

POLICY BRIDGE

Monitoring, reporting, and verification of marine carbon dioxide removal: Exploring scientific consensus and divergences across continents

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Marine Carbon Dioxide Removal (mCDR) approaches are increasingly considered for climate change mitigation as a supplement to rapid emissions reduction. However, it is still unclear if mCDR approaches could be effective, safe, and accountable. A critical requirement for mCDR to work, potentially, is robust monitoring, reporting, and verification (MRV) of greenhouse gas(es) removed through mCDR activities. MRV frameworks and protocols are currently developed in a scattered manner by individual stakeholders, so that the principles they are built upon may or may not appeal to the broader international community that is interested in the ocean commons. International agreement and consolidation on MRV for mCDR seem crucial to legitimize and validate mCDR, considering that the ocean is a globally interconnected fluid and that activities by some may affect many others. Here, we undertake a step toward consolidation of MRV by consulting the international scientific community. We established a global network of scientists organized into 6 “continental” nodes, each of which addressed the same set of MRV-related questions and whose thoughts were equally weighted in the synthesis. Our consultation shows that while there are many converging views on MRV (e.g., the importance of modeling for MRV), there are also differences in the regional MRV priorities (e.g., the importance of regional vs global models). The areas of consensus and divergence identified herein may be instrumental in the design of more widely accepted MRV frameworks, informed equally by scientists from 6 continents.

Keywords: Marine Carbon Dioxide Removal (mCDR), Monitoring Reporting Verification (MRV)

1. Introduction

Keeping global warming below 2°C will require increasingly urgent and drastic actions to reduce carbon dioxide (CO₂) emissions. However, a global decline in major greenhouse gases (GHGs) (CO₂, methane, nitrous oxide) has not yet been achieved (Filonchik et al., 2024). Insufficient decarbonization increases the need for large amounts of CO₂ to be actively removed from the atmosphere to limit global warming to less than 2°C. Currently, global carbon dioxide removal (CDR) efforts remove approximately 2 gigatonnes (Gt) of CO₂ per year largely through forestry-related carbon sequestration (Smith et al., 2024). Ambitious climate change mitigation scenarios, in addition to deep emissions reductions, envision this amount needs to be scaled up to 6–10 Gt CO₂ per year by 2050, using a diverse portfolio of mostly novel CDR techniques (Gidden et al., 2024). Terrestrial CDR methods using forests or soils often store carbon for relatively short periods (years to centuries, Babiker et al., 2022), compete for land resources required for other vital human activities, and are prone to carbon loss through events such as wildfires (Brack and King, 2021; Chiquier et al., 2022). As such, currently predominant terrestrial CDR methods may not be able to deliver the high CDR requirements needed. Marine CDR (mCDR) methods may have the capacity to overcome some of these limitations, therefore mCDR is being increasingly considered as a potential contributor to the CDR portfolio (GESAMP, 2019; NASEM, 2022). mCDR refers to a range of techniques that aim to increase the natural ability of the ocean to absorb and store anthropogenic CO₂ either through biological, chemical, or geological processes. Some of the techniques considered include ocean alkalinity enhancement, seaweed cultivation, artificial upwelling, ocean fertilization, and liquid CO₂ injection (Oschlies et al., 2025). However, mCDR methods face their own set of challenges, one of which is the monitoring, reporting, and verification (MRV) of additional carbon storage in the ocean.

MRV refers to the multistep process of monitoring the amount of GHG removed by a CDR activity and reporting

the results of the monitoring to a third party who verifies them (Ho et al., 2023). Robust protocols and guidelines for MRV are needed to assess efficacy, permanence, additionality, environmental risk, co-benefits, and scalability of mCDR methods all of which are essential not only for advancing scientific understanding but also for informing policymakers and carbon markets. MRV in terrestrial systems is already challenging, but most methods occur at a scale where carbon capture from the atmosphere and storage are coupled in a confined space, such as a forest or geological reservoir. By contrast, in the ocean, the 3 processes involved in mCDR (deployment, carbon capture, and carbon storage) may be separated in time and space. Carbon capture can occur far away from the mCDR deployment sites over areas as large as ocean basins (Zhou et al., 2025). Furthermore, after capture, storage would not be stationary due to ocean circulation and the movement of water masses. Depending on the mCDR method, carbon could be stored as organic biomass spread over vast areas of seafloor or as dissolved inorganic carbon (DIC) diluted in the entire ocean which amounts to 1.34 billion km³ of seawater (Shiklomanov, 1993). Indeed, the vastness and interconnectedness of the ocean are daunting when the goal is to track a relatively small number of additional CO₂ molecules therein (Cullen and Boyd, 2008; Bach et al., 2023; Palter et al., 2023). Perhaps partly due to these reasons, MRV approaches are currently much less developed for mCDR than for the few terrestrial CDR methods that are already widely applied (Arcusa and Sprenkle-Hyppolite, 2022).

The relatively limited developmental stage of MRV for mCDR to date could be seen as a disadvantage because it suggests that mCDR has not been developed to a point where its implementation could help to mitigate global warming. However, it also presents a unique opportunity to engage the scientific community because the lower maturity of MRV for mCDR provides a window of opportunity to influence and build it. International alignment is critically important in this sensitive period of MRV

development because of the abovementioned interconnectedness of the ocean carbon sink, which cannot be managed as, for example, a forest carbon sink on land. Part of the challenge includes jurisdictional complexities. Carbon could be stored in ocean areas beyond national jurisdictions or within the jurisdiction of a country other than the one applying mCDR. This could potentially complicate accountability, attribution, access to monitoring data, and equitable benefit-sharing. Given the amount of time and effort it has taken to develop MRV for terrestrial CDR and the urgency to assess and possibly implement mCDR, there is a need to accelerate the development of MRV for mCDR. The key motivation of this work was to consult scientists interested in mCDR worldwide to explore the commonalities and inconsistencies of the community's views on how MRV for mCDR should be designed. To realize this, we established nodes across 6 continents: Africa, Asia, Europe, North America, Oceania, and South America. Our study aims to provide better understanding of regional perspectives on MRV and to reveal consistencies and divergences. The goal is to support the design of more widely agreeable MRV frameworks that could function globally.

