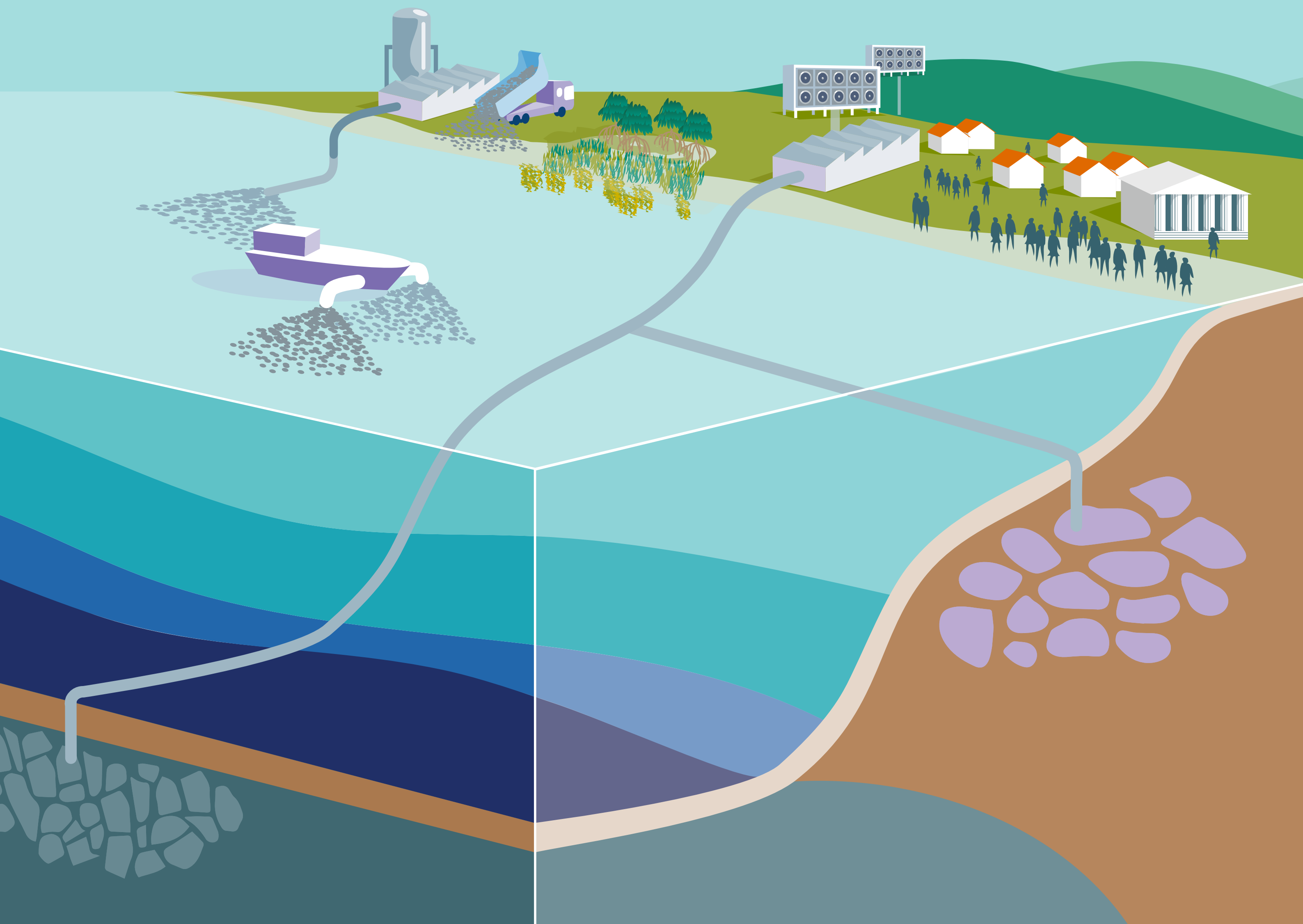
CDRmare

Research mission of the
German Marine Research Alliance (DAM)
»Marine carbon sinks in
decarbonisation pathways«

CDRmare HUB Workshop Report

Monitoring Environmental Impacts of mCDR Field Tests

FEBRUARY 2026



DAM GERMAN MARINE RESEARCH ALLIANCE

With funding from the:

Federal Ministry of Research, Technology and Space

Freie Hansestadt Bremen

Hamburg | Behörde für Wissenschaft, Forschung, Gleichstellung und Bezirke

MV Mecklenburg-Vorpommern

Niedersächsisches Ministerium für Wissenschaft und Kultur

SH Schleswig-Holstein Ministerium für Bildung, Wissenschaft und Kultur

Imprint

Publisher:

GEOMAR Helmholtz Centre for Ocean Research Kiel
Wischhofstr. 1 – 3
D-24148 Kiel
Germany

Authors:

Christian-Benjamin Sarpey, Sandy Avrutin, Robert Steenkamp, Andreas Oschlies, Ulrike Bernitt*, Miranda Böttcher, Nadine Mengis, Alexander Proelss

with input from Sam Dupont, Anna Madlener, Michael Sswat, Chelsey Baker, Lennart Bach, David Ho, Sina Löschke and all workshop participants.

*corresponding author

Disclaimer: This report reflects the authors' effort to provide a comprehensive synthesis of the workshop discussions. However, it does not necessarily represent the views of all individual workshop participants.

The authors gratefully acknowledge financial support from the German Federal Ministry of Research, Technology and Space (BMFTR) through CDRmare, the research mission "Marine carbon sinks in decarbonization pathways" (CDRmare) of the German Marine Research Alliance (DAM).

Recommended citation:
Sarpey, C.-B., Avrutin, S., Steenkamp, R., Oschlies, A., Bernitt, U., Böttcher, M., Mengis, N., Proelss, A. (2026). Monitoring Environmental Impacts of mCDR Field Tests: Workshop Report. pp. 1-19, DOI 10.3289/CDRmare.58

Executive Summary

The workshop *'Monitoring Environmental Impacts of mCDR Field Tests'*, held on 5 September 2025 at GEOMAR and organised by the CDRmare Social Sciences and Humanities Hub, convened a diverse group of scientists to advance a shared understanding of what constitutes responsible and feasible environmental monitoring, reporting, and verification (eMRV) for marine carbon dioxide removal (mCDR) field experiments. Given emerging developments in regulating mCDR research, such as the forthcoming amendments to Germany's High Seas Dumping Act, the workshop provided a great opportunity to examine interdisciplinary scientific and legal challenges associated with monitoring environmental impacts.

