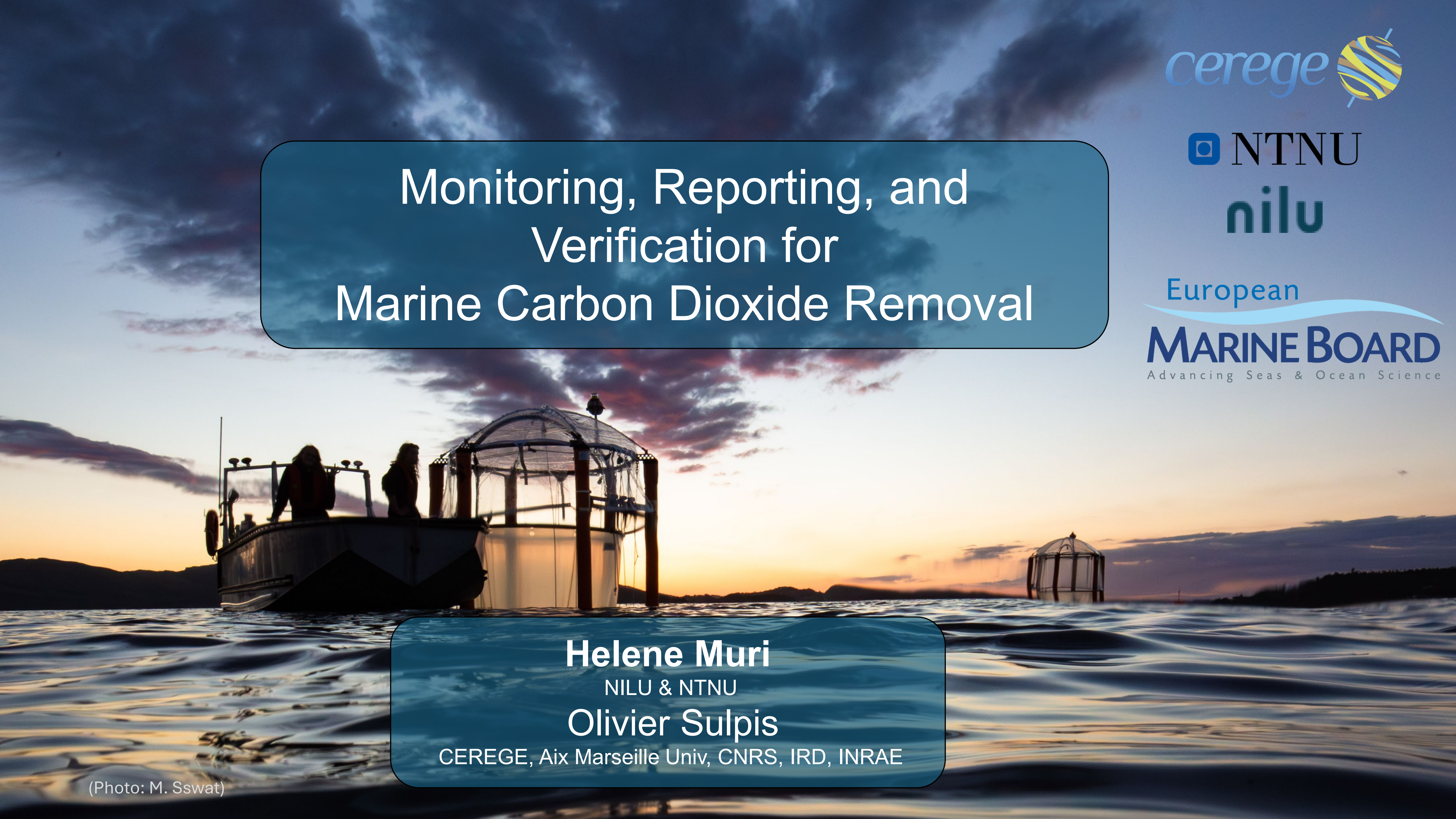
# Monitoring, Reporting, and Verification for Marine Carbon Dioxide Removal

**Helene Muri**
NILU & NTNU
Olivier Sulpis
CEREGE, Aix Marseille Univ, CNRS, IRD, INRAE



(Photo: M. Sswat)

