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EDITED BY

Kwon Rausis,
BluMetric Environmental Inc., Canada

REVIEWED BY

Phillip Williamson,
University of East Anglia, United Kingdom
Malte Winkler,
Perspectives Climate Research gGmbH,
Germany

*CORRESPONDENCE

Paul R. Halloran
✉ p.halloran@exeter.ac.uk

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Seawater carbonate chemistry based carbon dioxide removal: towards commonly agreed principles for carbon monitoring, reporting, and verification

Paul R. Halloran^{1*}, Thomas G. Bell², William J. Burt³,
Sophie N. Chu⁴, Sophie Gill⁵, Cameron Henderson⁶,
David T. Ho^{7,8}, Vassilis Kitidis², Erika La Plante^{9,10},
Monica Larrazabal¹¹, Socratis Loucaides¹²,
Christopher R. Pearce¹², Theresa Redding⁶, Phil Renforth¹³,
Fran Taylor¹⁴, Katherine Toome¹⁵, Riccardo Torres² and
Andrew Watson¹

¹Faculty of Environment, Science and Economy, University of Exeter, Exeter, United Kingdom, ²Plymouth Marine Laboratory, Plymouth, United Kingdom, ³Planetary Technologies, Dartmouth, NS, Canada, ⁴Captura, Pasadena, CA, United States, ⁵Isometric, London, United Kingdom, ⁶Department for Energy Security and Net Zero, London, United Kingdom, ⁷[C]Worthy, Boulder, CO, United States, ⁸Department of Oceanography, University of Hawai'i at Mānoa, Honolulu, HI, United States, ⁹Department of Materials Science and Engineering, University of California, Davis, Davis, CA, United States, ¹⁰Equatic Inc., Los Angeles, CA, United States, ¹¹SeaO2, Johannes Vermeerplein, Amsterdam, Netherlands, ¹²National Oceanography Centre, Southampton, United Kingdom, ¹³Research Centre for Carbon Solutions, Heriot-Watt University, Edinburgh, United Kingdom, ¹⁴Exeter Innovation, University of Exeter, Exeter, United Kingdom, ¹⁵Department for Environment, Food and Rural Affairs, London, United Kingdom

Carbon Dioxide Removal (CDR) from the atmosphere is unavoidable if we are to meet the Paris Agreement's goal of limiting global warming to 1.5°C, and almost certainly required to limit warming to 2°C. The ocean exchanges carbon dioxide (CO₂) with the atmosphere and is a large repository of carbon that could either be partially emptied to allow more CO₂ absorption or have its carbon storage capacity enhanced to allow it to remove additional CO₂ from the atmosphere. Early-stage techniques exist to utilise the ocean in atmospheric CO₂ removal, but typically, the atmospheric CO₂ removal these techniques stimulate happens downstream of their activity. Verifying the carbon removal associated with these techniques, while critical when evaluating the approaches and pricing the removal, is challenging. This study briefly reviews the challenges associated with verifying the carbon removal associated with non-biological (abiotic) engineered marine CDR approaches, specifically Ocean Alkalinity Enhancement and Direct Ocean Carbon Capture and Storage, and presents the findings from a workshop held with interested parties spanning industry to government, focused on their collective requirements for the Monitoring, Reporting, and Verification (MRV) of carbon removal. We find that it is possible to agree on a common set of principles for abiotic marine MRV, but identify that delivering this MRV with today's understanding and technology could be prohibitively expensive. We discuss focal areas to drive down marine MRV costs and highlight the importance of specification of MRV criteria by an ultimate regulator to stimulate investment into the required work. High-quality MRV is important to correctly price any CO₂ removal, but we identify that accessibility and transparency in MRV approaches are also key in realising the broader benefits of MRV to society.

KEYWORDS

marine carbon dioxide removal, monitoring reporting and verification, carbon dioxide removal, governance, ocean alkalinity enhancement, Direct Ocean Capture, Direct Ocean Carbon Capture, Direct Ocean Removal

Introduction

Aims

The ocean provides unique opportunities for atmospheric Carbon Dioxide Removal (CDR) (Gattuso et al., 2021). Seawater is carbon-rich and exchanges carbon dioxide (CO₂) freely with the atmosphere. Removal of carbon from seawater (enabling it to “refill” from the atmosphere), and enhancement of the chemistry that naturally allows seawater to hold carbon (so that additional carbon is taken up from the atmosphere), are two abiotic, i.e., non-biological, marine CDR (mCDR) approaches to the removal of CO₂ (Ho and Bopp, 2024). These approaches can theoretically remove carbon from the atmosphere at the scale required to complement deep decarbonisation and avoid passing the warming thresholds defined in the Paris Agreement (Renforth and Henderson, 2017; Oschlies et al., 2023). CO₂ can generally be considered “permanently” sequestered (i.e., for at least several centuries) (European Commission, 2022, and in most cases, millennia), when it is either removed from seawater and stored geologically, or dissolved into seawater where alkalinity [a measure of the water’s ability to resist changes in pH in response to acid addition—for a full definition see Dickson (1981) or Middelburg et al. (2020)] added to the water allows it to be converted to a non-CO₂ form so it can no longer exchange with the atmosphere. Despite these attractive features, in both the examples above, CO₂ is not removed from the atmosphere instantly on seawater processing, but occurs downstream of the processing, typically over several months to years (Emerson et al., 2022). This creates a challenge in how the extent of atmospheric CO₂ removal is monitored, reported and verified (a practice often referred to as MRV). The MRV of carbon removals is important in determining the value of that carbon removal in the voluntary carbon market, and will be central to the acceptance of removals within compliance markets as they are developed. Carbon removals can contribute to country’s Nationally Determined Contributions, nation’s commitments to reducing emissions within the United Nations Framework Convention on Climate Change (UNFCCC), although the movement of seawater across international borders complicates this in the marine realm (Berger et al., 2024). Defining rigorous and workable marine protocols for MRV is therefore central to international regulation governing progress towards the goals of the Paris agreement. International governance of mCDR MRV, alongside scrutiny of potential marine impacts will be critical in ensuring responsible application of mCDR.

