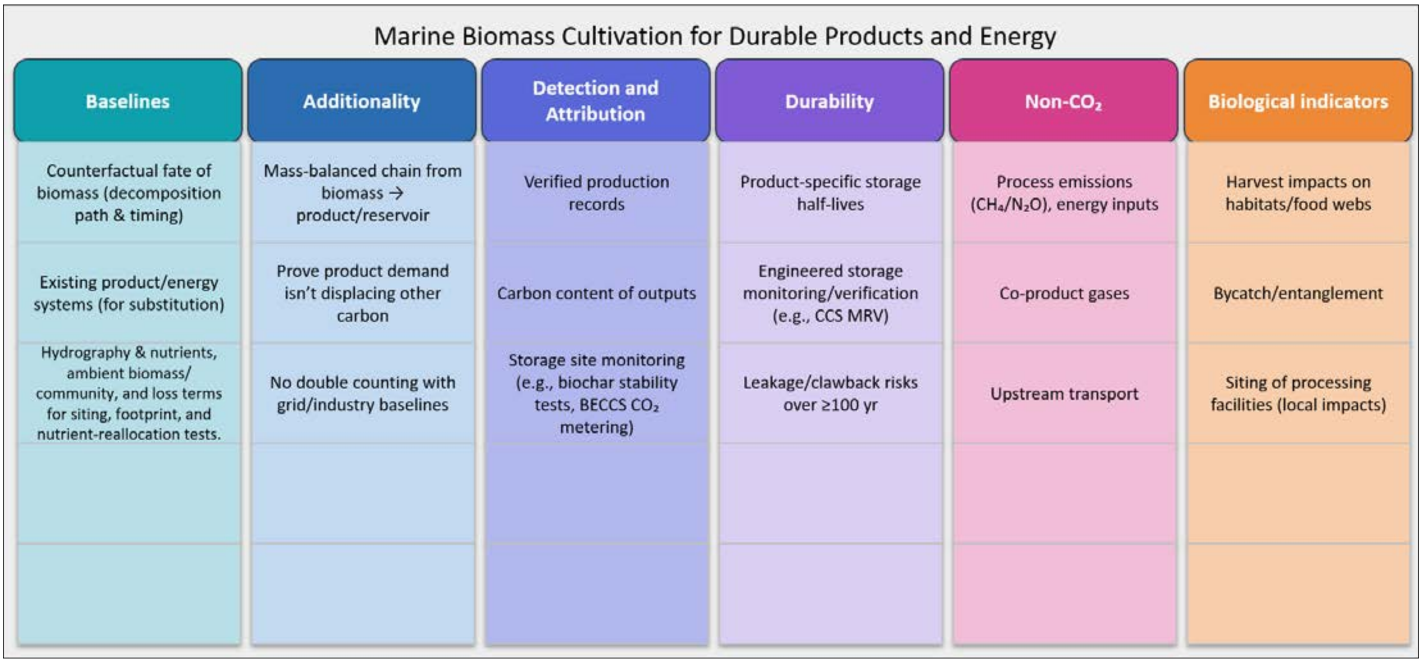
Pre-existing Marine Biomass Removal

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Natural bloom extent, drift, and decomposition timing/emissions	Show that without intervention the biomass would emit CO_2/CH_4 sooner	Verified tonnage removed	End-use storage horizon and stability	CH_4 from stockpiles/processing	Bycatch/habitat disturbance during removal
Shoreline accumulation	Demonstrate net increase in long-term storage	Carbon content	Avoided-emissions method documented and conservative	Leachates	Effects on nursery grounds
Existing removal activities		Chain-of-custody to storage/end-use		Fuel use for collection/logistics	Disposal-site impacts
		Shoreline GHG monitoring where relevant			