2. Materials and Methods

On December 4, 2023, scientists organized in the Surface Ocean-Lower Atmosphere Study (SOLAS) reached out to the scientific community via established communication channels (newsletters, social networks, OceanExpert) to encourage participation in continental nodes for exploration of key questions around MRV for mCDR. One hundred seventeen scientists initially responded to this call and signed up voluntarily for this effort. By the end of the project, 78 scientists remained which were organized in 6 continental nodes: Africa (Af), 8 members; Asia (As), 10 members; Europe (Eu), 18 members; North America (NA), 19 members; Oceania (Oc), 16 members; and South America (SA), 7 members. Scientists were free to choose which node to contribute to, which meant in a few cases that scientists currently working in one region (e.g., in Europe) would contribute to a different node they identified with (e.g., SA). Countries represented in each node were as follows: Af: Egypt, Kenya, Nigeria, South Africa, Tanzania, and Uganda; As: China, India, Indonesia, Pakistan, Philippines, South Korea, and Sri Lanka; Eu: Denmark, France, Germany, Ireland, Slovenia, Spain, Switzerland, and United Kingdom; NA: Canada, United States of America, and Mexico; Oc: Australia, Fiji, New Zealand, and Palau; SA: Argentina, Brazil, and Chile. Each node addressed the same set of 7 basic questions around MRV for mCDR (**Table 1**), for which the node was asked to derive the most plausible answers within the context of their regions. The questions were formulated by the project initiators (Hoffmann and Bach). These questions did not comprehensively cover MRV in its full complexity but were meant to stimulate discussions within the nodes regarding high-level uncertainties. The project initiators held brief introductory sessions with each node to present the questions. For this study, uncertainty was defined as “uncertainty that potentially exists but is currently not quantifiable (e.g., the loss

Table 1. Questions addressed by each continental node to stimulate discussion regarding the design of MRV frameworks for mCDR

Question 1	How far into the future do we have to monitor “removed CO ₂ ”?
Question 2	Do we have to measure CO ₂ removal or is modeling acceptable for all (or some) aspects of monitoring marine CDR?
Question 3	Should MRV be restricted to CO ₂ or would other processes affecting radiative forcing (e.g., methane or albedo) need to be essential components of an MRV framework?
Question 4	How, where, and in what form should the data be made available?
Question 5	How should we deal with “residual uncertainty”* in MRV frameworks?
	*This refers to uncertainty that potentially exists but is currently not quantifiable (e.g., the loss of efficiency in ocean alkalinity enhancement due to biotic calcification).
Question 6	Who is verifying the data and how?
Question 7	Which agency is overseeing the process?

of efficiency in ocean alkalinity enhancement due to biotic calcification)” (**Table 1**). This definition was explicitly included in the list of questions. The nodes then addressed and discussed these questions between March and November 2024 and submitted their documents to the SOLAS project leaders for synthesis. After submission, it was not possible to revise the answers. The process was facilitated by node leaders who were selected by each node at the beginning of the discussion phase. The SOLAS project initiators remained neutral by not participating in any of the nodes and not adding their own opinions/thoughts during the synthesis. Node leaders were provided with a copy of the synthesis to check that their nodes' contribution was correctly represented in the document. Comments and changes on other node's inputs were not considered. Equally, new ideas not mentioned in the original response of each node were not considered either. The discussion and conclusion sections were drafted by the SOLAS project initiators in December 2024 to April 2025 and comments by the nodes (compiled by the node leaders) were considered during revisions. For full transparency, the original documents submitted by each continental node to the SOLAS project leaders are archived on Zenodo (DOI 10.5281/zenodo.15653630).

3. Results

In total, 78 scientists from 78 affiliations in 31 countries participated actively across the 6 continental nodes (**Figure 1**). In the following, each section summarizes how the different nodes responded to the 7 questions listed in **Table 1**. We then synthesize consistencies and divergences in answers between the nodes and summarize them in **Table 2**.

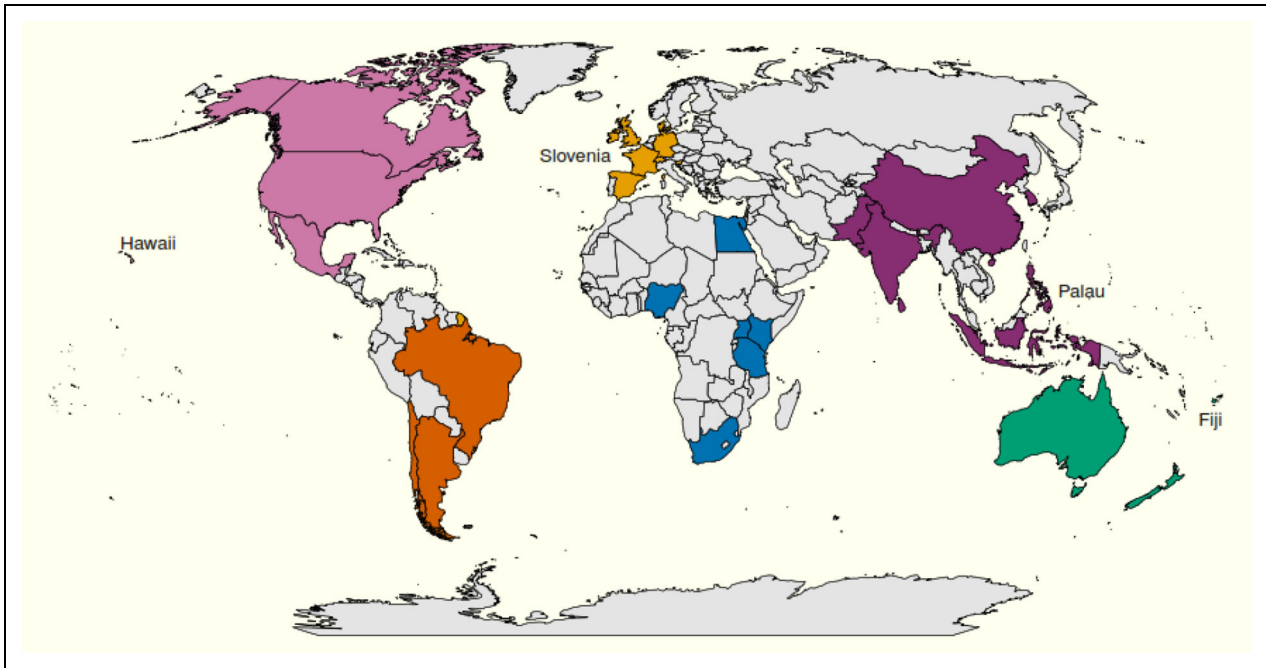


Figure 1. Countries represented in this study. Countries that participated in this study are highlighted. Blue: Af, African node; Dark purple: As, Asian node; Yellow: EU, European node; Pink: NA, North American node; Green: Oc, Oceania node; Orange: SA, South American node. Countries that are too small to be visible are labeled separately. Hawai'i is treated as part of the Oc node in this project.