# EMB Working Group:
# Marine Carbon Dioxide Removal

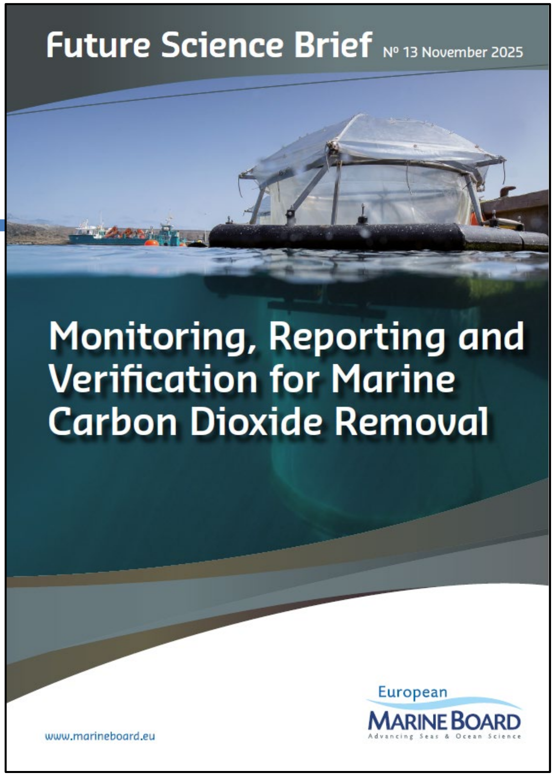
| | |
|---|---|
| **Helene Muri (Chair)** | NTNU & NILU, Norway |
| **Olivier Sulpis (Co-Chair)** | CEREGE - Aix-Marseille University, CNRS, IRD, France |
| **Gabriela Argüello** | University of Gothenburg, Sweden |
| **Chelsey Baker** | NOC, UK |
| **Miranda Böttcher** | Utrecht University & SWP, Netherlands & Germany |
| **Maribel García-Ibáñez** | Spanish Institute of Oceanography (IEO-CSIC), Spain |
| **Karol Kuliński** | IO PAN, Poland |
| **Angela Landolfi** | Institute of Marine Sciences (CNR-ISMAR), Italy |
| **Peter Landschützer** | VLIZ, Belgium |
| **Evin McGovern** | Marine Institute, Ireland |
| **Živana Ninčević Gladan** | Institute of Oceanography and Fisheries, Croatia |
| **Andreas Oschlies** | GEOMAR, Germany |
| **Elias A. Yfantis** | University of Nicosia, Cyprus |