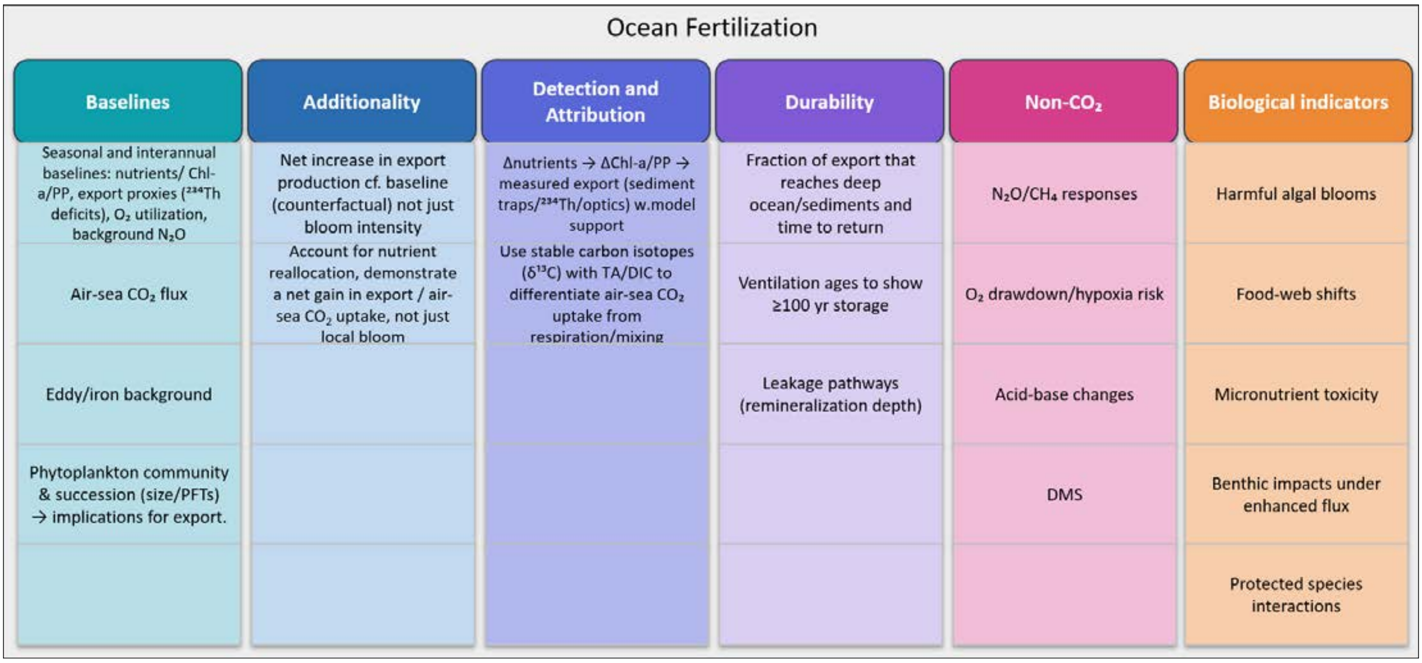
Marine Biomass Cultivation and Sinking

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Seasonal & interannual baselines: NPP/biomass, currents and loss terms	Net new biomass caused by cultivation (not displaced from wild stocks)	Harvest logs + biomass C content	Fraction reaching and remaining below ventilated layers/sediment	Anoxic decomposition → CH_4/N_2O	Farm footprint (shading/entanglement), invasive risk, benthic smothering at sink sites
Background detritus flux and benthic oxygen demand	Quantify avoided decomposition/emissions in counterfactual	Tracked sinking mass (tags/packets/acoustic)	Leakage via remineralization profiles	O_2 demand at seabed	Habitat displacement
Fishery/habitat		Flux at depth beneath disposal lines	Re-emission risk at sub-100 yr horizons	Nutrient leakage altering surrounding biogeochemistry	Biofouling communities
		D&A via enclosure/placement design			