Importantly, our summaries do not explicitly distinguish between individual voices within any node. As such, the summary statements below attempt to reflect as well as possible the responses that were received to the questions. The reader should keep in mind throughout that our summaries reflect the general statements provided by each node, while acknowledging that individuals from within a node may still disagree with these general statements.

Question 1: How far into the future do we have to monitor "removed CO₂"?

Af suggests different monitoring time frames (short, intermediate, and long-term) whereby the duration of each timescale depends on the mCDR method used. For biological methods like seaweed cultivation or mangrove restoration, short-term monitoring would last 5 years and long-term monitoring 10 to 20 years. For chemical methods like ocean alkalinity enhancement, short-term monitoring would range from 1 month to 5 years and long-term monitoring 20 to 30 years. For geological methods such as subsurface CO₂ injection, short-term monitoring should cover the first 5 years and long-term monitoring would be essential for 10 to 50 years.

As presents a range of suggested time frames, with estimates spanning from 25 to 30 years to up to 100 years, depending on the method. The group also stresses the need for consistent documentation and alignment with international agreements, such as the Paris Agreement. Some members pointed out that monitoring should not only focus on CO₂ but also include other GHGs (i.e., CH₄, N₂O) to ensure comprehensive climate mitigation.

Eu suggests a "like-for-like" approach to assess the length of time removals must meet to qualify as "durable" such that mCDR matches the timescales of the emissions being mitigated. For example, carbon removed to mitigate fossil fuel emissions would require long-term mCDR, likely exceeding 100 years. Shorter-lived emissions, such as those related to land-use changes, might warrant less durable mCDR. A separate timescale of monitoring and/or modeling should also be established to occur both before and "for a specified time" during and after mCDR to establish baselines and detect and account for potential carbon losses, respectively.

NA recommends that monitoring of mCDR carbon system and environmental impacts should be an ongoing process, treated as a semi-permanent global infrastructure with regional and local focuses, targeted in areas around deployments. Monitoring for baselines prior to deployments should be established globally, regionally, and locally, with attention to natural variability and spatial patterns, before interventions begin. They advocate for a principle of "monitoring until undetectable," meaning that monitoring should continue until the mCDR effects can no longer be distinguished from the natural variability. The group also highlights the challenges of detecting mCDR impacts in open systems, where advanced modeling will play a crucial role in determining effective monitoring periods.

Oc answered this and the other questions by suggesting a phased approach, with a "proof-of-concept" Phase 1, focusing on validating the durability and additionality of carbon sequestration of an mCDR method at its specific deployment site. Phase 2 involves operational reporting

Table 2. Summary of the agreement and divergences/differences^a

Agreement	Af	As	EU	NA	Oc	SA	Divergence/Differences
How far into the future do we have to monitor “removed CO₂”?							
Long-term monitoring is essential	Blue	Purple	Yellow	Pink	Green	Orange	<ul style="list-style-type: none"> • Duration of monitoring • Phased versus continuous monitoring • Regional and method-specific approaches • Challenges of open-system monitoring
Tailored monitoring based on method and location	Blue	Light Blue	Light Blue	Pink	Green	Orange	
Baseline monitoring and detection of reversals	Blue	Light Blue	Yellow	Pink	Green	Orange	
Need for continuous and adaptive monitoring	Blue	Purple	Yellow	Pink	Green	Orange	
Integration with global climate goals	Blue	Light Blue	Light Blue	Pink	Light Blue	Light Blue	
Do we have to measure CO₂ removal or is modeling acceptable for all (or some) aspects of monitoring marine CDR?							
Importance of field data for model accuracy	Blue	Purple	Yellow	Pink	Green	Orange	<ul style="list-style-type: none"> • Degree of reliance on models • Phased vs. continuous monitoring • Regional vs. global approaches • Uncertainty about boundaries and validation
Role of models in extrapolation and prediction	Blue	Purple	Yellow	Pink	Green	Orange	
Flexibility in approach	Blue	Purple	Yellow	Pink	Green	Orange	
Challenges with direct measurements	Light Blue	Light Blue	Yellow	Light Blue	Green	Orange	
Should MRV be restricted to CO₂ or would other processes affecting radiative forcing (e.g., methane or albedo) need to be essential components of an MRV framework?							
MRV should include non-CO ₂ GHGs	Blue	Purple	Yellow	Pink	Green	Orange	<ul style="list-style-type: none"> • Extent of non-CO₂ monitoring • Phased approach • Regulatory influence
How, where, and in what form should data be made available?							
Open access and transparency	Blue	Purple	Yellow	Pink	Light Blue	Orange	<ul style="list-style-type: none"> • National vs. global repositories • Private sector transparency
FAIR data principles	Blue	Light Blue	Yellow	Pink	Light Blue	Light Blue	
Standardization and metadata	Blue	Purple	Yellow	Pink	Light Blue	Orange	
Real-time data	Light Blue	Light Blue	Yellow	Pink	Green	Light Blue	
How should we deal with “residual uncertainty” in MRV frameworks?							
Need for continuous monitoring	Blue	Purple	Light Blue	Pink	Green	Light Blue	<ul style="list-style-type: none"> • Implementation methods • Capacity building and engagement • Pricing of uncertainty • Different foci in uncertainty management
Transparency and documentation	Blue	Purple	Yellow	Pink	Light Blue	Light Blue	
Quantification of uncertainty	Blue	Purple	Yellow	Pink	Green	Orange	
Need for adaptive management	Blue	Purple	Yellow	Pink	Green	Light Blue	

Table 2. (continued)

Agreement	Af	As	EU	NA	Oc	SA	Divergence/Differences
Who is verifying the data and how?							
Independent verification							<ul style="list-style-type: none"> • Unified vs. decentralized verification • Extent of verification • Community involvement • Verification timing
National oversight							
Transparency and accessibility							
Which agency should be overseeing the process (e.g., UNFCCC?)							
Importance of global agency							<ul style="list-style-type: none"> • Scope of oversight • Level of authority and enforcement
Role of national and regional bodies							

^aThe highlighted fields indicate that the node mentioned the specific aspect. The colors correspond to and reflect the geographical regions depicted in **Figure 1**.

and verification, where routine monitoring of key parameters is required though these may not necessarily be used in the estimation of issued carbon offset credits. Phase 3 emphasizes long-term global monitoring to ensure the broader success of mCDR at the ecosystem level, without tracking specific projects in isolation due to the complexity of oceanic systems.