This article presents the outcomes of a workshop held in March 2024, in London and online, that brought together marine CO₂ credit suppliers, those developing programmes to stimulate CO₂ removal, policymakers, members of the carbon removal verification community and academics, to discuss approaches for conducting abiotic mCDR MRV that satisfied the requirements of each interested party. The workshop then explored whether these MRV requirements were achievable today, and what the priority questions should be for achieving robust and scalable delivery of this MRV in the future.

The workshop brought together 19 participants, 18 of whom are authors on this manuscript and one who moved roles between the workshop and manuscript being written. Plenary sessions were used to provide the participants with the required background to fully engage with the workshop, covering the different abiotic CDR technologies and the challenges of delivering MRV from a scientific and practical standpoint. In small cross-sector groups, by plenary discussion, the participants explored the questions of what would be required to achieve “perfect MRV,” what acceptable MRV would look like, if this acceptable MRV was achievable today, and what challenges remained to delivering the MRV that the different stakeholders wanted to see. All stakeholders inputted to the discussion and arising conclusions. The conclusions drawn in this manuscript are intentionally constrained to what was discussed and agreed on during this workshop. By co-authoring this Policy and Practice Review the workshop participants intend to highlight MRV requirements that are likely to be acceptable across practitioners, regulators, policy makers, funders and academics, and minimises the risk of different groups working on activities that are subsequently considered to be unacceptable or not useful to other stakeholders.

The workshop, and therefore this article, focused exclusively on abiotic mCDR approaches, rather than biological techniques that might, for example, stimulate marine algae photosynthesis as a mechanism for CDR. This choice was made because verification of carbon removal from abiotic mCDR does not need to consider additional factors relevant to biotic mCDR approaches, such as the fate of the organic carbon, downstream impacts of reduced nutrient loads and production of non-CO₂ greenhouse gasses. See Boyd et al. (2024) for a discussion of some of this complexity. By narrowing the scope to abiotic approaches, it was felt that the group could more effectively advance the field. An important caveat is that while the discussed approaches to delivering CDR are abiotic, there could still be biological feedbacks on carbon cycling downstream of the process (e.g., Schulz et al., 2023; Bach, 2024). This article’s scope is restricted to monitoring, reporting on and verifying carbon removal, and not any ecosystem impacts of these activities. The latter is extremely important, but outside of the scope of the work presented here.

Background to abiotic marine carbon dioxide removal

The most studied abiotic mCDR approach is Ocean Alkalinity Enhancement (OAE). In the context of carbon removal, increasing (or enhancing) the seawater alkalinity converts CO₂ dissolved in seawater, present in the form of carbonic acid (H₂CO₃), into carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻) ions. Carbonate and bicarbonate ions cannot exchange directly with atmospheric CO₂, so the effect is to create an enhanced air-to-sea CO₂ gradient and transfer CO₂ from the atmosphere to the ocean until the partial pressure (essentially the concentration) of dissolved CO₂ is the same as the partial pressure of