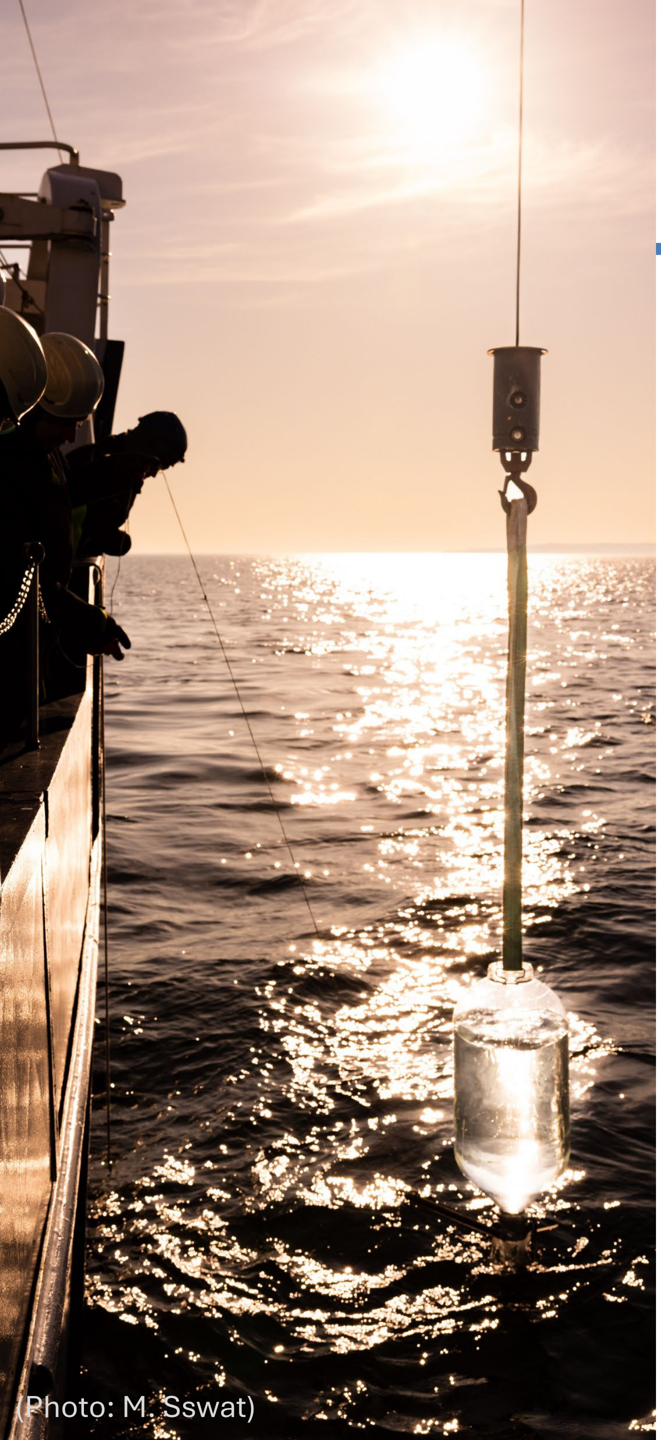
**WG launch August 2024**

**Publication 17th November 2025**

**Future Science Brief Nº 13**

Focus on monitoring, reporting and verification of marine carbon dioxide removal activities



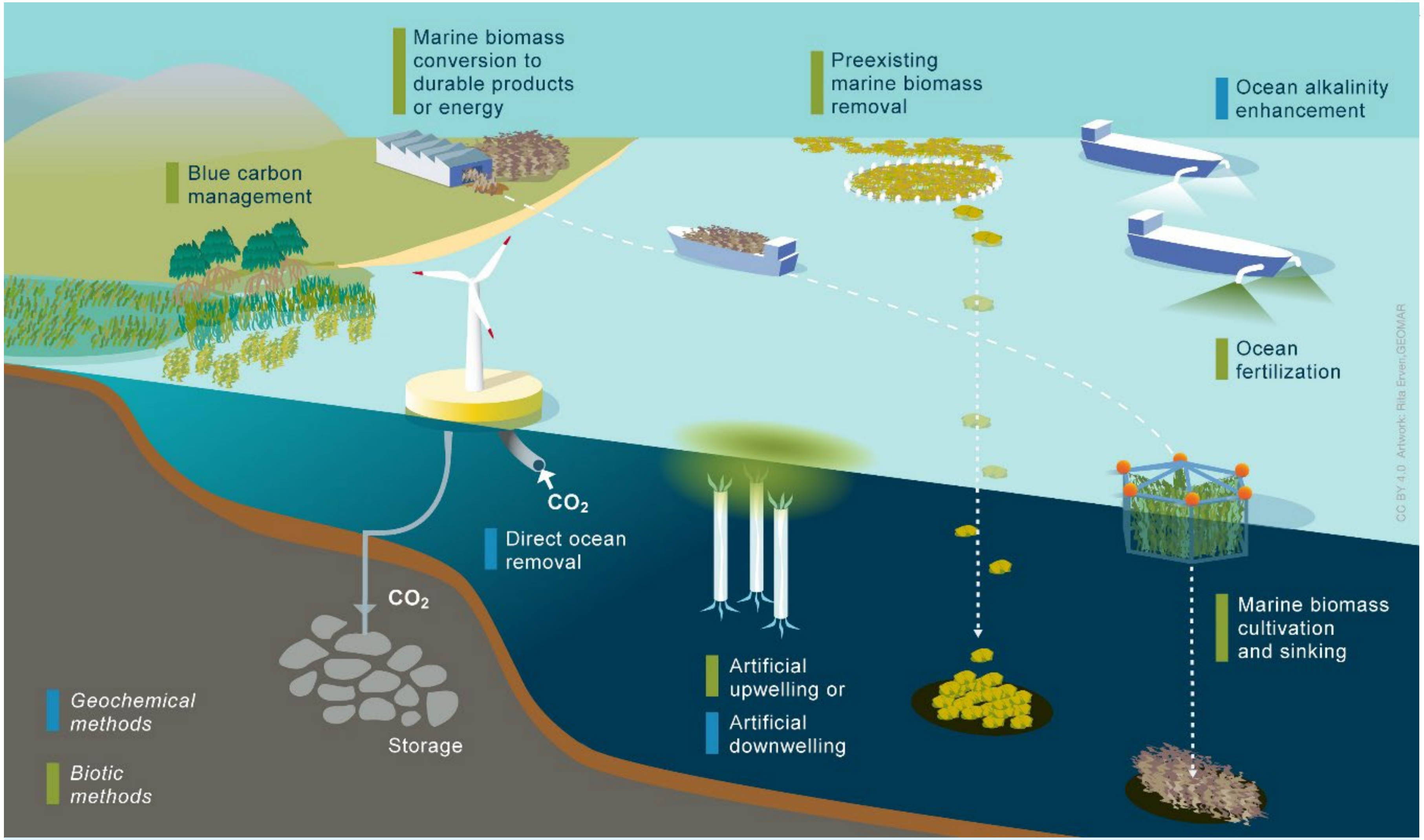

# Monitoring, reporting and verification for marine CDR

**Objective**: provide a state-of-the-art overview on the topic and conclude with relevant recommendations for policy, practitioners, and research funders. The document is primarily written from a European perspective, but due to the nature of marine CDR, it may have global relevance.