SA focuses on the uncertainties and feedback mechanisms of mCDR, stressing the need for constant monitoring, until the impacts are fully understood. They acknowledge that monitoring methods and frequencies will vary depending on the specific mCDR approach and environment. Biotic mCDR approaches may require short monitoring timescales, ranging from hours to years, while chemistry-based approaches such as ocean alkalinity enhancement may require longer periods. The group also raises concerns about the equitable global application of monitoring frameworks and the risk of scientific colonization, advocating for knowledge sharing and capacity building across different regions.

Agreements

Long-term monitoring is essential: All groups agree that monitoring needs to be carried out for an extended period, though they vary in their specific time frames potentially lasting decades or even centuries.

Tailored monitoring based on method and location: Af, NA, Oc, and SA emphasize that the duration and intensity of monitoring should depend on the type of mCDR method being employed and the local environmental context. They highlight the need for customized durations, baseline assessments, and targeted parameters to address natural variability, methodological differences, and local ecosystem dynamics, ensuring effective and context-sensitive evaluation of carbon removal.

Baseline monitoring and detection of reversals: Af, Eu, NA, Oc, and SA emphasize the need for establishing robust baseline data before mCDR interventions begin. This ensures that any changes or “reversals” (i.e., the release of sequestered carbon) can be effectively detected. Monitoring both before and after interventions is seen as necessary to measure the additionality and effectiveness of carbon removal. Urgency to start monitoring baselines now is emphasized across several groups.

Need for continuous and adaptive monitoring: All groups agree that monitoring should be ongoing and flexible. As conditions change and more is learned about the impacts and effectiveness of mCDR methods, the monitoring approach must evolve. They also highlight the role of adaptive management to update methods as more data becomes available.

Integration with global climate goals: Several groups (particularly As and NA) emphasize that monitoring should align with broader global climate targets, such as those in the Paris Agreement. This suggests a shared recognition that mCDR efforts must be part of a larger global strategy for mitigating climate change.

Divergence/Differences

Duration of monitoring: There is significant variation in the suggested monitoring timelines ranging from 1 month for short-term monitoring of chemical methods to over 100 years, depending on the mCDR method. Some groups are less specific, focusing instead on continuous monitoring “for at least several of the same temporal cycles beyond which the intervention becomes undetectable” (NA) or “until scientifically determined” (SA).

Phased versus continuous monitoring: The Oc node recommends a clear phased structure and defined aims for the continuous monitoring divided into 3 phases: proof-

of-concept validation, operational reporting, and global monitoring. This is a slightly different approach compared to groups like NA, which advocate for continuous monitoring that becomes part of semi-permanent global infrastructure although there may be steps along the way to achieve this. The Af node takes a hybrid approach, suggesting distinct monitoring phases for short, intermediate, and long-term durations depending on the mCDR method used.

Regional and method-specific approaches: The Af node emphasizes the implication of geographical differences, particularly in Africa, where varied coastal habitats require tailored monitoring plans. In contrast, Eu and Oc advocate for method-specific monitoring based on the type of carbon sequestration being pursued. The difference lies in how localized and context-sensitive the monitoring frameworks should be, with some groups calling for a more global, standardized approach and others advocating for regional adaptations.

Challenges of open-system monitoring: Some groups (especially NA and SA) acknowledge the difficulties of detecting mCDR impacts in open systems, where natural variability can obscure the effects of interventions.

Question 2: Do we have to measure CO₂ removal or is modeling acceptable for all (or some) aspects of monitoring marine CDR?

Af states that direct CO₂ measurements in the atmosphere, seawater, sediment, and biota are essential. However, the high costs and complex environments may make the use of models necessary. Models are especially helpful in regions where technology is still developing, or where monitoring larger areas is necessary.

As emphasizes the need for real-time field data building and calibrating models. Long-term monitoring (e.g., time-series data over 5 years) should inform and recalibrate models as specific biogeochemical processes may otherwise be overlooked. Modeling can predict the impacts of mCDR beyond specific locations and time frames, but field data are needed to quantify CO₂ sequestration, leakages, and stability.

Eu comments that direct measurements of CO₂ removal are ideal and important to build stakeholder confidence, particularly in dynamic systems such as coastal waters. However, they are not always practical nor economical and modeling will play a significant role. Modeling requires continuous high-quality data inputs, and a flexible, “fit-for-purpose” approach should be used. The mCDR industry should cofinance long-term modeling efforts while also supporting the extensive data collection needed.

NA states that both are essential for CO₂ monitoring from macro to microscale, with measurements supporting safety, validation, baseline conditions, and critical parameter tracking (e.g., pH, nutrient levels). Models must be transparent, reproducible, and validated by field data. Sensitivity analyses and cross-model validation are also crucial to understanding uncertainty. Existing standards and methodology for observing quality (e.g., BGC Argo, Surface Ocean CO₂ Atlas (SOCAT)) should be utilized.

Oc suggests that their proposed phase 1 (proof-of-concept) requires rigorous direct measurements. While in situ CO₂ removal measurement may not be feasible due to rapid ocean dilution, other evidence must convincingly demonstrate sequestration. This phase integrates direct measurements with advanced modeling to quantify uncertainties. Phase 2 builds on this framework to quantify sequestered carbon using observational models accredited in phase 1 and includes a life cycle analysis of project emissions. During phase 3, monitoring networks and data assimilation models are established for reliable marine carbon budget estimates, highlighting the need for improved techniques for DIC.

SA argues that while models are valuable for simulating seawater carbonate chemistry and physical processes, they cannot replace direct measurements. Models alone are insufficient and require validation through observations as well as laboratory and field experiments for validation and parameterization. The effectiveness of models depends on the specific mCDR method and deployment ecosystem. Continuous monitoring before, during, and after deployment is crucial for the success of MRV and model predictions.