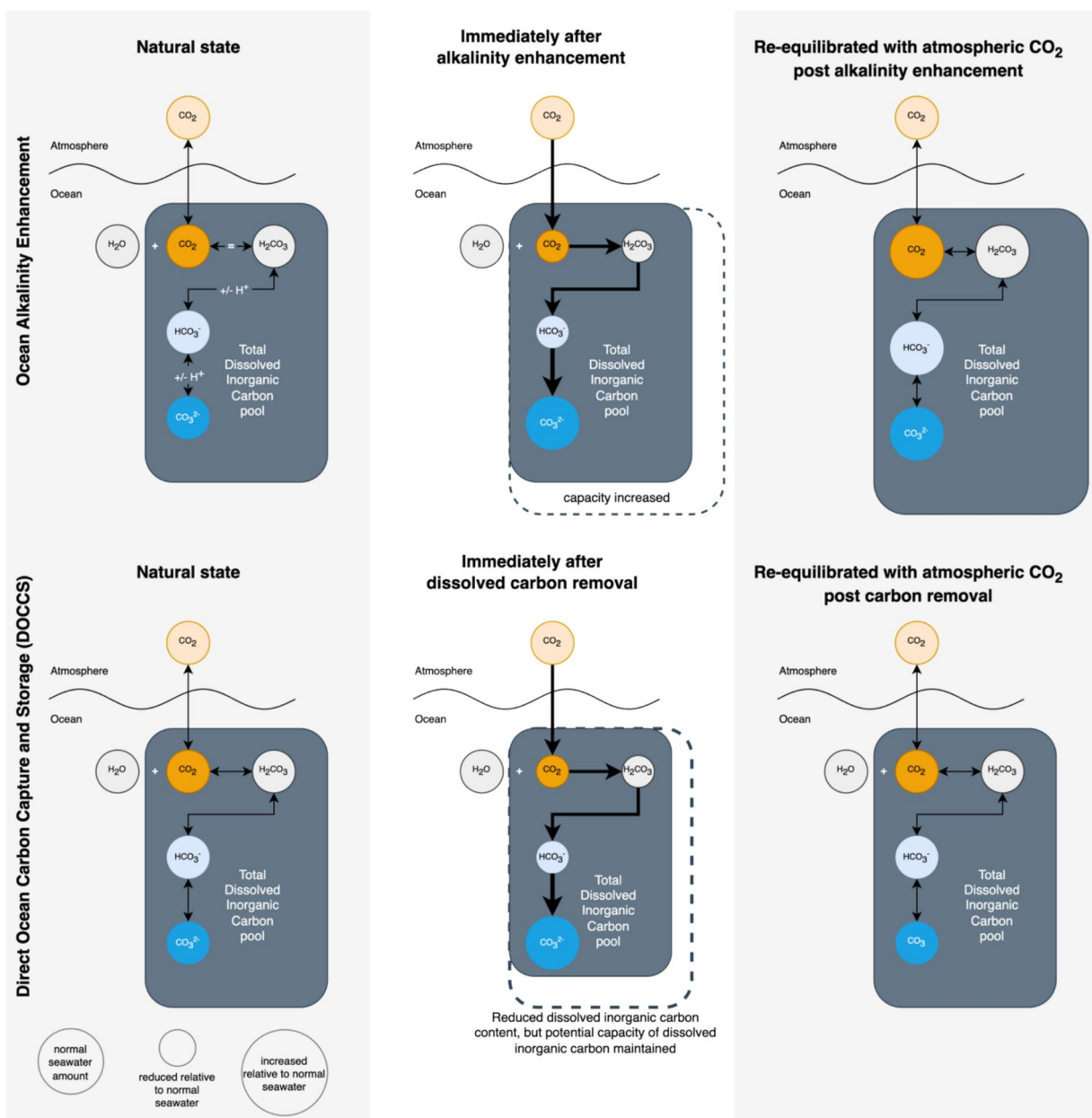
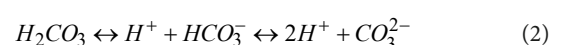
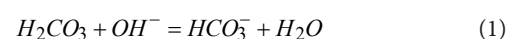
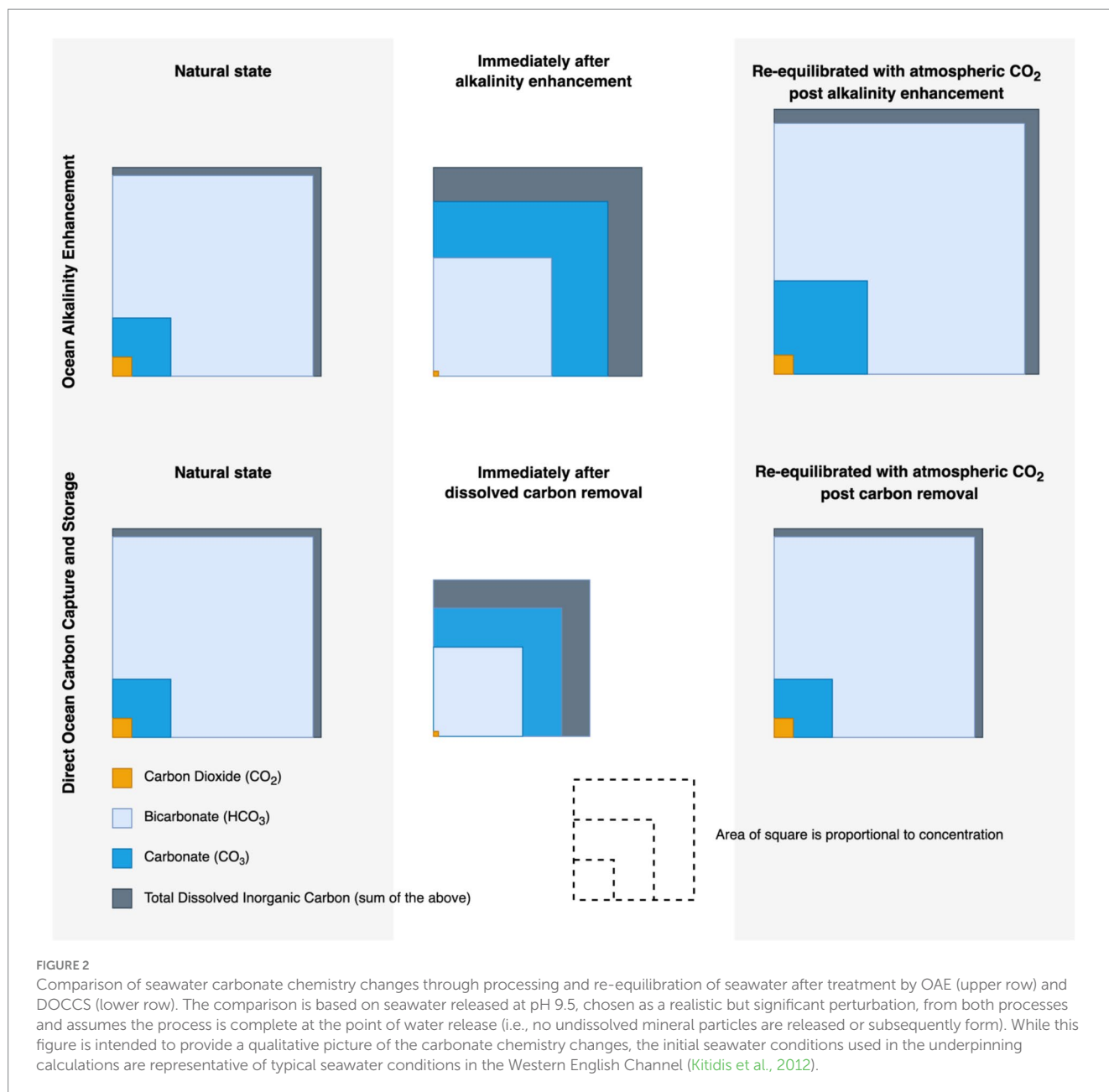