**The report provides an accessible summary of:**

- different marine CDR approaches
- key challenges for MRV
- assesses the current observational and modelling capabilities
- the state of regulations and governance
- highlights the major knowledge gaps and uncertainties
- knowledge needed for MRV of different methods
- and provides actionable recommendations.

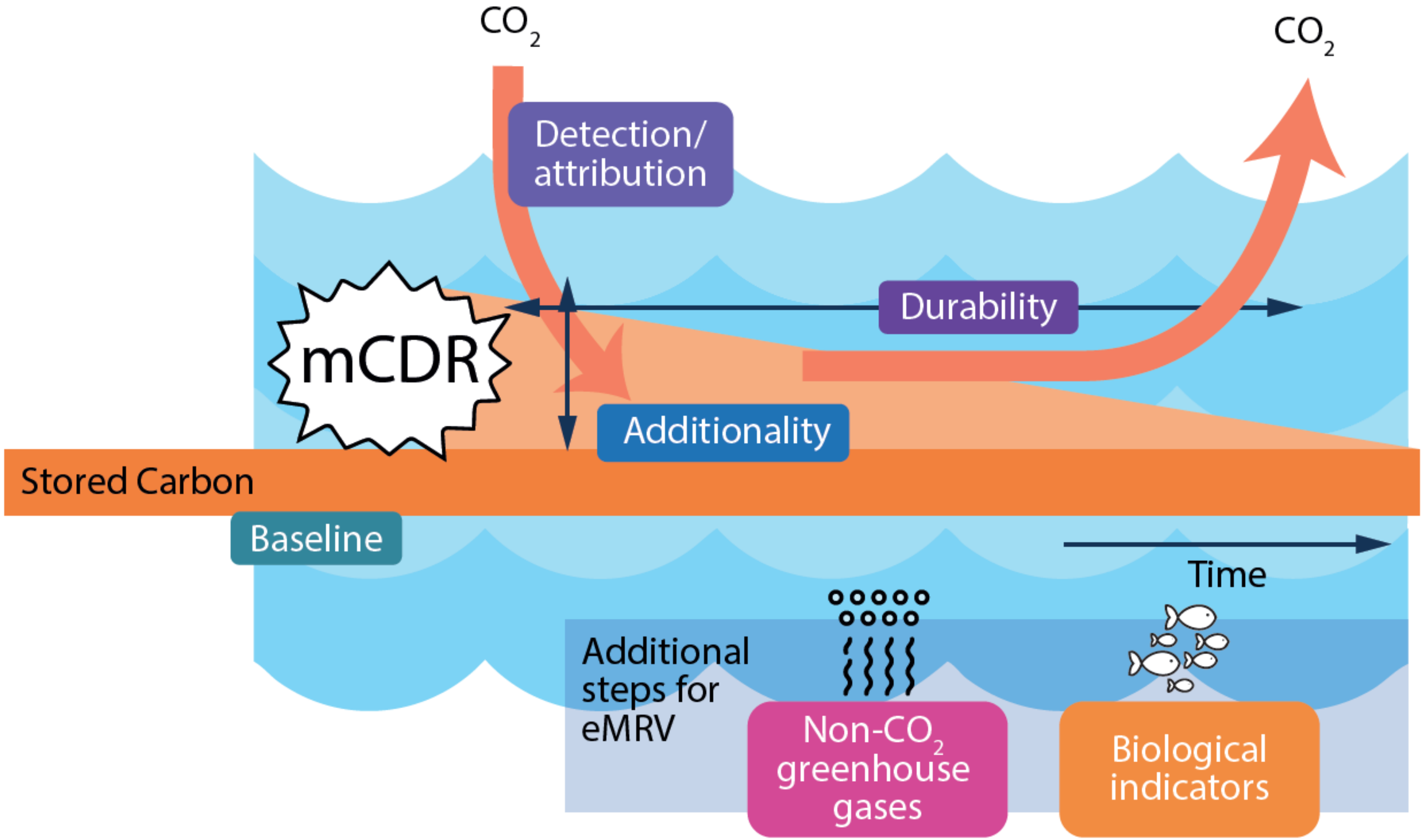
# Different methods of mCDR




Marine CDR: A range of biotic and geochemical methods that remove carbon from the atmosphere by enhancing ocean carbon uptake or storage through different mechanisms, scales, and pathways, each requiring its own tailored MRV.