Agreements

Importance of field data for model accuracy: All groups agree that a combination of models and direct measurements are essential but stress the importance of field data for validating and calibrating mCDR models.

Role of models in extrapolation and prediction: All groups mention that modeling plays a central role in predicting long-term impacts and extending monitoring beyond specific sites. In regions like the open ocean, models may often be the only way to estimate CO₂ removal and with proper validation, they can be a cost-effective way to do so across larger areas or time frames.

Flexibility in approach: The need for flexible, “fit-for-purpose” models that can be adapted to different scales (local, regional, global) and conditions (e.g., different marine environments) is mentioned across all groups.

Challenges with direct measurement: Eu, Oc, and SA highlight the difficulty of direct measurement, especially in open ocean systems, where mCDR signals become quickly diluted.

Divergence/Differences

Degree of reliance on models: While most of the groups mention that modeling needs to be validated by direct measurements, Eu and Oc stress that modeling will likely be the main tool for monitoring at larger scales, particularly in phases beyond pilot projects. As, SA, and Af argue that direct measurements should remain central for accuracy and reliability. NA advocates for balance of both observations and models.

Phased versus continuous monitoring: Oc advocates for a phased approach to monitoring, where different phases rely on a mix of measurements and modeling, starting with more direct observation and transitioning to a reliance on models. Other groups, like As and NA, stress

the need for both measurements and models throughout the duration of mCDR activities.

Regional versus global approaches: Different modeling approaches may be required for global versus regional impacts to ensure appropriate temporal and spatial resolution. Af highlights the need for regional approaches especially in areas, where models may be essential due to resource constraints. Oc and Eu lean toward a global, scalable framework where modeling becomes central to large-scale monitoring efforts.

Uncertainty boundaries and validation: NA and SA emphasize the importance of quantifying and reporting model uncertainties through validation and sensitivity testing. SA focuses more on the ongoing need for model refinement through experiments, while NA stresses transparency and reproducibility.

Question 3: Should MRV be restricted to CO₂ or would other processes affecting radiative forcing (e.g., methane or albedo) need to be essential components of an MRV framework?

Af suggests MRV should consider all processes that affect radiative forcing, not just CO₂. Methane emissions, other GHGs, and albedo changes should be included to ensure comprehensive assessments.

As states that MRV should encompass the carbonate system and other GHGs, especially methane. Key biological and chemical variables, like indicators of carbon capture (e.g., microalgae, seaweed, eDNA), should also be considered. A holistic MRV framework would facilitate informed decision-making for climate strategies and policies.

Eu recommends that the MRV framework should include other GHGs like methane (CH₄) and nitrous oxide (N₂O), as well as emissions of aerosols and their precursors and albedo alterations. Life cycle assessments (LCAs) should include monitoring of the 3 primary GHGs (CO₂, CH₄, N₂O). Monitoring should be method-specific, meaning that methods likely to affect non-CO₂ GHGs should include comprehensive monitoring of these gases or other climate impacts, such as changes in albedo. Conversely, methods with a lower likelihood of non-CO₂ emissions could begin with minimal monitoring but should expand if thresholds are exceeded.

NA suggests that the scope of MRV should depend on the specific mCDR pathway. Some methods, like biomass sinking and nutrient fertilization, could trigger biogeochemical feedbacks (e.g., CH₄, N₂O emissions, albedo changes) which would need to be accounted for both quantitatively and qualitatively. For methods with lower risks for such feedbacks, less explicit monitoring and modeling might be sufficient. Regulatory requirements must also be considered.

Oc proposes that during the first stage, MRV should focus on carbonate system variables and biomass. Other factors like dimethylsulfide (DMS) and N₂O should be monitored and taken into account. During the second phase, MRV requirements should be established based on evidence from phase 1. The third phase would involve setting baselines for all radiative forcing processes at

a global scale with less frequent monitoring unless significant changes in GHGs emerge.

SA states that MRV should not be restricted to CO₂ and include other GHGs like CH₄ and N₂O and DMS. Depending on the specific mCDR method used, these need to be calculated and compared with other fluxes like organic carbon burial and air-sea CO₂ exchange. Potential albedo changes should also be factored into MRV.

Agreement

MRV should include non-CO₂ GHGs: All groups agree that MRV should not be restricted to CO₂ and must account for other GHGs like CH₄ and N₂O. Methane is especially emphasized across all groups due to its high warming potential. Other factors affecting radiative forcing, such as albedo and secondary GHG emissions like DMS are also frequently mentioned.

Divergence/Differences

Extent of non-CO₂ monitoring: Some groups (e.g., Eu and SA) propose minimal monitoring for methods with a low likelihood of non-CO₂ emissions unless thresholds are surpassed, while others (e.g., Af) advocate for full inclusion of all radiative forcing factors.

Phased approach: Oc suggest a phased MRV approach, beginning with carbon system variables and expanding to other factors based on observed results, while other groups emphasize a more immediate and comprehensive scope.

Regulatory influence: NA stresses the need to consider regulatory requirements (e.g., national agency guidelines) in MRV frameworks, while others do not explicitly mention this aspect.

Question 4: How, where, and in what form should the data be made available?

Af suggests that data should be made available through national, regional, or international open-access platforms (e.g., Economic Community of West African States (ECOWAS), Abidjan Convention or global data centers, scientific journals). Data should be standardized, adhering to FAIR principles (Findable, Accessible, Interoperable, and Reusable), with comprehensive metadata describing collection methods, quality, and contextual information to ensure international collaboration and data consistency.

As recommends that the data should be made openly available on multiple platforms (World Data Center for Climate (WDCC), Zenodo, AGU portals, shipping company websites) following international, marine sector, and UN standards. Standard formats, comprehensive metadata, and tools like mobile apps or visualizations should be used to promote transparency and enable independent verification by different stakeholders. Privacy and security should be maintained.

Eu emphasizes that data should be shared in a "FAIR" manner and be made available in near real time. Repositories should be regional or national for academic use (e.g., SOCAT, ICOS), including more context for environmental data for regulators. Independent registries that share certified carbon credits would be needed for

sellers/buyers. Data structure should vary according to targeted audience. For example, the general public (including first nations, fisheries, NGOs) might be provided easy-access formats with visualizations, while other audiences (CDR market, regulatory/oversight, or academics) might well desire more detailed data and meta-data. Data storage and management should be a global representative and neutral body, for example the World Climate Research Programme (WCRP).