FIGURE 1
 Illustration of seawater carbon chemistry under Ocean Alkalinity Enhancement (OAE) (upper row of three) and Direct Ocean Carbon Capture and Storage (DOCCS) (lower row of three). Circle sizes represent an increase/decrease in pool magnitude relative to the size of that pool in normal seawater. Arrow direction demonstrated the gradient or chemistry-driven flows between pools in response to that step. The top left diagram presents the chemical equations describing the movement between each pool. Note in reality, prior to a perturbation the seawater CO_2 partial pressure may be slightly higher or lower than that of the atmosphere. This is omitted from this figure for simplicity.

CO_2 in the air (Figure 1, top). This re-equilibration can either happen naturally downstream of the CDR plant or location of seawater chemistry manipulation, or within the boundaries of a CDR plant through forced aeration of the seawater (La Plante et al., 2023). The result is an increase in the total amount of dissolved carbon in seawater and change in the relative proportion of the different dissolved inorganic carbon species (CO_2 , bicarbonate (HCO_3^-), and carbonate (CO_3^{2-})) (indicated in Figure 1 and quantified in Figure 2, top panels). Alkalinity can be added in various forms, but current trials and experiments typically involve silicate, oxide or hydroxide minerals (Eisaman et al., 2023). The dissolution of these minerals

makes hydroxide ions (OH^-) available, which combine with protons (H^+) from the carbonic acid to form water (H_2O), causing dissolved CO_2 (carbonic acid) to become bicarbonate (Equation 1). The degree of alkalinity in the seawater can then drive further speciation between bicarbonate, carbonic acid and carbonate (Equation 2).





Minerals can either be dissolved into seawater passively by adding material to coastal sediments, directly to seawater, or by actively dissolving minerals within a reaction vessel before release to the ocean (Eisaman et al., 2023). Alkalinity can also be generated electrochemically within seawater by the dissociation of water into hydroxide ions and protons (H_2O to $\text{OH}^- + \text{H}^+$) (Eisaman et al., 2023). In this situation, the protons (within the generated acid) must be disposed of in a way that they cannot return to the surface seawater or release uncaptured CO_2 .

The climate mitigation potential of Ocean Alkalinity Enhancement (e.g., Renforth and Henderson, 2017; He and Tyka, 2023) and its likely effectiveness (e.g., Bertagni and Porporato, 2022; Tyka, 2024; Yamamoto et al., 2024) has been the focus of a large number of studies in recent years.

The second abiotic mCDR approach considered here is the electrochemical removal of dissolved inorganic carbon from seawater (e.g., Willauer et al., 2011; Digdaya et al., 2020) such that upon release

back to the ocean, the seawater can take up CO_2 from the atmosphere until its dissolved carbon content is restored, and re-equilibration with atmospheric CO_2 has completed (Figure 1, bottom). This approach does not change the released seawater alkalinity or the final composition of the seawater. However, the carbon speciation of the seawater is modified until its dissolved inorganic carbon content has returned to ambient seawater levels. This approach is described as Direct Ocean Carbon Capture and Storage (DOCCS), Direct Ocean Capture (DOC) or Direct Ocean Removal (DOR) (Eisaman, 2024). DOCCS is achieved electrochemically by dissociating water into hydroxide (OH^-) ions and protons (H^+). In this approach, in contrast to electrochemical OAE, both the generated acid and base are directly utilised. The water enriched in protons (the acid stream) is used to reduce the pH of seawater to around pH 4, where the alkalinity of the seawater drops to zero. At this point, all the dissolved inorganic carbon in seawater is converted into CO_2 , which can be removed from the water using standard gas extraction approaches and purified for

geological storage or utilisation. The alkalinity must be returned to ambient seawater levels before it is discharged to the ocean, otherwise that water will not be able to absorb further atmospheric CO₂, so the hydroxide-enriched water (base stream) is mixed with the acidified stream allowing the protons (H⁺) and hydroxide ions (OH⁻) to recombine to form water (H₂O), a process that continues as CO₂ is absorbed from the atmosphere. The relative change in each carbon species under OAE and DOCCS is presented in Figure 2.