# Key challenges for MRV

- Marine CDR requires careful assessment of factors such as additionality, storage durability, and biological indicators.
- It includes monitoring stored carbon, tracking other GHG emissions, and and applying rigorous measurement and verification over time.




MRV is the systematic process of monitoring, reporting, and verifying carbon removals and their impacts to ensure they are real, additional, transparently documented, and scientifically robustly quantified.
This process should provide confidence that climate benefits are genuine, measurable, and can be independently validated.

# MRV regulations and governance: current landscape



- International frameworks guide MRV for marine CDR, but no binding obligations exist yet.
- Deployments mostly restricted to sceintific research under international law, and national permits.

**Global Agreements**

- UNCLOS
- BBNJ Agreement
- UNFCCC, Kyoto, Paris
- CBD – Convention on biodiversity

**Environmental Impact Assessments**

- Required for activities that may cause significant harm
- Legal interpretation includes mCDR

**London Protocol**

- Assessment framework relevant for MRV
- Must justify purpose, scale, methods, location, benefits and risks

*«Adequate scientific basis and risk consideration for biodiversity and socio-economic impacts»*

# Paris Agreement Article 6.4 – Crediting mechanisms and MRV

European MARINE BOARD Advancing Seas & Ocean Science

- Enables cooperation between countries by transferring carbon credits from verified emission reductions or removals.
- Credits support countries in meeting their NDCs.
- Removal activities with reversal risks require monitoring beyond the crediting period to ensure durability.

Projects seeking Article 6.4 credits must report on:

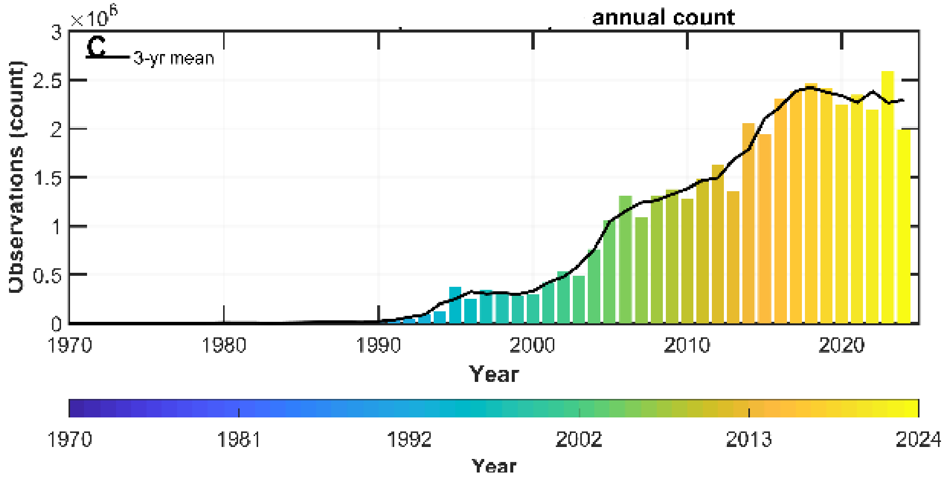
1. Monitoring methods
2. Net removal estimates and uncertainties
3. Associated GHG release events
4. Assessments of environmental and social impacts.

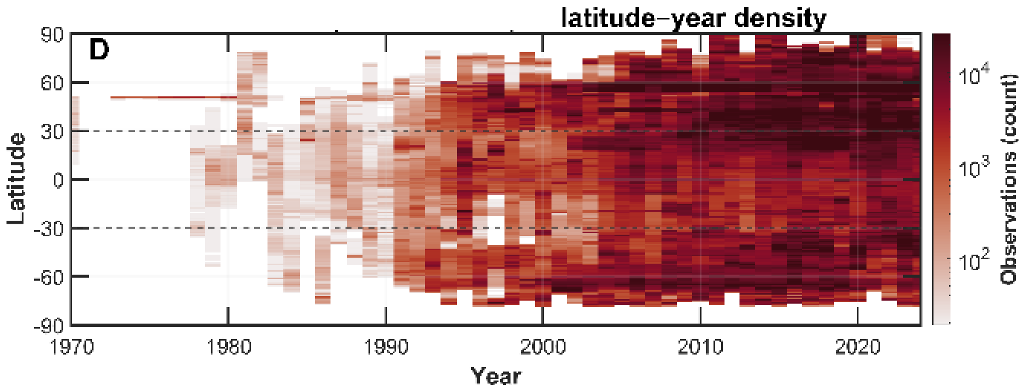
*Implication for mCDR: any activity generating Paris-compatible credits must meet these requirements for transparency, integrity and risk management.*