Across three thematic sessions, international experts provided insights into the current state of scientific knowledge, lessons learned from conducted and planned field experiments, and the evolving legal landscape relevant to mCDR-related eMRV. The discussions underscored that, although environmental monitoring is essential for safeguarding marine ecosystems, practical guidance for implementing eMRV for field experiments remains limited. Achieving consensus on such guidance will remain challenging, as several open questions persist, including how to establish robust baselines, integrate modelling approaches, and manage and communicate uncertainty. Another central challenge concerns the formulation of an impact hypothesis and the respective selection of appropriate parameters, as these steps must balance unknown risks against the practical limits of monitoring. Defining regulatory requirements is similarly complex, as existing legal frameworks for mCDR are fragmented and only rarely address eMRV explicitly. Nevertheless, experiences shared from ongoing and past experiments highlighted emerging best practices that can offer valuable direction even in the absence of comprehensive regulation.

The workshop underscored that eMRV for mCDR field experiments will continue to evolve as scientific understanding, data availability, and regulatory frameworks advance. Participants agreed that responsible experimentation requires balancing scientific comprehensiveness with operational practicality and that regulatory systems must remain adaptive to new insights. The event demonstrated both the complexity of developing robust eMRV systems and the momentum within the research community to jointly develop shared, science-based principles.

This workshop report synthesises the key points discussed. Next steps include using this synthesis, along with the network of participating experts, to prepare consolidated scientific publications as scientific input for the dynamic debate on mCDR eMRV governance.

CDRmare

CDRmare is a research mission of the German Marine Research Alliance (DAM) funded by the Federal Ministry of Research, Technology and Space. CDRmare addresses whether and to what extent the ocean can play a substantial role in removing and storing CO_2 from the atmosphere. Within this research mission, the Social Sciences and Humanities Hub (HUB) is a forum established to enable and increase academic co-operation between social science and humanities scholars involved in CDRmare. It addresses current questions on the regulation and governance of marine CDR options, responding to inputs from politics, regulation, and method-specific projects.

I. Overview

Methods for removing carbon dioxide from the atmosphere, including marine carbon dioxide removal (mCDR), are increasingly recognised as necessary complements to deep, immediate emissions reductions to meet the climate targets of the Paris Agreement. Alongside discussions of their potential climate benefits, the environmental impacts of mCDR have become a pressing issue in scientific debates across disciplines.

In this context, the interdisciplinary workshop "Monitoring Environmental Impacts of mCDR Field Tests", held on 5 September 2025 at the GEOMAR Helmholtz Centre for Ocean Research Kiel, provided a dedicated forum for advancing these conversations. Organised by the CDRmare Hub (Box 1), it brought together a diverse group of experts to examine the scientific and governance challenges associated with monitoring the environmental effects of mCDR field experiments.

This report summarises the workshop programme and presents an initial synthesis of the key points raised during the discussions.

Motivation and Goals

The motivation for convening this workshop arose from recently drafted amendments to Germany's High Seas Dumping Act, which now includes a provision requiring environmental monitoring, reporting, and verification (eMRV) for mCDR research activities. Considering the fact that the practical implications for researchers as well as the competent permitting authorities under the amendments remain unclear, there is a need for a shared understanding of what mCDR eMRV should entail. This is important not only for Germany but also for the European Union (given Germany's leading role in mCDR research), as well as internationally (given the increased global attention being paid to mCDR and its crucial role in fulfilling climate change obligations).

The workshop sought to bring together different scientific perspectives to discuss what constitutes feasible and responsible eMRV for scientific mCDR field tests. Since questions surrounding the environmental impacts of mCDR have so far been addressed within separate research communities and experimental efforts, one key objective was to foster interdisciplinary exchange and mutual learning. In doing so, the workshop aimed to build a shared understanding of the current state of scientific knowledge, including by highlighting remaining uncertainties and critical gaps. Overall, the workshop aimed to address the following overarching questions:

- **What do we currently know – and not yet know – about monitoring the environmental impact of scientific mCDR field tests?**
- **How can eMRV frameworks contribute to building scientific and societal trust, safeguarding against harmful experiments, and enabling responsible field testing?**
- **To what extent can such frameworks be integrated into existing legal structures, and where might future regulation be required?**

By exploring these questions collaboratively, the workshop intended to support the development of a clearer, scientifically grounded foundation for defining and implementing mCDR eMRV requirements. Importantly, the scope was focused explicitly on small-scale, research-driven field experiments, including academic and public-private demonstrations. The discussions were therefore centred on scientific, technological, data-related, and regulatory feasibility and did not extend to economic viability. Broader issues such as public perception and societal acceptance, while highly relevant, were considered beyond the scope of the meeting. It should also be noted that, given the advanced stages of research into ocean alkalinity enhancement (OAE), much of the discussion centred around this mCDR method. That said, the workshop was not specifically aimed at OAE, and it is hoped that results from OAE will also help guide discussions of other mCDR methods.

Programme and Participants

Fig. 1: Group photo of the on-site workshop participants (Source: Laura von Stebut – CDRmare)

The workshop programme was designed to combine focused input presentations with structured discussion formats (Annex I). Following an initial introduction to the overarching themes of the workshop and the relevance of establishing consensus on what mCDR-related eMRV should entail, the programme continued with three sessions of input and framing presentations. These were intended to provide deeper insights from diverse research perspectives and to create a common basis for exploring several guiding questions. Each session concluded with a plenary discussion on these questions, and two working groups later in the day offered space to synthesise the results.