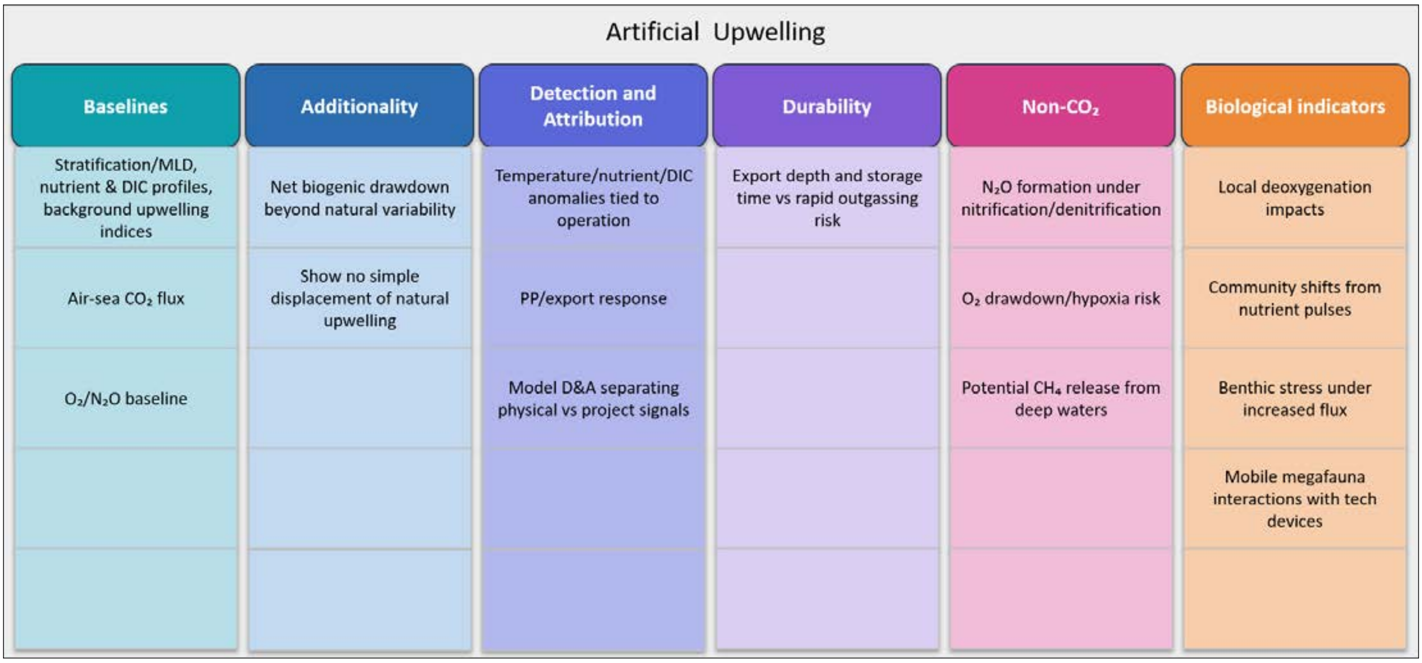
Marine Biomass Cultivation for Durable Products and Energy

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Counterfactual fate of biomass (decomposition path & timing)	Mass-balanced chain from biomass → product/reservoir	Verified production records	Product-specific storage half-lives	Process emissions (CH_4/N_2O), energy inputs	Harvest impacts on habitats/food webs
Existing product/energy systems (for substitution)	Prove product demand isn't displacing other carbon	Carbon content of outputs	Engineered storage monitoring/verification (e.g., CCS MRV)	Co-product gases	Bycatch/entanglement
Hydrography & nutrients, ambient biomass/ community, and loss terms for siting, footprint, and nutrient-reallocation tests.	No double counting with grid/industry baselines	Storage site monitoring (e.g., biochar stability tests, BECCS CO_2 metering)	Leakage/clawback risks over ≥100 yr	Upstream transport	Siting of processing facilities (local impacts)



