Carbon to Sea Initiative

October 31, 2025

Feedback to CRCF Expert Group: Review of Carbon Removal by Ocean Alkalinity Enhancement

Overview

Carbon to Sea (CTS) is the largest non-commercial initiative evaluating if and how ocean-based carbon dioxide removal (oCDR) could be part of the global response to climate change. Our research program and grantmaking centers on rigorously answering three questions: Is OAE safe for people and the environment? Is it effective at removing legacy carbon from the atmosphere? And can it scale to be a climate-relevant solution?

We have committed more than $30 million in research and technology development projects across the globe that address those questions. Our grantees include dozens of world-leading experts at academic institutions and at companies on subjects ranging from geochemistry to ecotoxicology to physical oceanography. We also engage civil society and coastal communities.

We explored multiple potential carbon removal solutions before deciding to focus on accelerating the evaluation of OAE. Our focus on OAE is rooted in the fact that leading scientists have independently identified OAE as a high-potential solution – including the National Academies of Sciences in the United States.

After several years of intensive work on research, technology, and governance related to OAE, we believe governments have a critical — and time sensitive – role to ensure the quality and integrity of carbon removals by OAE and the CRCF's posture is hugely influential.

While philanthropy and the private sector are currently driving much of the early research and development, only public institutions have the legitimacy and capacity to ensure that this work proceeds in the public interest. Decisions made in the next few years – about data standards, permitting, and certification – will help determine whether oCDR evolves as a rigorous enterprise or as a space that lacks transparency or trust.

Specifically, it is critical for the CRCF to have a clear view on quantification of carbon removals by OAE. Robust regulatory and permitting regimes must also include a focus on ecosystem health and environmental safety, but the CRCF is uniquely positioned to advance rigorous quantification guidance.

By establishing clear regulatory pathways, supporting open data, and aligning certification efforts with high quality research strategies, policymakers can anchor this field in scientific integrity. The opportunity includes fostering a significant industry — and more importantly, defining what responsible ocean carbon removal looks like around the world.

Executive Summary of Feedback on Technical Scoping Paper

Efficiency of carbon removal

Dissolution rate of mineral feedstocks, equilibration of alkalized seawater, and resulting changes in biogeochemical processes (such as secondary precipitation, biological calcification, and sediment alkalinity flux), are the main drivers of the efficiency of carbon removal via OAE. For technologies introducing powdered mineral feedstocks, calculating dissolution rate, and associated uncertainty, is a prerequisite for quantification and merits clear requirements by certifiers. If those conditions can be met, choice of feedstock and dissolution method is otherwise an economic and operational decision for the project operator, and threshold requirements for pre-dissolution or rate of dissolution are not necessary.

Secondary precipitation and premature seawater subduction, if it occurs, could have a significant effect on project efficiency. The effect on efficiency of any OAE-driven changes in biological calcification and sediment alkalinity flux is likely to be much less but is less well understood. These effects should be further studied both to reduce uncertainty and to evaluate potential ecological impacts. Current science provides a good indication of what environmental thresholds are for measures such as pH and aragonite saturation. These should be incorporated into certification requirements and can be adjusted as new information is available.

MRV

Rigorous measuring/monitoring, reporting, and verification (MRV) is foundational for development and certification of safe and effective OAE. Requirements for certification should include specification of parameters to be measured, the geographic scale, and the frequency of measurement. Certification protocols should distinguish the role of measurements and monitoring in providing operational evidence, model validation, and environmental impact assessment, although these uses are not mutually exclusive. It is vitally important that OAE certification protocols ensure that MRV data and modeling results are readily available from accessible repositories. This will greatly facilitate assessment of, and improvements in, efficiency and environmental safety that are needed to inform potential expansion of scale.

Modeling

Because of the spatial and temporal scale involved, models will always be needed to estimate feedstock addition and subsequent alkalinity conversion, transport, and equilibration. Better, and better-coupled, models are needed, and Carbon to Sea is funding research in this area. But this is not an obstacle to certification of high-quality credits if uncertainties are rigorously assessed and used to determine appropriate discounting of estimated carbon removal. While modeling suggests full equilibration of alkalized seawater may not be reached for 10-15 years, it also projects that most uptake occurs within the first five years in many regions. Since uncertainty is likely easier to constrain for shorter time and spatial intervals, this could allow projects to receive ex-post credits for the portion of the alkalinity modeled to have resulted in CO_2 equilibration for a defined period.