# Global ocean carbon observations: gaps and challenges

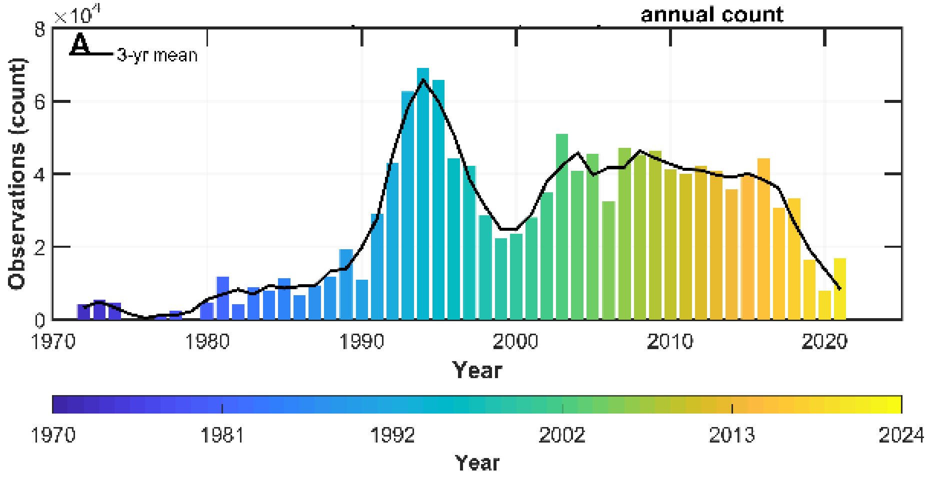
## Challenges in Coverage and Measurement Accuracy

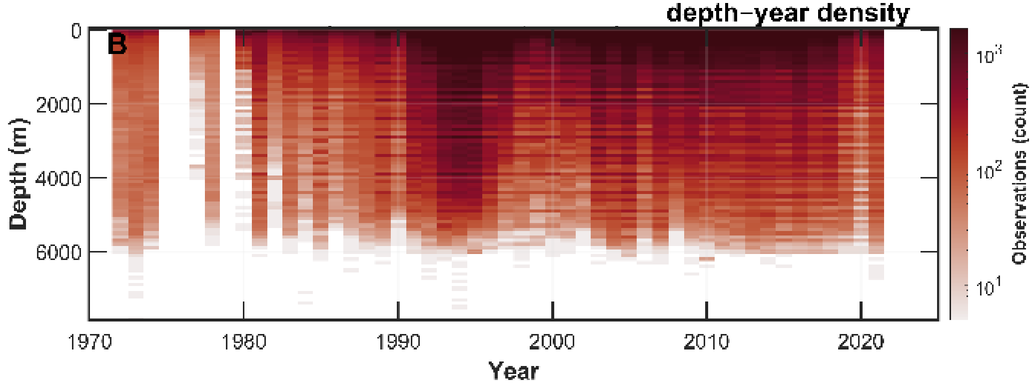
### Surface $CO_2$ measurements (SOCAT) – annual and latitudinal distributions




### Subsurface DIC measurements (GLODAP) – annual count and depth distributions



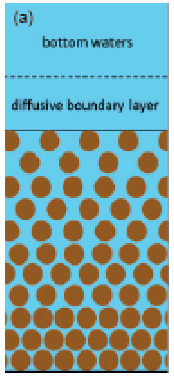

Credit: Alizée Roobaert.

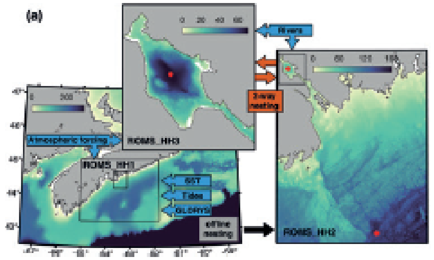
- The observing system is patchy, not sustained at the scales needed for MRV.
- Major gaps in depth coverage, regional sampling, seasonality, and long-term consistency.