NA states that data sharing should be transparent following FAIR and CARE principles. While there are research policy frameworks in places like North America that emphasize transparency, these often lack specific data requirements. Private sector projects may have intellectual property concerns, but transparency is generally favored to ensure public accountability. Researchers should adhere to the highest transparency standards, making real-time data available when possible and annotated with context about environmental variability.

Oc suggests that in phase 1 (proof-of-concept validation), data reporting should focus on detailed reports for carbon credit validation. In phase 2 (operational reporting), real-time estimates of carbon sequestration should be provided online, with data standardized for comparison and including full LCA. All data reporting should be provided in a standardized way to an accreditation body and verified by on-site observers. Phase 3 (global monitoring) should feature a federated data repository system offering both raw and gridded data products, tailored for different stakeholders.

SA states that in Latin America, mCDR data sharing practices are still developing, offering an opportunity to align with the United Nations Framework Convention on Climate Change's (UNFCCC) Enhanced Transparency Framework (ETF). Data should be made available in centralized national repositories and aligned with existing frameworks in sectors like mining and energy. Although bureaucratic and technical challenges exist, standardization and easy access to data (e.g., downloadable dashboards or summary reports) are crucial for advancing mCDR data sharing in the region.

Agreements

Open access and transparency: Af, As, Eu, NA, and SA specifically emphasize the importance of open access and transparent data sharing. Data should be made available to multiple stakeholders, including the public, researchers, and regulators, through standardized, open-access platforms.

FAIR data principles: Af, Eu, and NA specifically mention the need to adhere to FAIR data principles, ensuring consistency and accessibility across platforms.

Standardization and metadata: Af, As, Eu, NA, and SA mention that data should be provided in standardized formats with comprehensive metadata to ensure usability, particularly for research and verification purposes.

Real-time data: Several groups (Eu, NA, Oc) highlight the need for real-time or near-real-time data, especially for monitoring environmental impacts and ensuring quick responses.

Divergence/Differences

National versus global repositories: Af, As, and NA lean toward global platforms for consistency and accessibility, whereas Eu and SA emphasize national or regional data repositories. However, SA suggests developing a common data repository, still satisfying the regional needs.

Private sector transparency: NA acknowledges potential issues with private sector intellectual property, balancing transparency with legal concerns, while other groups do not explicitly mention this tension.

Question 5: How should we deal with "residual uncertainty" in MRV frameworks?*

*This refers to uncertainty that potentially exists but is currently not quantifiable (e.g., the loss of efficiency in ocean alkalinity enhancement due to biotic calcification).

Af proposes a multifaceted approach, including enhanced monitoring, data management, quality assurance, and documentation. Ongoing technical support, capacity building, and financial assistance are key as well as strengthening institutional frameworks and engaging stakeholders, including Indigenous knowledge. Legal mechanisms should sustain best practices, particularly in marine social science. Continuous monitoring is essential to address recurring issues, and third-party verification, through external organizations or labs, can ensure data reliability.

As suggests monitoring parameters of unquantifiable uncertainties over 5 years with a focus on comprehensive documentation. Independent labs should conduct sensitivity analyses to determine the impact of uncertainties. MRV frameworks should be dynamic, continuously updating as new data emerges, with transparency in data collection and methods being critical to stakeholder understanding.

Eu proposes a comprehensive, uniform, and transparent approach to residual uncertainty in MRV frameworks, applying discount factors to ensure credits reflect conservative estimates of actual removals. Evaluations must be adjustable to account for the most recent verification information. Credit pricing should scale with certainty, granting credits only for a "Lowest Certifiable Amount." Impartial oversight is essential to ensure fair pricing and prevent poor accounting issues seen in avoided emissions.

NA acknowledges that accounting for residual uncertainty would require an extraordinarily well-defined baseline and close accounting of every possible carbon system perturbation which are unlikely to be achievable. Therefore, the pursuit of residual uncertainty has to be a continuous process with necessary technical and knowledge updates rapidly implemented. This will require strong future synthesis projects and data model comparisons, transparent data release including uncertainties, transparency in the methods used, continuous monitoring of carbon baselines, especially in high-variability coastal environments, continuous assessment of the risks resulting from uncertainty, and additional funding for research on residual uncertainty.

Oc proposes that during phase 1, uncertainty estimation for physical and biogeochemical measurements and

modeling will be a central aspect of MRV and critical to the valuation of carbon credits. While sequestration time-scales may be relatively stable for individual mCDR projects, the uncertainties will be time-dependent and this must be accounted for in carbon trading. During the second phase, uncertainty will impact carbon credit pricing, with projects with lower uncertainties resulting from detailed monitoring gaining higher market value. Global monitoring during phase 3 must include uncertainty metrics, which will inform adaptive management practices, ensuring safe and accurate carbon sequestration across the entire mCDR program.

SA states that environmental variability rather than measurement issues causes substantial uncertainty. They propose setting thresholds for residual uncertainty according to area of interest, and an approach to represent propagated uncertainties in a standard unit, like pCO₂, to evaluate methods. They suggest matching regions to mCDR methods based on biogeochemical understanding and to prevent the application of knowledge from well-studied areas to regions where the biogeochemistry is poorly understood.

Agreements

Need for continuous monitoring: Af, As, NA, and Oc agree that managing residual uncertainty requires continuous monitoring and updating of MRV frameworks.

Transparency and documentation: Transparency in data collection, method documentation, and sensitivity analyses is seen as essential by Af, As, Eu, and NA.

Quantification of uncertainty: There is consensus that uncertainty needs to be quantified within carbon credit markets to reflect the true level of removals.

Need for adaptive management: Af, As, Eu, NA, and Oc highlight the need for adaptive management strategies that evolve as more data becomes available, Af and Eu further mention the need for independent oversight or third-party verification.

Divergence/Differences

Implementation methods: The nodes differ in their suggested approaches to residual uncertainty specifically if uncertainty metrics should be integrated into carbon pricing and management strategies.

Capacity building and engagement: Af and As stress capacity building, stakeholder engagement, and institutional support as critical mechanisms to deal with uncertainty, which is less emphasized by other groups.