The opening session included presentations on the scientific foundations of eMRV for mCDR, covering considerations for parameter selection, the role of modelling approaches, and best practices in data management and sharing. The session focused on exploring the current state of science from a theoretical standpoint and on identifying how existing methodologies, models, and protocols can be adopted or adapted to the purposes of mCDR eMRV. Each presentation was followed by a short Q&A, and the session concluded with an open discussion on the following guiding questions:

- **Q1**: Can we agree on fundamental indicators or methods for environmental monitoring that are globally applicable, independent of the mCDR method and ocean region? Can we define a global standard, or at least a national or regional one (e.g., the North Atlantic)?
- **Q2**: What is the minimum monitoring duration and spatial scale to detect both immediate and long-term environmental impacts?
- **Q3**: Baseline data are critical for eMRV – how can we deal with the absence of baseline data (including models) in many ocean regions?

- **Q4**: How could the monitoring requirements be established? Through guiding questions or a core set of general parameters, monitoring design, and /or modelling approaches?

In the second session, attention turned to lessons learned from past, ongoing, and planned OAE research projects. Presentations on the cross-project initiatives OAEPIIP and the Carbon to Sea OAE MRV Database[1] offered participants a broad overview of the monitoring approach across the diverse trials captured. Complementary case studies from LOC-NESS, the Röst Marine Research Centre, VESTA, and the Halifax Project provided concrete examples of how different research teams have approached stakeholder engagement, interactions with permitting authorities, and the design and implementation of monitoring plans. The session then moved to current projects aimed at developing broader methodological guidance. Carbon to Sea presented their environmental impact monitoring framework draft developed in partnership with PML Applications, Ocean Visions' presented their impact-assessment framework initiative, and Hourglass Climate introduced its emerging framework for ecotoxicological modelling of mCDR impacts. Together, these contributions showcased both project-specific insights and the growing efforts to translate field experience into generalisable frameworks.

This comprehensive overview set the stage for a discussion around the guiding questions for Session 2:

- **Q5**: How could we guide decision-makers with respect to what counts as sufficient monitoring – including scale, duration, and interpretation of results –, and who should interpret the data?
- **Q6**: Which mechanisms can ensure that all results – including failed or inconclusive experiments – are reported and accessible?
- **Q7**: How can 'show-stopper criteria' and associated thresholds for environmentally safe mCDR field tests be established?
- **Q8**: What are the best practices for the interaction of research efforts and regulatory agencies with respect to environmental monitoring?

Session 3 addressed the regulatory dimensions of mCDR. Three presentations examined emerging provisions within international frameworks, as well as existing monitoring requirements under EU and US legislation. Overall, the session clarified the distinction between eMRV, environmental impact assessments (EIAs), and carbon MRV (cMRV), with the latter two having received considerably more regulatory attention to date. The session thus highlighted the novelty of eMRV regulation and identified potential linkages and gaps for implementing eMRV within current frameworks. In the discussion that followed, participants explored how these considerations could be linked with scientific recommendations and requirements, thus addressing the following guiding questions:

- **Q9:** To what extent can science-led monitoring and reporting serve as the foundation for regulatory eMRV, and what regulatory mechanisms are needed to ensure transparency and legitimacy?
- **Q10**: Under which conditions do modelling tools and model results make reliable contributions to eMRV?
- **Q11**: How can regulatory frameworks for mCDR eMRV remain adaptive and trustworthy by setting clear standards (baselines, monitoring, modelling, stopping criteria, and cross-border issues) while at the same time also allowing updates as new insights emerge?
- **Q12**: How to handle monitoring across border regions with overlapping jurisdictions?

[1] The final version is expected to be released in early 2026. Release announcements will be posted on Carbon to Sea's website (www.carbontosea.org)

After the three sessions, participants joined two parallel working groups to formulate key considerations identified in the respective sessions. One group addressed the scientific requirements for eMRV, while the second group concentrated on regulatory frameworks relevant to mCDR eMRV. The main insights from the working group discussions were summarised and presented during a subsequent plenary meeting.

Reaching out to researchers across the globe and offering a hybrid event format facilitated access to a wide range of expertise, allowing external and international specialists to participate and contribute actively throughout the day. In total, the workshop brought together 41 participants from 16 research institutions, reflecting the growing global scientific and regulatory interest in mCDR-related eMRV. This diversity of backgrounds enriched the technical discussions and interdisciplinary exchanges, ensuring that multiple perspectives from field experimentation to governance were represented (Annex II).

To support transparent and collective documentation, the workshop operated under Chatham House Rules, and a live document was maintained where both the organising team and participants could record discussion points and additional observations in real time. The results of this "living document" are synthesised in the next chapter.

II. Discussion Synthesis

Key measurement challenges

Baselines

Establishing a robust baseline represents a central challenge for monitoring the environmental impacts of mCDR. Baselines are not static but constantly changing, raising questions about how a baseline should be determined, how frequently it must be reviewed, and who should decide which baseline to adopt. Here, it is important to acknowledge that the nature of eMRV is different from the nature of carbon-related MRV (cMRV). For cMRV, the fundamental concept is quantification of carbon removal. It is therefore important to quantify, along with uncertainty, the departure from the baseline state following the implementation of mCDR. However, for eMRV, the fundamental concept is operation within the limits of ecological safety. This means that the pre-industrial state of the area and the subsequent impact of climate change up until the point of implementation may be considered alongside the contemporary mean state and variability, since the implementation of mCDR may in some cases bring the mean state back towards or away from the pre-industrial state – and changes in either direction may be positive, neutral, or negative depending on the method and the quantity being measured.

A major difficulty is that, in most cases, robust long-term baseline data for ecosystems are lacking. This raises the question of whether mCDR field experiments should be prioritised in regions where systems and their baselines are already well characterised. However, even in areas without established baselines, field trials may proceed if insufficient site-specific data are supplemented with observations from analogous control sites. These measurements can be collected before and during the trial and should be derived from long-term monitoring series located geographically close enough to the trial area to remain ecologically relevant, yet sufficiently distant to avoid direct influence from ongoing mCDR activities. One option is to use modelling to determine an appropriate location for this comparison. In the case of OAE, numerical models have already been used to assess how ocean dynamics laterally mix alkalinity. This is usually intended to assess the desired extent of monitoring for carbon drawdown, but similar results could also be used to identify potential areas for collecting time-series data for eMRV. Critically, such control sites serve only as pragmatic supplements and cannot replace site-specific baseline data entirely. While comparative reference sites offer valuable context, they carry inherent limitations due to spatial heterogeneity and differences in ecological histories, making it difficult to define and validate whether a given site qualifies as sufficiently comparable.