Marine MRV and challenges

A fundamental challenge with verifying most mCDR techniques is that CO₂ is removed from the atmosphere by the ocean downstream of the mCDR activity (Ho et al., 2023); although this is not the case if re-equilibration happens within the plant's boundaries (La Plante et al., 2023). As the seawater is transported, several factors have the potential to degrade the efficiency of CO₂ removal (Figure 3) (Siegel et al., 2021; Bertagni and Porporato, 2022; He and Tyka, 2023; Yamamoto et al., 2024). CO₂ removal will typically take place over several months (Emerson et al., 2022), during which time the water can potentially travel hundreds of kilometers (Figure 4). In the case where seawater is subducted below the ocean's surface mixed layer, and is therefore no longer in contact with the atmosphere, the carbon removal will not occur until ocean circulation brings the water back into contact with the atmosphere. In some situations, this could take hundreds of years.

In addition to knowing how long the water is in contact with the atmosphere, it is important to know how quickly the CO₂ is being transferred from the air to the seawater. This is primarily controlled by the air-to-sea CO₂ partial pressure gradient and turbulence caused by wind or currents, but can also be influenced by the temperature, formation of bubbles and biological activity (Wanninkhof et al., 2009; Deike, 2022).

The remaining factors that may impact the resulting carbon removal will differ between the various abiotic approaches we have

discussed. Critical to mineral-based OAE is to what degree potential alkalinity added to the water in the form of minerals is dissolving into the seawater, releasing alkalinity (Eisaman et al., 2023). If those minerals are being buried in sediments, or fine-grained minerals are transported by ocean currents without dissolving, the seawater alkalinity may not increase as expected over the time or space scales assessed. Similarly, if the alkalinity or pH of the water is high, resulting in elevated carbonate ion concentrations, alkaline minerals (e.g., magnesium hydroxide or calcium carbonate) can inorganically precipitate within seawater potentially resulting in long-term removal of alkalinity from that water (Schulz et al., 2023; Bach, 2024). Removal of alkalinity from the water results in a reduction in the atmospheric CO₂ removal capacity of that water.

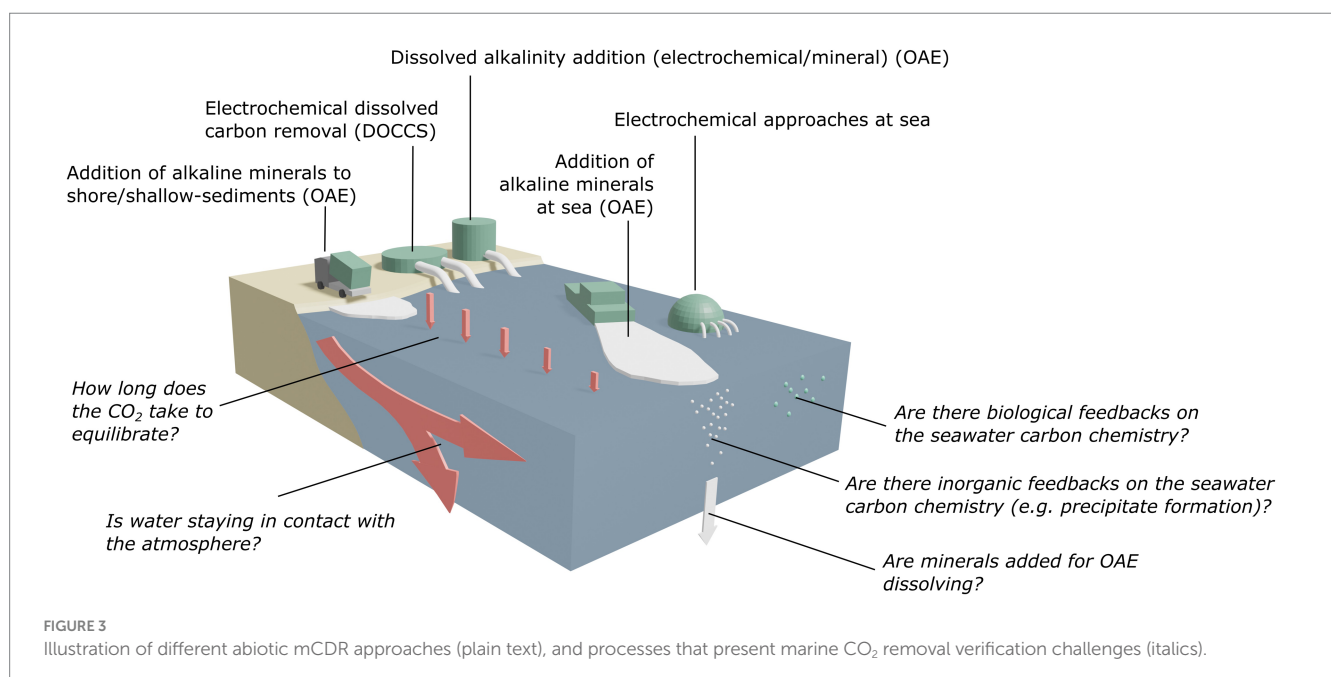
Finally, and most difficult to monitor *in situ* or model, is the potential impact of modified seawater chemistry (following CO₂ removal) on biological activity (Fakhraee et al., 2023). This could, for example, suppress photosynthesis, which may otherwise be resulting in natural atmospheric CO₂ drawdown, promote the biological formation of alkalinity-consuming minerals in the form of shells, or alter seawater alkalinity by changing nutrient cycling.