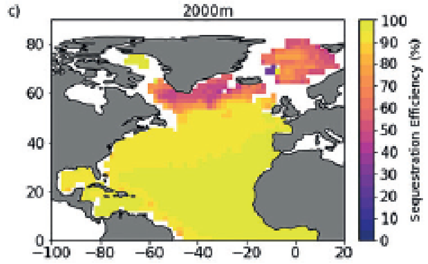
# Modeling approaches for mCDR: from mechanistic to Earth system

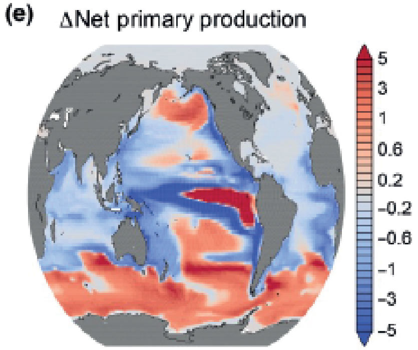
*Blue arrow: progression of modeling complexity.*
*Purple arrow: examples of outputs relevant to MRV.*

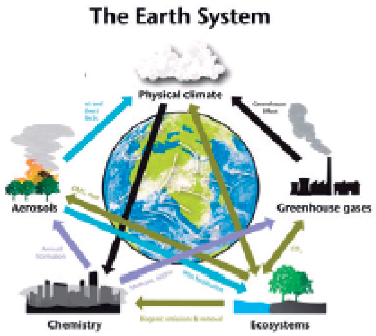
**Mechanistic** | **Local-regional** | **Basin-scale** | **Global** | **Earth System**




- Alkalinity release
- Biomass growth

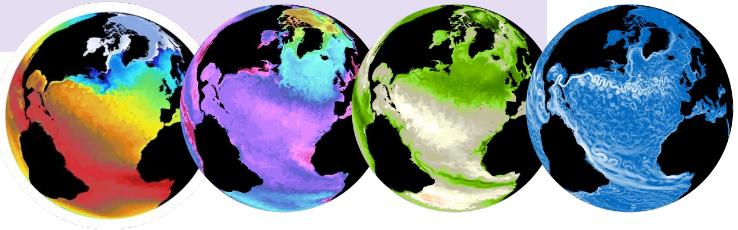
- Plume tracking
- Air-sea $CO_2$ flux

- Counterfactual determination
- Durability

- Environmental impacts
- Durability

- Additionality issues via feedbacks on other carbon sinks

Earth System models capture feedbacks but require integration with mechanistic and regional models for accuracy.



Credit: EMB based on a concept by Chelsey Baker. 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.

# State of MRV readiness for mCDR methods

European MARINE BOARD
Advancing Seas & Ocean Science

**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 | ■ | ■ | ▲ | ▲ |

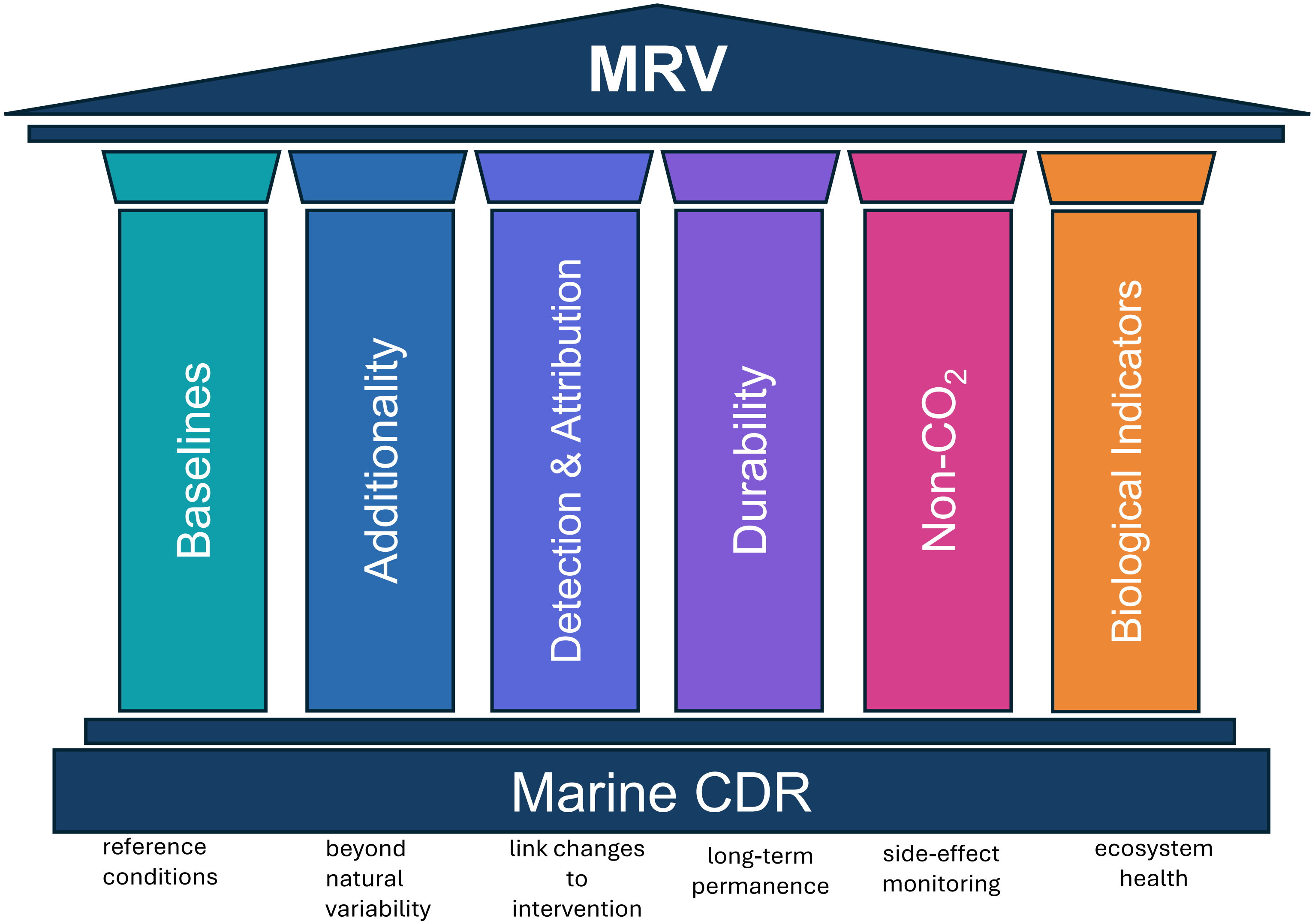
Pilot-scale MRV readiness varies widely across mCDR methods, with only a few methods, with only a few approaches showing mature baseline and monitoring frameworks, while most remain only partially ready or still lack foundational MRV components.