Another important consideration is the timescale of monitoring before, during, and after the mCDR test to assess changes relative to the baselines. In some cases, it may be beneficial to continue monitoring until the system returns to its pre-trial state. However, in other cases, the objective may explicitly be a durable shift away from the baseline – for example, to enhance ecosystem services or increase alkalinity. In this case, as mentioned before, understanding of the pre-industrial state of the area can be a useful point of comparison for what may be considered 'safe' change, and information about unperturbed (by mCDR) analogous sites can also provide insight into how the area may have changed in a counterfactual case, helping to disentangle the impacts of mCDR, natural variability and (depending on the length of the trial and the severity of change) climate change. This calls for careful scientifically-informed consideration by regulators of what types of change and variability are permissible, what needs to be monitored, and for how long. This should be considered alongside what co-benefits may be integrated into the assessment, and who is ultimately responsible for deciding this and for determining whether deviations from the baseline are problematic.

Finally, the characterization of baselines requires explicit attention to dominant modes of natural variability, on various scales. Shorter and smaller-scale processes to consider involve tidal mixing, diurnal and seasonal cycles, and spatial variability driven by storms, eddies and fronts. Larger-scale variability relates to interannual events such as El Niño, the North Atlantic Oscillation and the Pacific Decadal Oscillation.

Additionally, the rate of change must be considered in relation to the life cycles and generational turnover of species, as ecological responses may lag behind physical or chemical perturbations. Defining the appropriate temporal and spatial resolution for baseline data is therefore essential to ensure that monitoring frameworks adequately capture both natural variability and anthropogenic influences.

Modelling

Models play a crucial role in projecting and assessing the impacts of mCDR, but their application requires careful design, calibration, and validation using observational data. One approach is to use ensemble means, either through multiple models or a single model with varying parameterisations. Yet models for environmental impacts, particularly with respect to ecology, remain underdeveloped. This makes validation through observation all the more necessary. While observations and models should complement each other, it must be made explicit what each can contribute. Furthermore, models may require extending the spatial scale of monitoring beyond the immediate intervention site in order to adequately capture system-level dynamics.

The advantages of models are multifaceted. They enable a better understanding of dilution processes and help identify where impacts are concentrated, including when critical thresholds may be crossed. Models can provide insights into the expected extent and temporal evolution of impacts, thereby informing decisions such as when monitoring may be concluded. They are also indispensable for disentangling the effects of mCDR from broader climate change signals, allowing for more robust detection and attribution. During early project stages, such as environmental impact assessments (EIAs), models can project risks and uncertainties, helping to formulate the impact hypothesis to be tested through monitoring. At later stages, their utility depends on iterative improvement, for example using observational data to tune parameters. Beyond site-specific applications, replicated modelling exercises across multiple environments can help identify overarching response patterns and generalizable system behaviours.

At the same time, it is important to recognise the limits of modelling. No single model can address all relevant questions. Therefore, regulators must articulate specific questions for which tailored models can be applied. Certain environmental impact assessment frameworks may already include modelling approaches that could be drawn on for mCDR, suggesting that adaptation of current tools may be more effective than designing new systems. However, it must be acknowledged that new, purpose-built systems cannot be entirely avoided, as local and regional models remain insufficiently developed. Importantly, model development must extend beyond carbon cycling to incorporate relevant environmental indicators and robust ecosystem components, acknowledging that models become weaker and their results more uncertain the further they move toward ecosystem-level modelling. A particular issue is the poor parameterisation, or even absence, of the combined effects of multiple drivers leading to an under-estimation of the impacts of mCDR. Poor parameterisation can, in theory, be improved via the collection of experimental and observational data that can be used for either parameter tuning or data assimilation, however a lack of models that capture process understanding of the effects of combined drivers and ecosystem dynamics is still an issue.

To contribute to robust eMRV systems, models should adhere to certain standards. They should be based on clearly stated assumptions and allow for comparability across studies. They should be informed and validated by observational data, requiring monitoring plans that explicitly link empirical and modelled components. Models should further allow for bidirectional aggregation, integrating regional insights into global-level syntheses and vice versa. Interoperability across model types and scales is equally essential, ensuring that insights from one modelling framework can inform others.

The question of model selection may also have regulatory implications. In some jurisdictions, only pre-approved models may be used, and obtaining approval for new models can be complex. Domestic legislation typically mandates the use of "best available models" or "best available science," which, in practice, requires models to be peer-reviewed, broadly supported by the scientific community, and gradually established through practice. Finally, the private sector may contribute to the evolution of more sophisticated models, as buyers of carbon credits have a direct financial incentive to demand high accuracy in carbon accounting. Such advances may eventually extend to environmental monitoring as well, particularly as reputational incentives strengthen and regulatory expectations for eMRV become better established.

Parameters

A key challenge in designing eMRV protocols is selecting appropriate parameters for monitoring. As with baselines and modelling, parameter selection must account for the complexity, variability, and context-specificity of marine ecosystems. For carbon-focused metrics, the choice of parameters to monitor is better defined (predominantly carbonate system parameters), although their scope and frequency is still debated. On top of this, many of the other parameters measured (salinity, temperature, oxygen) are often measured in order to comply with existing requirements for environmental monitoring, or to aid with model calibration/verification. However, these parameters may not provide a complete picture of the environmental impacts of an mCDR trial, and choosing parameters that meaningfully capture ecological responses across different spatial and temporal scales is not simple. Although existing environmental monitoring programmes can (and should) be taken into account, they must be adapted differently depending on the specific mCDR intervention, as the ecological response is highly pathway-, site-, and feedstock-dependent. There is also still a lack of mechanistic understanding of the long-term, ecosystem-level response to mCDR implementations, which further complicates the process of adapting pre-existing monitoring programmes. This has also been demonstrated by decades of ocean acidification research: early attempts at defining universal indicators ultimately showed that biological and ecological responses are highly population- or species-specific, mostly as a consequence of local adaptation.