Further exploration of the challenges inherent in mCDR MRV can be found in existing review articles (GESAMP, 2019; National Academies of Sciences, Engineering, and Medicine, 2022; Doney et al., 2024), along with studies asking what is required to do this responsibly (Bach et al., 2023; Palter et al., 2023).

Towards commonly agreed principles for monitoring, reporting, and verification

The experts gathered for the workshop examined three topics:

- What "perfect" abiotic marine MRV looks like



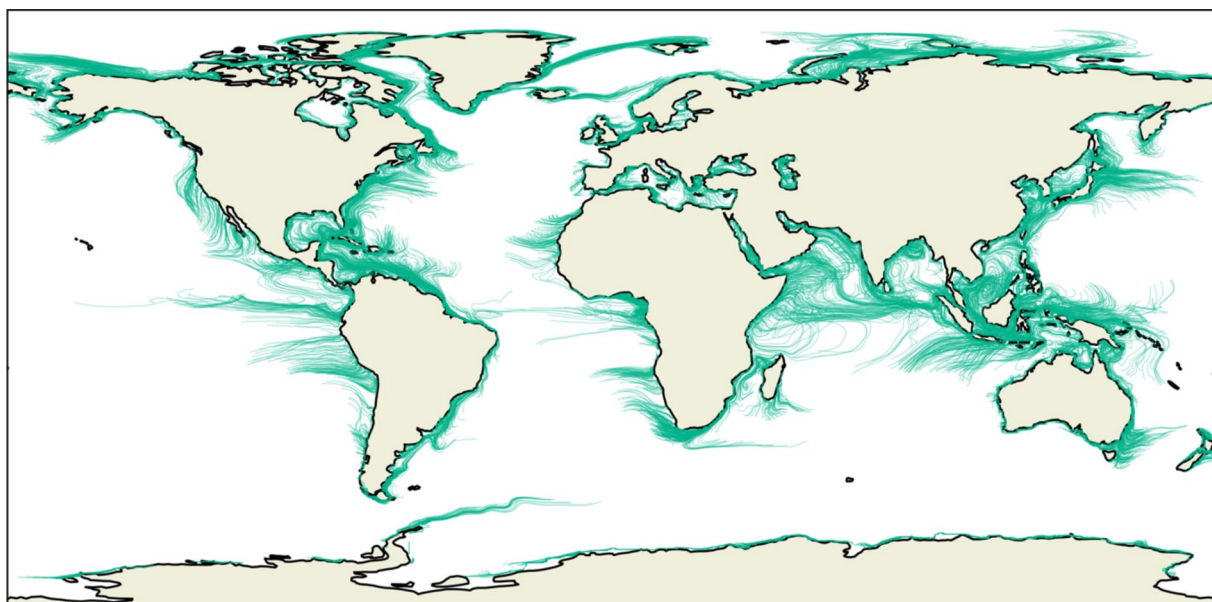


FIGURE 4

Surface ocean pathways covered within a year after water was in contact with coastlines around the globe. Water was tracked with neutrally buoyant particles released into the model velocity fields every month over a three-year period, then tracked for 12 months as they passively followed the currents. Particle tracking was performed using OceanParcels (Lange and van Sebille, 2017). Ocean velocity fields used to drive the simulation were taken from a one-degree global ocean model (NEMO) 1976–2005 simulation (Blaker, 2023). Global ocean models do not yet represent shelf sea physics well enough to provide accurate trajectories for waters released at the coast, however they will typically describe the broad trajectory of that water once in the open ocean. For this reason this figure provides a general picture of the spatial area that can be covered by water over 12 months following release from the coast, rather than attempting to describe the exact trajectories water would take and therefore where it might pass between Exclusive Economic Zones (EEZs) or EEZs and the open ocean.

- What “acceptable” abiotic marine MRV looks like and could interested parties agree on this.
- Is “acceptable” abiotic marine MRV achievable today, and what challenges still need to be overcome.

The conclusions collectively arrived at by interested parties are presented below.

What “perfect” abiotic marine MRV looks like

The participating experts were closely aligned on what idealised unequivocal verification of the removal of CO₂ from the atmosphere would look like: an exact measure of the total CO₂ flux between the air and ocean, together with a perfect digital twin of the natural system to quantify what would have happened without the CDR activity. An important outcome of the workshop was that even if you could do this, it might not necessarily be desirable to every interested party.

In addition to being scientifically robust, perfect MRV must be affordable. To be rapidly adopted, mCDR techniques will need to be competitive on cost with non-marine CDR. As an example, directly comparing Direct Air Carbon Capture and Storage (DACCS) and Direct Ocean Carbon Capture and Storage (DOCCS), both will need to account for their lifecycle emissions within their MRV, but DOCCS would additionally need to quantify the downstream air-sea CO₂ uptake as discussed above. The cost of delivering this to the highest possible standard could easily more than offset any capital or operational cost advantage DOCCS may have over

DACCS. Furthermore, the lifecycle emissions associated with delivering the intensive observational activity at sea required for delivering the highest possible standard MRV will impact the net carbon removal achieved, further increasing the cost of delivering a unit of carbon dioxide removal.