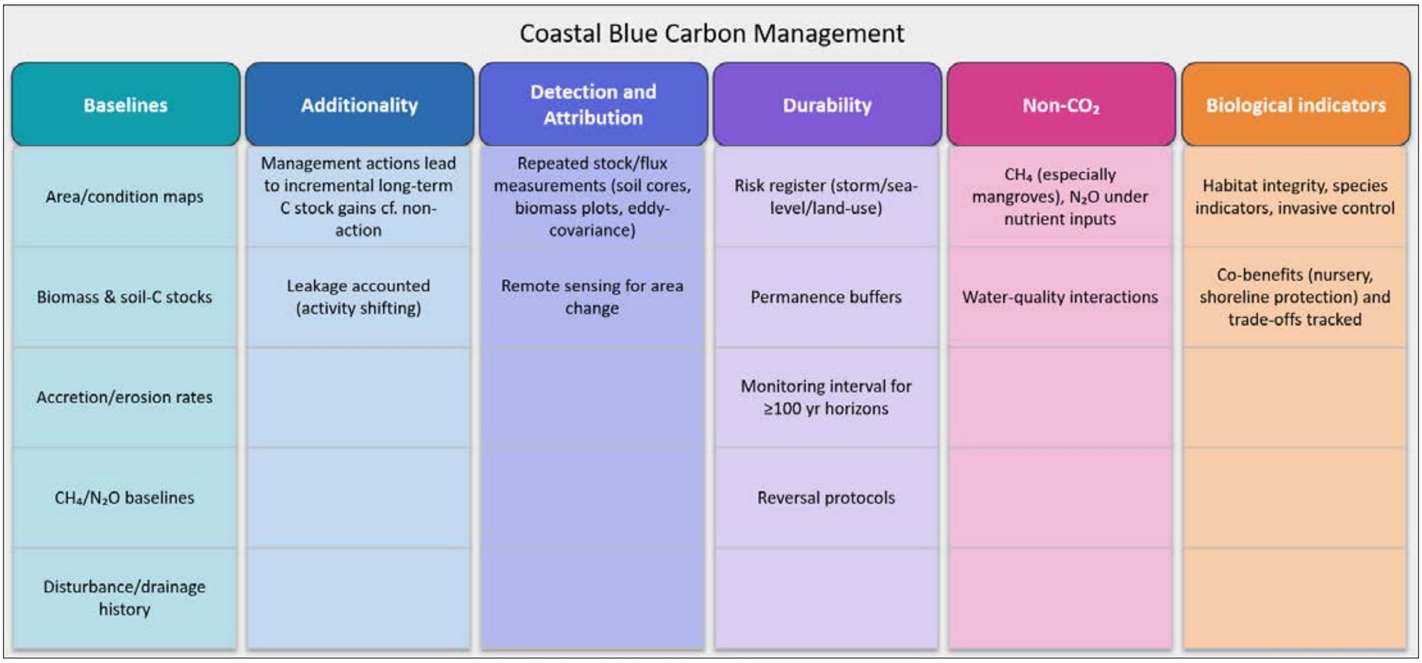
Ocean Fertilization

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Seasonal and interannual baselines: nutrients/ Chl-a/PP, export proxies (^{234}Th deficits), O_2 utilization, background N_2O	Net increase in export production cf. baseline (counterfactual) not just bloom intensity	Δnutrients → ΔChl-a/PP → measured export (sediment traps/^{234}Th/optics) w.model support	Fraction of export that reaches deep ocean/sediments and time to return	N_2O/CH_4 responses	Harmful algal blooms
Air-sea CO_2 flux	Account for nutrient reallocation, demonstrate a net gain in export / air-sea CO_2 uptake, not just local bloom	Use stable carbon isotopes ($\delta^{13}C$) with TA/DIC to differentiate air-sea CO_2 uptake from respiration/mixing	Ventilation ages to show ≥100 yr storage	O_2 drawdown/hypoxia risk	Food-web shifts
Eddy/iron background			Leakage pathways (remineralization depth)	Acid-base changes	Micronutrient toxicity
Phytoplankton community & succession (size/PFTs) → implications for export.				DMS	Benthic impacts under enhanced flux
					Protected species interactions