Against this backdrop, prescribing a uniform list of parameters would not be scientifically defensible. Instead, a 'parameter-pool approach' offers a more flexible and robust pathway. Under such an approach, a core set of parameters could be applied across projects to ensure a minimum level of comparability. Additional parameters could then be selected on a case-by-case basis, informed by the impact hypothesis (see below), local ecological sensitivities, and the characteristics of the intervention. This avoids premature over-standardisation while ensuring that key environmental dimensions are not overlooked. Thresholds associated with these parameters cannot be universally defined; instead, they must be derived locally, acknowledging ecological histories, existing stressors and their potential interactions, and regional variation in natural variability. Regulators will therefore require clear guidance on how to set such context-specific thresholds.

Temporal considerations further complicate parameter choice. Generally, monitoring should begin before the intervention to establish baselines, continue throughout the entire intervention, and extend beyond it to assess recovery or persistence of impacts. However, the appropriate post-intervention duration remains difficult to define as environmental impacts unfold along very different timescales, ranging from immediate physiological responses to multi-decadal ecosystem-level changes. While long-term monitoring is essential for detecting slow or cumulative biodiversity and community-level impacts, early-warning indicators may offer pragmatic ways to infer such potential long-term risks in the short term. These proxies may therefore play an important role in monitoring frameworks, provided their relevance, sensitivity, and interpretability are well validated. The challenge lies in selecting proxies that provide meaningful insight without overstating their predictive power.

Spatial scales must likewise be considered. Local monitoring at trial and control sites is crucial for assessing ecological safety and distinguishing mCDR impacts from natural variability in the directly affected area. Yet broader spatial monitoring may be necessary, as any mCDR intervention might generate impacts that disperse beyond the test site. In parallel, the nonlinear accumulation of local impacts at the regional and global scale must be considered, accounting for complex nonlinear relationships.

Taken together, these considerations underscore that parameter selection cannot follow a 'one-size-fits-all' model. Scientifically credible eMRV systems must instead be adaptive, grounded in local ecological understanding, and structured around explicit hypotheses regarding expected impacts. Parameters should be chosen to ensure both operational feasibility and ecological relevance, enabling regulators and project proponents to detect and interpret change in ways that support safe, transparent, and responsible field testing.

Uncertainty

A central challenge in the governance of mCDR is how to effectively communicate and manage uncertainty. Uncertainties surrounding environmental impacts will remain, in part due to the limited development of environmental models and an incomplete mechanistic understanding of how mCDR affects ecosystems. These uncertainties need to be identified and meaningfully quantified. One possible approach would be to adapt structured assessment methods, such as the IPCC's confidence language, in combination with thresholds or acceptable ranges of variability. This could help clarify the degree of certainty regarding specific thresholds and, by extension, how comprehensively different parameters must be monitored. In this context, a distinction must be drawn between certainty (a quantitative measure of likelihood) and confidence (a qualitative measure of the validity of the theory, models, and data used to arrive at a conclusion), as the two concepts are not synonymous. The issue of uncertainty is already prominent in the London Protocol's assessment framework for ocean fertilization.

Communication strategies, particularly communication of uncertainty, must also be tailored to different audiences, including the scientific community, regulators, and the general public. In public and regulatory contexts, it is essential to acknowledge that experimental setbacks are inevitable and to frame them as opportunities for adjustment and learning, rather than reasons to halt activities. Moreover, clarity is required about what indicators reveal, what conclusions can be justifiably drawn, and whether such conclusions are significant. The field should also move beyond simplistic threshold thinking, recognising that not all positive and negative results carry equal weight. Importantly, failures should be acknowledged as integral to legitimate scientific inquiry and farsighted policymaking, particularly in international fora.

Stage-gating provides a mechanism for managing uncertainty by linking the scale of deployment to the level of uncertainty: the greater the uncertainty, the smaller the permissible scale of deployment. Under this approach, projects must first demonstrate viability, adherence to best practices, and the measurement of relevant parameters at smaller scales before advancing to larger interventions. Notably, scale should not be defined solely by the magnitude of achieved CDR, but also by the operational scale of activities that may increase environmental impacts associated with a given intervention.

Impact Hypothesis

Uncertainty is compounded by unknown risks, particularly regarding the impact hypothesis. The impact hypothesis is a predictive statement describing how a stressor is expected to change ecological conditions, while explicitly acknowledging incomplete knowledge regarding the system, the mechanisms, and the magnitude of potential outcomes. Legally, it provides a basis for deciding whether to approve the project and, if so, under which circumstances (see below). Here, trade-offs must be managed between the risk of overlooking unknown impacts and the impracticality of exhaustive monitoring. A balanced approach might begin with a *de minimis* set of core parameters, expanded through iterative refinement of the Impact Hypothesis as more information is gathered during the project's lifetime. Mechanisms for incorporating new knowledge, as well as input from a broader spectrum of expertise – including both scientific and local or practitioner perspectives – will be essential. The responsibility for establishing the Impact Hypothesis raises further governance questions. Ideally, an Impact Hypothesis should be developed, or at least reviewed, by an independent group of experts. It seems that this is only partly reflected in current domestic practices. Regarding the international level, under the London Protocol, the Impact Hypothesis is formally developed by the project proposer, followed by some interaction with regulators after submission. In practice, however, regulatory engagement remains limited, leaving the primary responsibility with the project proponents themselves.