To many interested parties, perfect MRV would be simple to understand, transparent, and accessible. While the purpose of MRV is foremost to make sure that the CDR activity leads to a net reduction in atmospheric CO₂ concentrations, the MRV is also critical in:

- giving the public confidence that the CDR activity should proceed;
- helping give policymakers the confidence that they are enabling the right technologies;
- ensuring any removals counted towards Nationally Determined Contributions (NDCs) or similar are legally defensible;
- helping give investors confidence in supporting the right technologies;
- enabling carbon removal purchasers to determine a price commensurate with the degree of confidence they have in the removal.

In most cases these audiences will not be experts in ocean carbon cycling, so simplicity and accessibility in the MRV approach may be preferred over the very highest possible level of scientific rigour. Finally, assessment of the MRV must not be overly burdensome on permitting organisations, otherwise promising CDR techniques may be prevented from efficiently moving forwards.

The timescale over which observations would need to be made in a perfect MRV system is also important to consider. For DOCCS, once

the seawater CO₂ has re-equilibrated with atmospheric CO₂, the seawater chemistry is back to that of ambient seawater, whereas under OAE the seawater chemistry is permanently altered (Figure 2). Perfect OAE MRV would potentially require monitoring even after it had taken up its expected quotient of CO₂ from the atmosphere because feedbacks resulting from the elevated alkalinity, for example long-term increases in calcification, may continue. The requirement for this post-equilibration monitoring would depend on the magnitude of the CDR activity. Alkalinity anomalies associated with small scale CDR would be diluted to the point where they are biologically insignificant very quickly, but at very large scales the alkalinity anomaly could persist for much longer. Timescale also influences how challenging it will be to deliver high-quality MRV. On very short timescales (days to weeks) the local ocean and atmosphere dynamics will have a big impact on the rate of CO₂ uptake from the atmosphere. On the timescale of months the vertical movement of water away from the surface could become important, then over years it is reasonable to assume that any water staying at the surface has equilibrated with atmospheric CO₂.

“Acceptable” abiotic marine MRV that satisfies interested parties

In seeking to understand what acceptable abiotic mCDR MRV looks like, it is important to acknowledge that perfect MRV is not achievable, and even what is currently achievable, may not be practical. However, there are strong signals that markets will move in the direction of highly verifiable removal (Mistry et al., 2023; Axelsson et al., 2024; The White House et al., 2024), so there is a powerful motivation to raise the standards as rapidly as possible.

[C]Worthy, a non-profit research organization working on mCDR MRV has identified the following characteristics of pragmatic mCDR MRV related to the verification of carbon removal:

- methods are scientifically credible with uncertainties that are sufficiently accurate to be of use to customers;
- answers can be provided quickly enough to enable suppliers to make necessary decisions;
- the cost of undertaking MRV is acceptable within the constraints of the carbon credit price ([C]Worthy—FAQ, 2024).

Building on this we identified a common set of a minimum requirement for the practical delivery of mCDR MRV:

- Continuous monitoring of the carbon-depleted or alkalinity enhanced water being introduced to the ocean, to characterise its carbon chemistry and allow calculation of the carbon chemistry immediately on mixing with ambient seawater. This requires high quality measurement of two of; Dissolved Inorganic Carbon, alkalinity, partial pressure of CO₂ (pCO₂) or pH, in addition to temperature and salinity. Caution should however be applied when attempting to characterise seawater carbon chemistry using either pCO₂ or pH, or this pair of measurements, because the measurement uncertainty in these variables can lead to uncertainties in the carbon chemistry larger than the perturbation attempting to be observed.
- Use of a high fidelity coupled physical-biogeochemical model capturing the discharge and its dilution and CO₂ uptake to the point where the water has reached an agreed threshold of

removal. This model would be used to quantify downstream removal in line with existing recommendations (e.g., Ho et al., 2023).

- Near-field monitoring of physical and carbon cycle variables beyond the discharge point to be used to initially verify the model, particularly initial dilution, and enable quantification of removal uncertainty.
- Periodic repetition of near-field monitoring to confirm the ongoing suitability of the model and associated uncertainties.

The workshop considered it highly desirable that MRV is best done or overseen by an independent body, either auditing the process or delivering the MRV activity.

An important consideration is how frequently the measurements and model simulations need to be repeated. Different locations will experience different degrees of natural variability or rates of background change in response to carbon emissions and climate change. These will impact the effort required to quantify the baseline conditions, or the length of time over which a baseline characterisation remains applicable. This frequency will have a big impact on the affordability and therefore competitiveness of mCDR credits because observational campaigns conducted today are reliant on boat time, bespoke or specialist instrumentation, and expert scientists, all of which are expensive. This frequency will be site-specific, but it would be valuable if a threshold could be defined to indicate when re-characterisation of a site should occur.

Quantification of uncertainty is extremely important to determine the validity of a removal technique, but also to understand how to discount any credits sold. Robust uncertainty quantification is likely to be one of the most challenging aspects of any MRV, particularly determining whether there are any biological feedbacks that modify the removal efficacy. It is likely that the quantification of uncertainties at this level cannot be undertaken on a site by site basis, and will require dedicated laboratory and field trials in such a way that the outcomes can be robustly generalised. Transparency and peer review of MRV uncertainty quantification will be critical for stakeholders to have confidence in enabling marine CDR.