Colours signal readiness:
**Green = ready** (established protocols exist)
**Yellow = partially ready** (important gaps remain)
**Red = not ready** (foundational methods missing)

# Building Confidence in Marine Carbon Dioxide Removal
## - A Six-Pillar MRV Framework

**Robust MRV for mCDR rests on six core pillars**

These pillars ensure removals are real, additional, durable, and environmentally safe



# MRV

| 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 $\Delta pCO_2$ 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, $\Delta pCO_2$, 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 |

Ocean Alkalinity Enhancement

# Recommendations

**Overarching recommendation:**

We recommend that rapid reductions in $CO_2$ emissions remain the top priority.

# Recommendations for policymakers and regulators

1. Develop a standardised, comprehensive regulatory framework for MRV.
2. Standardise the collection and reporting of mCDR MRV information across diverse regulatory fora.
3. Develop regulations for baseline monitoring covering both carbon and ecology, using these to establish additionality 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, complement with modelling and machine learning.
5. Limit scaling and co-deployment until MRV protocols for individual methods have been proven, and assess changes in efficacy in co-deployment scenarios.
6. Consider the requirements of key legislation, for the implementation and monitoring of mCDR methods in the EU.

# Recommendations for science funders (national, European and philanthropic)

1. 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.
2. Fund projects that produce observational data for the purpose of validating and refining models, particularly on deep-Ocean.
3. Fund projects to investigate how biological processes respond to environmental change as part of MRV assessments, to ensure these changes do not compromise Ocean health.
4. Fund projects to close knowledge gaps on the long-term efficacy, environmental impacts and scalability of mCDR.
5. Require transparent data-sharing policies, and open-access publications and project outcomes.
6. Support practical applications of real-world MRV for mCDR, to complement the fundamental research behind mCDR methods.
7. Support multi-disciplinary and trans-disciplinary MRV research projects that scope and map the regulatory landscape, while actively engaging stakeholders and local communities.

# Recommendations for MRV scientists, practitioners and project planners

1. Establish robust local-, regional-, and large-scale baselines of carbon fluxes.
2. 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.
3. Determine thresholds for unacceptable ecological and environmental side effects that would trigger policy or management response.
4. Quantify the durability of the $CO_2$ removal, in addition to its magnitude.
5. Establish how interactions between various mCDR methods being co-deployed may be credited within MRV and carbon removal accounting frameworks.
6. Conduct rigorous Life Cycle Assessments (LCAs) to quantify the net carbon removal.
7. Develop standardised environmental MRV (eMRV) guidance and baselines, for detecting and attributing ecological impacts and non-$CO_2$ forcers.
8. Describe environmental and ecological risks, at least qualitatively, and quantify when possible.
9. Follow ethical principles and codes of conduct for research, and prioritise funding from transparent sources.

European MARINE BOARD
Advancing Seas & Ocean Science


https://marineboard.eu/marine-carbon-dioxide-removal