Regulatory Status Quo

Regarding the regulation of scientific mCDR field experiments, understanding the differences and overlaps among EIAs, eMRV, and cMRV is particularly important. From a legal perspective, these three concepts serve distinct but complementary functions. EIAs constitute an *ex ante* regulatory tool required under international frameworks such as the United Nations Convention on the Law of the Sea (UNCLOS) and the London Protocol, as well as under supranational and national laws. In this context, EIAs assess the likely environmental effects of a proposed mCDR activity *before* it is authorised, and help identify baseline conditions and potential permitting requirements. These assessments can then provide the basis for eMRV, which, however, serves a different function. Building on prior baseline data, eMRV is generally an environmental safeguard mechanism mandated *during* and *after* deployment, providing continuous or periodic monitoring of the environment, ensuring adherence to safety thresholds and identifying impacts if they occur. Such monitoring is essential for ascertaining ongoing compliance with permitting conditions and ensuring adaptive management. In contrast, cMRV is not concerned with the environmental impacts of a given mCDR activity, but with quantifying, reporting, and independently verifying how much carbon dioxide is removed, stored, and durably sequestered by it for the purposes of generating credible climate mitigation outcomes or carbon credits ('carbon accounting').

Regulation within the European Union

Within the European Union (EU), no dedicated eMRV regulation currently exists, nor is there a specific EIA framework for mCDR. However, existing legislative acts provide partial entry points. The Water Framework Directive mandates improving the ecological and chemical status of coastal waters, while the Marine Strategy Framework Directive (MSFD) requires member States to develop strategies for achieving good environmental status in marine waters, including monitoring programs. At the EU level, the MSFD is currently the most detailed regulatory tool that prescribes environmentally relevant parameters. It could thus be operationalized for eMRV by aligning eMRV parameters with MSFD descriptors. In Germany, eMRV is currently discussed in the context of the planned amendments to the High Seas Dumping Act, but uncertainties exist as to the exact indicators to be applied. The lack of clear and constructive guidance may partly be addressed by drawing on experiences, structures and methodological guidelines from existing EIA regulations.

Regulation within the United States

In the United States, several regulatory instruments are relevant, but because they were not specifically designed for mCDR, the regulation is fragmented. Under the National Environmental Policy Act, most mCDR methods require an Environmental Impact Statement, which, although not equivalent to eMRV, informs subsequent monitoring requirements – again highlighting the logical connection between EIAs and eMRV (even if carried out at different times). The Marine Protection, Research and Sanctuaries Act regulates ocean dumping, requiring permits based on potential impacts to marine and human environments. Additional frameworks, such as the Clean Water Act and the Rivers and Harbors Act, require permits for pollutant discharge, dredging, or activities obstructing navigation. The mCDR projects so far permitted under these two regulations had to adhere to environmental monitoring and reporting standards, but the exact requirements first had to be established in an iterative process between the project planners and the relevant permitting authorities.

London Protocol

At the international level, regulatory initiatives are advancing but remain incomplete. For the first time at the international level, the 2013 amendment to the London Protocol provides a definition for "marine geoengineering", and provides the contracting parties with the possibility to list relevant activities in a new Annex 4. Although this amendment is not yet in force at the international level as it has not been ratified by the requisite number of contracting parties, it has already been implemented in the domestic legal systems of several States, including Germany (see the 2018 revision of the High Seas Dumping Act). Once listed, these Annex 4 activities are accepted as "marine geoengineering" and are then subject to the regulatory purview of the London Protocol. As a general rule, all those activities that are listed are generally prohibited unless they fulfil the requirements of method-specific assessment frameworks that may be used to determine whether a particular activity amounts to legitimate scientific research. Annex 5 of the 2013 amendment broadly outlines the minimum contents of these frameworks, including the establishment of an impact hypothesis (see above), which could be the basis for deciding whether to approve, reject, or suggest revisions to any proposed placement activity, to define risk management and mitigation measures, and to establish environmental monitoring requirements. To date, only ocean iron fertilization (OIF) is listed in Annex 4 as a marine geoengineering activity and is subject to its own Specific Assessment Framework. However, the monitoring provisions in this framework merely state that a monitoring plan should be implemented in accordance with the conditions set by the Contracting countries and the assumptions underlying the impact hypothesis. As a result, this framework provides only loose guidance and lacks clear minimum requirements.

Transboundary Monitoring

Transboundary monitoring presents additional challenges. Customary international law prescribes that an EIA must be conducted in case a given activity is likely to result in transboundary environmental damage. It also seems safe to assume that the EIA outcomes must be shared with all States potentially affected by a given activity. In contrast, it is not completely clear whether customary international law also compels the initiating States to conduct ongoing or post-project transboundary monitoring. With regard to the relations between its contracting parties, the 1991 Espoo Convention on Environmental Impact Assessment in a Transboundary Context requires ongoing and post-project reporting on transboundary impacts, even though this is only required upon request. According to this binding international agreement ratified by 45 mostly European States, certain activities trigger a harmonized transboundary EIA process, but mCDR is not an activity listed in Appendix I to the Convention, which would trigger such a process. Non-listed activities may still be subject to the regime of the Espoo Convention if the affected States agree that the activities concerned are likely to cause significant adverse transboundary impacts. In such a case, the Espoo Convention will only apply between those States. The criteria used to evaluate significant adverse impact, based on the project's size, location, and resulting effects, are outlined in Appendix III to the Convention.

Other Relevant International Frameworks

Several other international frameworks are potentially relevant for mCDR, including the United Nations Framework Convention on Climate Change, the Paris Agreement, the Convention on Biological Diversity, the Agreement on Biodiversity Beyond National Jurisdiction (BBNJ), and UNCLOS. UNCLOS, for example, sets out rights and obligations regarding the conduct of marine scientific research and imposes an overarching obligation on all contracting parties to protect and preserve the marine environment. Regarding the high seas, the BBNJ Agreement may play an important role once it enters into force in January 2026. The BBNJ Agreement introduces a tiered approach to evaluating the effects that an activity planned on the high seas may have on the marine environment. This tiered approach includes screening any planned activity that may have more than a "minor or transitory effect" on the marine environment, or which effects are unknown or poorly understood; a scoping process to ensure that all key environmental and other associated impacts (economic, social, cultural and human health), as well as any cumulative impacts thereof, are identified; a full and detailed EIA (which includes most, if not all, those elements already identified in the screening and scoping stages); and the identification and analysis of potential adverse effects with a view to preventing, mitigating and managing any such impacts. While there is not yet any process for evaluating EIAs of planned activities, the entry into force of the BBNJ Agreement in January 2026 and the establishment of institutions such as the Conference of the Parties and the Scientific and Technical Body created under the Agreement, it will likely provide a basis for establishing such requirements and suitable forums for developing and further delineating the regulatory requirements for EIAs and eMRV.