Pricing of uncertainty: While some regions took an exclusively research-focused approach rather than attempting to describe private sector or market pathways, Eu and Oc mention explicitly that uncertainty of mCDR methods should be reflected in carbon pricing.

Different foci in uncertainty management: NA focuses heavily on the challenge of baselining carbon systems and sees reducing residual uncertainty as a long-term, continuous process. SA highlights environmental variability and the need for models to capture that, while other groups focus more on measurement uncertainty.

Question 6: Who is verifying the data and how?

Af focuses on the African context, where national governments, regional organizations, and academic institutions play key roles in MRV. The African Union and regional economic communities support the development of MRV frameworks, while universities and research centers contribute to verification through independent studies and data models. Regional and national data repositories should be established to ensure broader data availability and verification.

As recommends multiple verification entities, including independent companies, government agencies, regional institutions, peer-reviewed journals, scientists, independent auditors, and even citizen scientists. They suggest a comprehensive approach involving audits, stakeholder participation, interlaboratory validation, and scientific community oversight to ensure transparency and compliance.

Eu highlights that a primary challenge is ensuring data verifiers are independent while acknowledging that verification will incur costs, complicating their incentives. Therefore, legal oversight will be necessary to ensure accountability for verification outcomes. Since a model for a central oversight body for verification is not clearly established, they suggest using nationally regulated verification firms, similar to accounting audits, which leverage local knowledge, historical datasets, and existing infrastructure and stakeholder networks for mCDR projects.

NA suggests an independent international commission for data synthesis and verification, although they admit that such a commission may be untenable especially for projects occurring within a given country's Exclusive Economic Zone (EEZ). They recommend developing regular synthesis products, akin to updates of SOCAT or the Global Ocean Data Analysis Project (GLODAP).

Oc proposes MRV should be managed under a unified regulatory accreditation body for mCDR, similar to current fisheries management, starting at national to continental levels before evolving to an international scale. Verification processes will vary by country, and MRV is at different development stages across the region (New Zealand and Pacific Island countries lagging behind Australia). Data verification for certification may involve either public or private sectors with standardized protocols. Nationally, specialized bodies like Australia's DCCEEW or New Zealand's Ministry for the Environment could oversee carbon accounting and link to a federated data aggregation framework, ensuring oversight of project accreditation.

SA advocates for a multilevel process involving (1) internal verification by the mCDR company, (2) external verification by certification companies like local universities and independent certification bodies like RINA, ICONTEC, BUREAU VERITAS, and DNV, and (3) audits by local communities (NGOs, stakeholders, environmental agencies, scientists). The process should align with international standards (e.g., ISO 14064). Transparency and public availability of the data (background, operation, and post-operation) are emphasized, alongside the need for ongoing, biannual verification of durability, additionality, and leakage.

Agreements

Independent verification: All groups emphasize the need for independent bodies or external auditors to verify mCDR data to avoid conflicts of interest.

National oversight: Af, As, Eu, Oc, and SA mention the role of national governments or regional bodies in overseeing or managing verification processes, especially in the absence of a unified international body.

Transparency and accessibility: NA, Oc, and SA agree on the need for data transparency, allowing public access to data across project phases (background, operation, and post-operation) to support stakeholder trust and independent verification.

Divergence/Differences

Unified versus decentralized verification: Oc and NA suggest a unified international accreditation body, while Af, As, Eu, and SA focus on national or regional frameworks.

Extent of verification: NA argues for rigorous-yet-implementable systems. Although gold-standard monitoring should be encouraged, more realistic pathways such as spot-checking high-impact projects instead of verifying every project may be more achievable. SA and As similarly propose comprehensive verification frameworks involving multiple entities and layers of checks.

Community involvement: While all groups stress the importance of professional or governmental verification bodies, SA and As also advocate for community and local stakeholder involvement.

Verification timing: NA emphasizes long-term monitoring to assess potential leakages, while SA calls for at least biannual verifications to check for seasonal impacts, reflecting different approaches to ongoing verification needs.

Question 7: Which agency is overseeing the process (e.g., UNFCCC?)

Af states that the UNFCCC serves as the main body for overseeing data reporting through National Communications, biennial update reports, and Nationally Determined Contributions (NDCs). Additional organizations like the Green Climate Fund (GCF) and Global Environment Facility (GEF) require MRV systems for climate projects. Regional bodies, like the proposed Indian Ocean Region Forum, are also developing oversight frameworks.

As identifies multiple bodies overseeing mCDR activities such as private companies, international organizations, government research institutes, and intergovernmental bodies like the UNFCCC and IPCC. The ISO 14000 standards and International Accreditation Forum (IAF) help ensure that MRV processes meet international standards. National agencies, such as environmental ministries, oversee regional compliance.

Eu highlights oversight of mCDR activities depending on the context. In voluntary markets, formal oversight remains limited and largely driven by market standards in the absence of legal action. In compliance markets, oversight could be provided by international agencies, similar to the International Atomic Energy Agency (IAEA)

in the nuclear sector. For NDCs, the UNFCCC is expected to provide oversight for removals. For non-NDC activities, UNFCCC's role is less likely unless it becomes a de facto standard-setting body.

NA proposes an independent international commission to oversee both carbon removal data and verification. However, this international commission might be untenable for enforcing standards within individual countries; national agencies would need the authority and mandate to implement the guidance of the international commission.

Oc questions whether the UNFCCC is the best agency overseeing mCDR due to its political nature. Alternatives suggested include UNESCO, WCRP, and IAEA, using models similar to regional fisheries management councils. The overseeing agency must have the authority to revoke accreditations if projects fail to meet the standards.

SA advocates for a scientifically independent, fair-minded global agency adaptable to evolving best practices to ensure credibility. The global MRV could potentially function under the UNFCCC umbrella and set state-of-the-art guidelines, which national agencies would then follow, tailored to their domestic contexts. It should facilitate regular reporting, similar to NDCs, promoting transparency and reducing risks of greenwashing.

Agreements

Importance of global agency: All groups agree that a global agency is important to oversee mCDR activities, with many pointing to the UNFCCC as a possible fit. However, potential limitations (political entanglements, capacity) are acknowledged, and alternatives such as regional verification and validation bodies are proposed.

Role for national and regional bodies: All groups mention that both national and regional bodies should play a role in oversight, aligning with global standards but adapting to specific local contexts.