Delivering “acceptable” abiotic marine MRV

It is accepted that monitoring and verification of mCDR will require the use of both observations and modelling (Bach et al., 2023; Fennel et al., 2023; Ho et al., 2023). While not optimised for MRV, marine carbon-cycle observation and modelling in the context of understanding the natural system is relatively mature. Accurate measurement of seawater carbon parameters to the level required to determine air-sea carbon fluxes can be performed in the lab, and are increasingly being made on autonomous platforms (e.g., Bushinsky et al., 2019). Direct measurement of air-sea CO₂ fluxes is challenging but becoming possible, and high fidelity local-scale modelling of the seawater hydrodynamics and carbon (Cazenave et al., 2021) now complement more established models designed to understand the regional-to-global ocean carbon cycle (e.g., Yool et al., 2021). Recent work has shown that nearfield observations at sea can be used to verify modelled OAE (Kitidis et al., 2024). We therefore have the tools and know-how to perform abiotic mCDR MRV, but the community has spent relatively little time considering the application of these tools to

MRV. Organisations like [C]worthy are working on making these tools operational, and groups like the Surface Ocean Lower Atmosphere Study (SOLAS) mCDR network are working on international coordination of these activities to inform policy. Two key challenges that remain are:

- being able to perform the required MRV for a cost that does not prevent mCDR from being viable;
- being able to undertake abiotic marine MRV with uncertainties that projects, governments, investors, the general public and other stakeholders consider acceptable.

The questions of cost and uncertainty partially align because lower-cost observations allow for more observations and lower uncertainties. However, as identified above, dedicated research is also required to improve techniques and deliver a reduction in measurement and model uncertainties.

While evidence is being generated and tools are being developed by research projects and organisations there is currently no ultimate regulator of MRV. Such a regulator, potentially existing to underpin a compliance market for carbon credits, would clarify the necessary standards. This would give funders and investors confidence in committing resources to overcome these challenges, and would help ensure that time, effort and funding focused on developing marine MRV capabilities were spent most appropriately. There is presently movement within the public sector in the UK, EU, USA and Japan to become more involved in this space, which may begin to resolve this issue. The London Convention/London Protocol has to-date played an important role in the governance of marine geoengineering through a decision made to prevent commercial marine iron fertilisation activity. Current proposals could see this being extended to biomass sinking and ocean alkalinity enhancement, suggesting that there may be a leading role for the London Convention/London Protocol in mCDR MRV regulation in the future.

Conclusion

It is important to emphasised that the conclusions presented here draw on consensus from a single workshop, and should therefore be treated as a starting point for further work rather than conclusive recommendations. However, we found that stakeholders could agree on a common set of principles for abiotic mCDR MRV that were achievable today, but delivering this MRV with today's technology and know-how is unlikely to be economically viable in a mature commercial market. Achieving economic viability will involve driving down uncertainties (which will push up obtainable credit prices) and driving down operational costs. To drive down costs, the community will need to focus on the development of higher quality autonomous instrumentation and platforms, more computationally efficient modelling tools with lower barriers to use, a skilled workforce able to deliver marine MRV activities outside of the research sector and clarity from an ultimate regulator on MRV requirements.

In parallel to progress on costs reductions and site-specific uncertainties associated with a CDR activity's MRV, the research community should use controlled laboratory experiments and large-scale field trials to constrain the process uncertainties and verify model capability. From a supplier perspective, undertaking more

comprehensive MRV will only be viable if it pays for itself, therefore addressing these uncertainties as a public good may be pivotal in allowing mCDR to achieve its potential for atmospheric CO₂ reductions. Finally, the challenges of mCDR MRV are not just scientific and technical. Seawater is mobile, in many situations unequibrated water will pass between Exclusive Economic Zones, raising the question of who takes credit for (reports) the associated atmospheric CO₂ removal. Robust legal and policy frameworks will need to be developed to address the wider challenges of reporting and verification.

The climate crisis affords us little time to answer these questions, particularly because of the significant timescales associated with refining and scaling promising technologies. By rapidly defining and agreeing on a robust, practical approach to abiotic mCDR MRV, financiers can gain confidence in the return on their investments and regulators can, where appropriate, enable the early stages of scaling these technologies. Well evidenced decision by regulators will also be important in building the social licence for marine CDR. Furthermore, robust MRV will help unviable approaches to fail quickly, honestly and transparently so society can most efficiently converge on the solutions that will ultimately help us achieve an acceptable, stable climate.

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Author contributions

PH: Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. TB: Writing – original draft, Writing – review & editing. WB: Writing – original draft, Writing – review & editing. SC: Writing – original draft, Writing – review & editing. SG: Writing – original draft, Writing – review & editing. CH: Writing – original draft, Writing – review & editing. DH: Writing – original draft, Writing – review & editing. VK: Writing – original draft, Writing – review & editing. EL: Writing – original draft, Writing – review & editing. ML: Writing – original draft, Writing – review & editing. SL: Writing – original draft, Writing – review & editing. CP: Writing – original draft, Writing – review & editing. TR: Writing – original draft, Writing – review & editing. PR: Writing – original draft, Writing – review & editing. FT: Writing – original draft, Writing – review & editing. KT: Writing – original draft, Writing – review & editing. RT: Writing – original draft, Writing – review & editing. AW: Writing – original draft, Writing – review & editing.

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Conflict of interest

Author WB was employed by company Planetary Technologies. Author SC was employed by company Captura. Author SG was

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