Lessons from the field

Field trials are essential for generating insights that shape future permitting and regulatory frameworks. They can help confirm whether ecological baselines and thresholds are sufficiently understood and facilitate interaction among project leads, stakeholders, and regulatory authorities.

Regulatory practice varies significantly across jurisdictions, but where permits were granted, experiences shared at the workshop suggest that constructive engagement between regulators and project proposers is possible. Best practices for this interaction and for designing, implementing, and communicating eMRV protocols are beginning to emerge. These include:

- Undertaking initial Environmental Impact Assessments.
- Involving independent observers to ensure transparency and credibility, although it introduces additional project costs.
- Conducting iterative rounds of public comment and stakeholder involvement, and incorporating their input into experimental design, especially for site selection.
- Implementing live or rapid processing and publication of all data (ideally within one year of the experiment).
- Establishing a trusted and transparent research team.
- Accepting longer permit timelines (two to three years), which may improve both project design and monitoring plans.

- Publishing monitoring plans openly.
- Aiming for at least one, ideally multiple, control site(s) located sufficiently far from the experimental area.
- Conducting pre-deployment laboratory-based assessments.
- Designing monitoring programs as complements to, not substitutes for, risk mitigation measures.
- Differentiating monitoring strategies according to intervention scale (from zero to tens, hundreds, or thousands of tonnes).
- Embracing the learning-by-doing character of field trials by treating mistakes as opportunities for adjustment rather than triggers to terminate entire programs. This perspective fosters transparency by discouraging the concealment of failures.

Overarching Recommendations for an mCDR eMRV Framework

The design of eMRV systems for mCDR must be scientifically robust while **remaining operational** for regulators and project developers. Environmental monitoring must therefore balance scientific comprehensiveness with regulatory clarity, while allowing for iterative learning and adaptive governance.

Case- and method-specificity are central. While universal guidelines are needed to ensure comparability, justice, and universally safe implementation, differences in methods, deployment details, and environmental settings mandate individual requirements. Two complementary approaches to structuring monitoring design can be suggested:

- A **case-by-case approach**, beginning with an impact hypothesis (as outlined in the London Protocol Annex 2 and echoed in the BBNJ pre-screening process), in which the most likely impacts are identified, and an individual monitoring strategy is adjusted accordingly.
- A **decision-tree approach**, offering stepwise guidance that adjusts monitoring requirements depending on preconditions, which then trigger pre-defined monitoring requirements, for example, when certain species of special concern may be affected.

Determining what constitutes **sufficient monitoring** requires reference to international standards, but also depends on project scale, impact hypotheses, and risk assessments. Guidelines should emphasize process-oriented evaluation of best available monitoring rather than prescriptive thresholds. A narrow focus on ecotoxicology is insufficient; impacts must be framed within the broader context of global environmental change, and limits or recommendations should be motivated by mechanistic understanding of ecological or environmental impacts.

Transparency and **data accessibility** are another pillar. While raw data alone are not usable for broader audiences, quality-controlled and processed datasets should be made available, ideally in (semi-) automated ways. Independent observers and a global, independent **project registry** could provide transparency by cataloguing projects and differentiating them by trial stage. Initiatives such as the Ocean Visions mCDR Field Trials Database and the developing OAE Field Data Commons by Carbon to Sea and Submarine Scientific represent important steps toward such infrastructure.

Permitting for early field trials should follow an **interactive and trust-based process**. Regulators and proponents must jointly define acceptable levels of risk and "safety." Trials should incorporate monitoring at intervention and control sites, with linkages between observational monitoring and biogeochemical models. Collaboration across the mCDR and global change communities will be critical to integrate interdisciplinary knowledge and account for multiple stressors.

Moreover, the governance of eMRV must remain **iterative and adaptive**. Regulatory frameworks should not be locked in at an early stage but should evolve through structured learning loops between regulators, scientists, and integrating stakeholders meaningfully. Regular reviews and updates of regulatory guidelines are essential to align standards with accumulating experience.

III. Conclusion and Outlook

The workshop provided the opportunity for substantial interdisciplinary exchange and active engagement across all sessions. Participants emphasised the value of bringing together diverse scientific perspectives, which enabled a deeper appreciation of both the complexity of eMRV for mCDR field tests and the progress already being made in different research communities. While some areas of emerging consensus were identified, it was also evident that there are no universal or simple answers. Many considerations will remain inherently project-specific, shaped by method, scale, location, and regulatory context. The workshop thus highlighted both the challenges and the momentum within the mCDR community toward developing shared, science-based approaches.

Several open questions were also identified that warrant further reflection and coordinated work:

- As many of the examples discussed during the workshop were drawn from ocean alkalinity enhancement (OAE), it remains to be explored whether additional or distinct considerations apply to other mCDR approaches.
- Given that any mCDR activity will influence the marine environment to some degree, questions arise about where acceptable boundaries should be drawn – and who should be responsible for making such determinations.
- The potential use of ecosystem services as parameters for environmental impact monitoring remains an open methodological debate.
- A further regulatory challenge concerns the risk that project developers may relocate activities to jurisdictions with less stringent requirements if best-practice eMRV becomes anchored only in some national frameworks.
- The role of community perspectives in shaping eMRV protocols also deserves deeper examination, especially when stakeholder expectations diverge from scientific assessments of what constitutes meaningful monitoring.
- Finally, the workshop raised the broader governance question of whether adapting existing laws and regulatory structures is sufficient, or whether entirely new legislative approaches or institutions may ultimately be needed to reflect the state of science in mCDR.