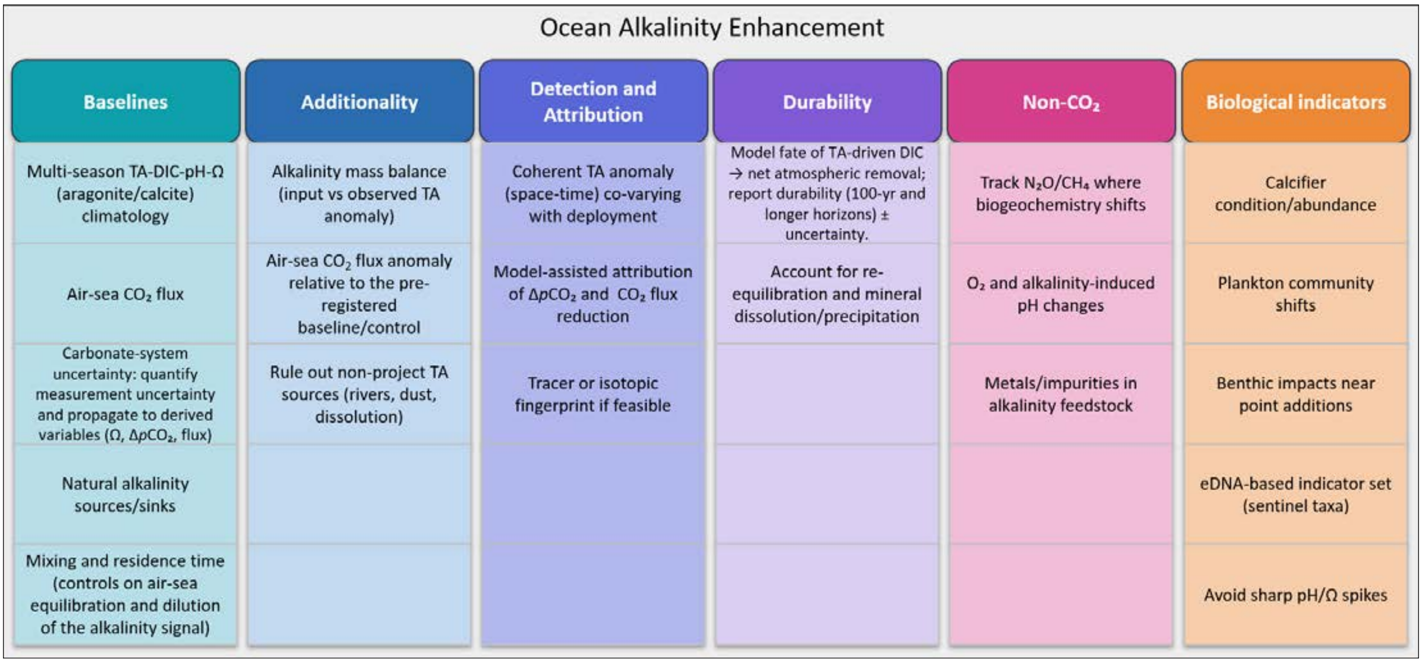
Artificial Upwelling

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Stratification/MLD, nutrient & DIC profiles, background upwelling indices	Net biogenic drawdown beyond natural variability	Temperature/nutrient/DIC anomalies tied to operation	Export depth and storage time vs rapid outgassing risk	N_2O formation under nitrification/denitrification	Local deoxygenation impacts
Air-sea CO_2 flux	Show no simple displacement of natural upwelling	PP/export response		O_2 drawdown/hypoxia risk	Community shifts from nutrient pulses
O_2/N_2O baseline		Model D&A separating physical vs project signals		Potential CH_4 release from deep waters	Benthic stress under increased flux
					Mobile megafauna interactions with tech devices