Divergence/Differences

Scope of oversight: NA, for example, suggests that spot-checks and synthesis reports may be more feasible than verifying every project, while other groups advocate for more comprehensive verification frameworks.

Level of authority and enforcement: Oc calls for an overseeing body that can revoke certifications, while NA acknowledges that enforcing standards might be impossible for an international commission.

4. Discussion

The diverse responses by the continental nodes to the questions suggest that scientists from different continents have not yet conceived a consistent MRV framework for mCDR. Instead, the varying degrees of agreement and divergences suggest that the scientific community is still in an exploratory stage and that international consensus remains to be established. The differences between the nodes highlight the influence of local and regional expertise, priorities, and existing regulatory structures and likely stem from the specific knowledge and experiences of the node members involved in these discussions. We

emphasize that outcomes discussed in this study are not representative for the marine scientific community in general. Instead, our study reflects thoughts and opinions of a cohort of scientists that were made aware of this exercise and were motivated (and had capacity) to engage in it. As such, there is a representative bias toward scientists that have an interest to align MRV internationally. It is also important to note that despite our best efforts, each node represents only a subset of nations within a given continent or geographical region. Consequently, perspectives from nonrepresented regions (e.g., Eastern Europe, Russia, Middle East, and others) are not considered.

When interpreting the agreements and divergences in the responses of the nodes (**Table 2**), it is important to keep in mind that each node worked independently of each other and could not revise their answers after submission. This approach was intentional, as the goal was to capture unbiased, independent perspectives from each node. Consequently, if a particular aspect is not mentioned in a response, this does not necessarily indicate disagreement. Rather, it may simply reflect differences in interpretation of the question and the specific expertise of members of the individual nodes. In question 5, for the purpose of this study, we define residual uncertainty as uncertainty that potentially exists but is currently not quantifiable (e.g., the loss of efficiency in ocean alkalinity enhancement due to biotic calcification). We recognize that the definition of “uncertainty” in a scientific context is often different and rather refers to a quantifiable range of values such as measurement error, model spread, instrument limitations, natural variability, and system complexity rather than unknown unknowns.

Also, we did not specify if the MRV guidelines would be intended for research only, commercial ventures, or both, which led to different interpretations by some of the nodes. For example, in the NA node there was a sentiment that we should only focus on MRV for research without considering carbon credit validation, whereas this was interpreted differently by other groups.

Eu has a focus on regulatory integration and discusses technicalities how to do so. This node has gone the furthest in integrating MRV frameworks into jurisdictional frameworks. This may be attributed to large and comparatively early mCDR projects such as OceanNETs (Keller et al., 2022), which have explored the requirements and challenges of implementing MRV for mCDR in a European context. This experience with regulatory integration will be useful in developing a global MRV framework, though adaptations will be necessary for other regions based on local conditions. In contrast, a recurring topic mentioned by the SA node was environmental safety. The emphasis on safeguarding marine ecosystems suggests a more cautious approach to mCDR in general, ensuring that interventions do not cause unintended harm. NA's emphasis on identifying challenges and limitations of mCDR appears to moderate expectations and may reflect a pragmatic assessment informed by extensive expertise in oceanographic research and carbon accounting. One of the key discussion points raised by NA was the issue of leakage, referring to unintended releases or movement

of captured carbon back into the atmosphere or other reservoirs. This concern is critical, as leakage would undermine the efficacy of mCDR efforts. Developing methodologies to account for and mitigate leakage will be essential in ensuring the credibility and effectiveness of mCDR strategies and ultimately also requires air-sea flux measurements which was also mentioned by SA. The importance of applying FAIR data principles was agreed on by all nodes, however NA raises the point that private sector projects may have intellectual property concerns. The focus in Af appeared to be more inward-looking, with discussions primarily centered on the continent's specific needs and challenges rather than international integration. This may reflect both regional priorities and the necessity of addressing local environmental and socioeconomic conditions before engaging in broader collaborations. Such an approach underscores the importance of tailoring MRV systems to regional contexts rather than assuming that the same framework would work everywhere. As highlights the need for robust field data monitoring, with models playing only a complementary role to extrapolate findings. Transparency and standardization in data access and verification were also consistently highlighted, with calls for open data, international collaboration, and rigorous, independent oversight. They also emphasize that MRV frameworks must remain adaptive and transparent, to allow for adjustments as scientific knowledge and monitoring technologies improve. The Oc node proposed a structured, phased approach to MRV starting with a rigorous proof-of-concept validation, followed by operational verification of accredited methodologies, and concluding in global monitoring to ensure consistency between observed ocean carbon storage and issued carbon credits. Countries contributing to the Oc node generally have large EEZs (relative to land mass) and so phasing of goals enables more effective research, management, and regulation of these large areas of ocean as mCDR technologies scale. Also, Oc and Eu mentioned carbon pricing regularly and Oc suggests for example that estimates of carbon residence times should inform carbon credit pricing. This contrasted with the NA position, that pricing discussions should remain outside the scope of MRV, at least in the context of this comparative study.

The differences in responses highlight the need for a globally inclusive and multidisciplinary approach when developing MRV frameworks. However, because of the independence of the different nodes, a more promising approach might be to focus on the areas of general agreement such as: the requirement for long-term and continuous monitoring, the importance of models, the need to include non-CO₂ GHGs, quantification of uncertainty, the importance of independent verification led by a global agency, and the role of national and regional bodies in this process.

5. Conclusion

MRV for mCDR is still in its early stages (Arcusa and Sprenkle-Hyppolite, 2022), and this project highlights both shared concerns and regionally distinct priorities. The conversation is evolving, and continued international

collaboration will be necessary to establish a robust and widely accepted MRV framework for mCDR. Addressing uncertainties and aligning diverse regional priorities will be crucial steps in advancing this field. At the same time, this exercise has shown many areas where there is already broad consensus. By highlighting these points of agreement and divergences, this document will help to advance the urgently needed discussion about a general agreement on MRV for global mCDR and accelerate the process of developing a global MRV framework while accounting for the complexity of ocean systems and the diversity of potential mCDR techniques.

Data accessibility statement

The original responses of each node can be accessed here: DOI: 10.5281/zenodo.15653630.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

LJH and LTB developed the conceptual design of the study. All authors contributed to the intellectual content of the manuscript. LJH wrote the original draft. All authors revised the manuscript and approved the submission.

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