As a next step, the workshop organisers propose to build on the synthesis developed here and to mobilise the network of experts brought together by this event to prepare joint, peer-reviewed scientific publications. These contributions aim to support ongoing regulatory efforts with the best available science and to articulate elements of good practice for mCDR-related eMRV. Discussions on the scope, format, and publication venues are underway, and initial responses from participants have been positive, signalling strong interest in continued collaboration.

List of Abbreviations

Acronym	Full Title
BBNJ	Biodiversity Beyond National Jurisdiction Agreement
CDR	Carbon Dioxide Removal
EIA	Environmental Impact Assessment
eMRV	environmental Monitoring, Reporting, and Verification
EU	European Union
mCDR	marine Carbon Dioxide Removal
MRV	Monitoring, Reporting, and Verification
MSFD	Marine Strategy Framework Directive
OIF	Ocean Iron Fertilization
UNCLOS	United Nations Convention on the Law of the Sea
WFD	Water Framework Directive

Annex I: Agenda

Timeslot	Agenda Item
08:30 - 09:00	**Welcome and introduction (Alexander Proelss)**
09:00 - 10:15	**Session 1: Scientific understanding of environmental impact monitoring** • Safety for field test: Parameters and Indicators for environmental impact monitoring (presented by S. Dupont) • Modelling approaches (presented by D. Ho) • Data sharing and infrastructure (presented by H. Mehrtens) • Open Discussion (moderated by A. Oschlies)
10:15 - 10:30	**Coffee Break**
10:30–11:30	**Session 2a Lessons from past, ongoing, and future mCDR experiments** • Case 1: OAEPIIP (presented by L. Bach) • Case 2: LOC-NESS (presented by L. Marx) • Case 3: Röst Marine Research Centre (presented by I. Polnyi) • Case 4: VESTA / eMRV protocol (presented by S. Romaniello) • Case 5: Halifax Project (presented by T. Cross) • Open discussion (moderated by A. Madlener)
11:30 - 12:30	**Session 2b: Status quo of eMRV protocols, guidelines and databases** • Carbon to Sea Database (presented by A. Madlener) • Carbon to Sea EIMF (presented by I. Polnyi) • Ocean Visions EIAF (presented by C. Baker) • Hourglass Climate (presented by G. Andrews) • Open discussion (moderated by G. Faucher)
12:30 - 13:30	**Lunch Break**
13:30–14:45	**Session 3 – Regulatory landscape** • Guidance from London Protocol Annex V (presented by R. Steenkamp) • European Directives: Water Framework, Marine Strategy Framework, Marine Spatial Planning (presented by A. Proelss) • National Regulatory Insights – Inputs from US, Canada, Australia, Germany (presented by R. Webb)

	• Open discussion (moderated by M. Böttcher)
14:45 - 16:30	**Parallel working groups – outline for subsequent publications** • Scientific requirements for environmental impact monitoring (moderated by S. Avrutin & A. Oschlies) • Regulatory frameworks (moderated by M. Böttcher & R. Steenkamp)
16:45 - 18:00	**Presentation and discussion of group results (moderated by A. Proelss)**
18:00 - 18:15	**Wrap-up and next steps (moderated by A. Proelss)**
18:30	**Dinner**

Annex II: Participants

Name	**Project / Institute**
Andrews, Grace	Hourglass Climate
Avrutin, Sandy	GEOMAR Helmholtz Centre for Ocean Research Kiel
Bach, Lennart	University of Tasmania
Baker, Chelsey	National Oceanography Centre
Bernitt, Ulrike	GEOMAR Helmholtz Centre for Ocean Research Kiel
Böhnke-Brandt, Stefanie	GEOMAR Helmholtz Centre for Ocean Research Kiel
Böttcher, Miranda	German Institute for International and Security Affairs (SWP)
Britten, Damon	University of Tasmania
Burt, Will	Planetary Technologies
Cabus, Toni	Kiel University
Cross, Tim	Planetary Technologies
De Sisto, Makcim	GEOMAR Helmholtz Centre for Ocean Research Kiel
Dupont, Sam	University of Gothenburg
Faucher, Giulia	GEOMAR Helmholtz Centre for Ocean Research Kiel
Gill, Sophie	Isometric
Göhlich, Henry	GEOMAR Helmholtz Centre for Ocean Research Kiel
Hain, Stefan	Alfred Wegener Institute
Hepach, Helmke	GEOMAR Helmholtz Centre for Ocean Research Kiel
Ho, David	University of Hawaii at Manoa
Kittu, Leila	GEOMAR Helmholtz Centre for Ocean Research Kiel
Löschke, Sina	Kiel University
Madlener, Anna	Carbon to Sea Initiative
Marx, Lukas	Woods Hole Oceanographic Institution (WHOI)
Matz, Judith	GEOMAR Helmholtz Centre for Ocean Research Kiel
Mehrtens, Hela	GEOMAR Helmholtz Centre for Ocean Research Kiel
Mengis, Nadine	GEOMAR Helmholtz Centre for Ocean Research Kiel
Oschlies, Andreas	GEOMAR Helmholtz Centre for Ocean Research Kiel
Pearce, Christopher	National Oceanography Centre (NOC)
Polnyi, Irene	Carbon to Sea Initiative
Proelss, Alexander	University of Hamburg
Romaniello, Steve	Arizona State University
Sarpey, Christian-Benjamin	GEOMAR Helmholtz Centre for Ocean Research Kiel
Schulz, Kai	GEOMAR Helmholtz Centre for Ocean Research Kiel

Sswat, Michael	GEOMAR Helmholtz Centre for Ocean Research Kiel
Swoboda, Steffen	GEOMAR Helmholtz Centre for Ocean Research Kiel
Stebut, Laura von	GEOMAR Helmholtz Centre for Ocean Research Kiel
Steenkamp, Rob	University of Hamburg
Vivian, Chris	Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP)
Wallmann, Klaus	GEOMAR Helmholtz Centre for Ocean Research Kiel
Webb, Romany	Columbia University
Wölfelschneider, Mirco	Leibniz Centre for Tropical Marine Research
Zimmer, Martin	Leibniz Centre for Tropical Marine Research