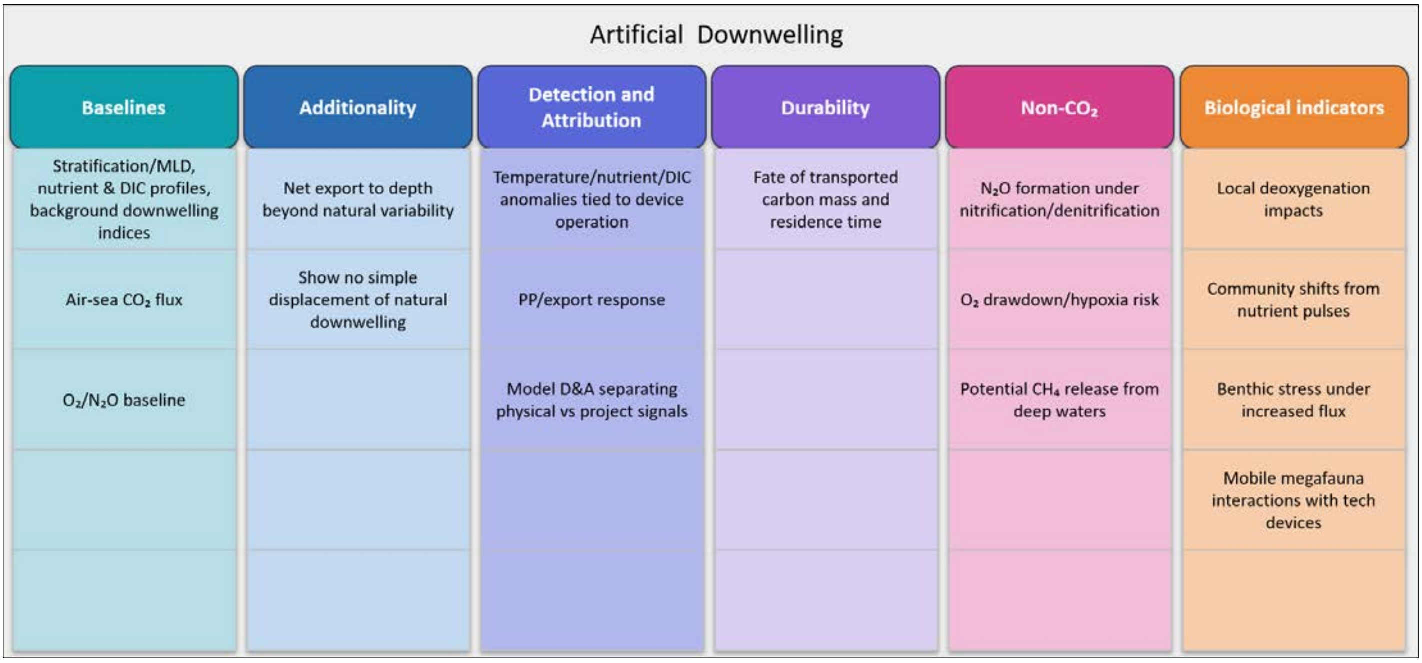
Coastal Blue Carbon Management

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Area/condition maps	Management actions lead to incremental long-term C stock gains cf. non-action	Repeated stock/flux measurements (soil cores, biomass plots, eddy-covariance)	Risk register (storm/sea-level/land-use)	CH_4 (especially mangroves), N_2O under nutrient inputs	Habitat integrity, species indicators, invasive control
Biomass & soil-C stocks	Leakage accounted (activity shifting)	Remote sensing for area change	Permanence buffers	Water-quality interactions	Co-benefits (nursery, shoreline protection) and trade-offs tracked
Accretion/erosion rates			Monitoring interval for ≥100 yr horizons		
CH_4/N_2O baselines			Reversal protocols		
Disturbance/drainage history					



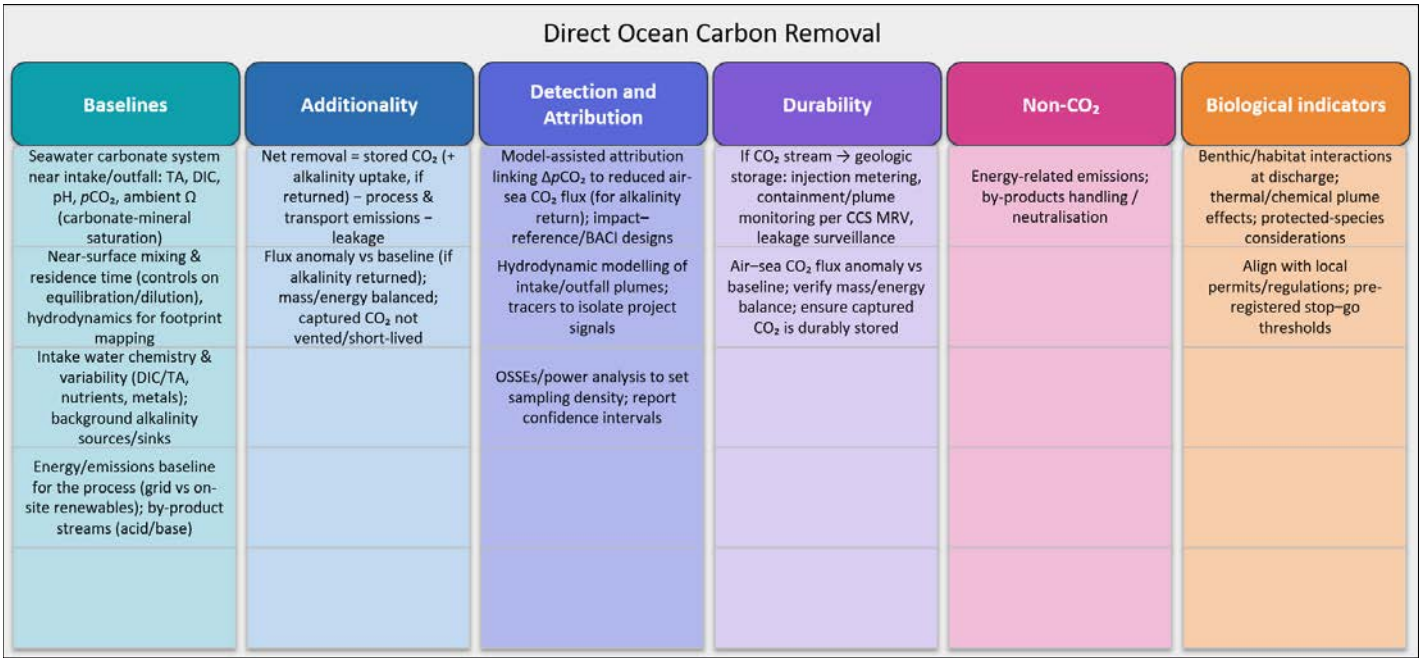
Ocean Alkalinity Enhancement

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Multi-season TA-DIC-pH-Ω (aragonite/calcite) climatology	Alkalinity mass balance (input vs observed TA anomaly)	Coherent TA anomaly (space-time) co-varying with deployment	Model fate of TA-driven DIC → net atmospheric removal; report durability (100-yr and longer horizons) ± uncertainty.	Track N_2O/CH_4 where biogeochemistry shifts	Calcifier condition/abundance
Air-sea CO_2 flux	Air-sea CO_2 flux anomaly relative to the pre-registered baseline/control	Model-assisted attribution of $\Delta p CO_2$ and CO_2 flux reduction	Account for re-equilibration and mineral dissolution/precipitation	O_2 and alkalinity-induced pH changes	Plankton community shifts
Carbonate-system uncertainty: quantify measurement uncertainty and propagate to derived variables (Ω, $\Delta p CO_2$, flux)	Rule out non-project TA sources (rivers, dust, dissolution)	Tracer or isotopic fingerprint if feasible		Metals/impurities in alkalinity feedstock	Benthic impacts near point additions
Natural alkalinity sources/sinks					eDNA-based indicator set (sentinel taxa)
Mixing and residence time (controls on air-sea equilibration and dilution of the alkalinity signal)					Avoid sharp pH/Ω spikes



Artificial Downwelling

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Stratification/MLD, nutrient & DIC profiles, background downwelling indices	Net export to depth beyond natural variability	Temperature/nutrient/DIC anomalies tied to device operation	Fate of transported carbon mass and residence time	N_2O formation under nitrification/denitrification	Local deoxygenation impacts
Air-sea CO_2 flux	Show no simple displacement of natural downwelling	PP/export response		O_2 drawdown/hypoxia risk	Community shifts from nutrient pulses
O_2/N_2O baseline		Model D&A separating physical vs project signals		Potential CH_4 release from deep waters	Benthic stress under increased flux
					Mobile megafauna interactions with tech devices



Direct Ocean Carbon Removal

Baselines	Additionality	Detection and Attribution	Durability	Non-CO_2	Biological indicators
Seawater carbonate system near intake/outfall: TA, DIC, pH, pCO_2, ambient Ω (carbonate-mineral saturation)	Net removal = stored CO_2 (+ alkalinity uptake, if returned) − process & transport emissions − leakage	Model-assisted attribution linking ΔpCO_2 to reduced air-sea CO_2 flux (for alkalinity return); impact–reference/BACI designs	If CO_2 stream → geologic storage: injection metering, containment/plume monitoring per CCS MRV, leakage surveillance	Energy-related emissions; by-products handling / neutralisation	Benthic/habitat interactions at discharge; thermal/chemical plume effects; protected-species considerations
Near-surface mixing & residence time (controls on equilibration/dilution), hydrodynamics for footprint mapping	Flux anomaly vs baseline (if alkalinity returned); mass/energy balanced; captured CO_2 not vented/short-lived	Hydrodynamic modelling of intake/outfall plumes; tracers to isolate project signals	Air–sea CO_2 flux anomaly vs baseline; verify mass/energy balance; ensure captured CO_2 is durably stored		Align with local permits/regulations; pre-registered stop–go thresholds
Intake water chemistry & variability (DIC/TA, nutrients, metals); background alkalinity sources/sinks		OSSEs/power analysis to set sampling density; report confidence intervals			
Energy/emissions baseline for the process (grid vs on-site renewables); by-product streams (acid/base)					

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