Managing uncertainty

Models inherently carry uncertainty from varying sources as they aim to represent the real world in a simplified way. Based on the experience to date with certification of OAE, Carbon to Sea recommends development of a shared uncertainty taxonomy for model-based quantification. This would improve consistency across projects, clarify which uncertainties are not yet adequately represented, and facilitate comparing project reports against protocol requirements. In addition, unquantified uncertainties must be reported unambiguously and more thoroughly accounted for.

We believe that uncertainty associated with in situ dissolution can also be reasonably quantified and managed. Development of a consistent methodology for deriving and reporting dissolution rates, including measured and modeled inputs, will help. In addition, dissolution rates should be confirmed in situ through proxy measurements where possible and coupled with strong estimates of transport of alkalized seawater to get the full picture of carbon removal.

In section 4.1.6, the review paper states that "it will be important to recognise that early OAE activities will have greater uncertainties around carbon removed but will add the greatest value to the process of constraining and improving model-based MRV for future OAE deployments." We agree early activities are required to reduce uncertainties. As a result, it will be important that certification schemes are sufficiently flexible to accommodate greater uncertainty in early-stage, small-scale projects. Uncertainty quantification could potentially increase stepwise, with small pilots applying conservative, tractable methods, and more mature projects incorporating progressively more comprehensive uncertainty categorization and quantification. While many challenges around uncertainty cannot be resolved by a single project, they could be addressed in certification regimes by requiring discounting of awarded credits based on comprehensive assessments of uncertainty done under guidance from the CRCF.

Environmental safety and sustainability

Although early indications are encouraging, we still know too little about the environmental effects of OAE to confidently call for its large-scale expansion. To build toward a strong understanding of the environmental tradeoffs associated with OAE at the scale required for it to play a significant role in mitigation of climate change, expanded environmental MRV is needed for current smaller scale in situ projects. Results from such monitoring should be used to avoid, minimize, identify design solutions for project level impacts that may be associated with long-term and large-scale efforts.

Because of its growing importance for access to both voluntary and regulatory carbon markets, certification can play an important role by setting strong standards and requirements for environmental monitoring and protection. Based on experience to date, we recommend expanding environmental monitoring beyond that required by existing certification regimes on a site- and case-specific basis. Carbon to Sea's Environmental Impact Monitoring Framework, which was recently opened for public comment, can assist researchers, project developers and certifying bodies in deciding what parameters (in addition to permit requirements) should be included.

Detailed Response to Issues Raised in “Review of Carbon Removal by Ocean Alkalinity Enhancement”

Quantification/MRV

We agree that establishing a common set of measurement requirements is critical for development and certification of responsible OAE. This should include specification of parameters to be measured, the geographic scale, and the frequency of measurement and monitoring. Such measurements are necessary to support modeling for quantification, such as through comparison of model results with observations for validation, and to provide operational and environmental assessment.

As required by the Isometric protocol, we support:

- Measurement of--
    - pH
    - salinity
    - temperature
    - at least one of total alkalinity, dissolved inorganic carbon (DIC), or pCO2
    - total suspended solids
    - turbidity
    - dissolved oxygen
    - seafloor deposition of undissolved feedstock
        - While this is required for assessing dissolution, it can also useful for assessing sediment alkalinity feedbacks depending on the parameter chosen to be observed
- Establishment of action thresholds designed to suspend operations if thresholds for required parameters are exceeded.

In addition, we recommend that protocols further specify how projects are required to derive spatial and temporal scales for these measurements, potentially going beyond Isometric’s option to exclusively measure parameters at the edge of the mixing zone.

In addition, we recommend expanded environmental monitoring that is site- and case-specific. Some parameters are always essential to monitor, and for these site- and case- specificity is more about where to sample and at what frequency. For some OAE pathways there are specific additional parameters that need to be monitored, for example, if interaction with the benthos is expected when a slower dissolving feedstock is used.

To assist in making these sorts of decisions, Carbon to Sea funded the development of an Environmental Impact Monitoring Framework, which was recently released for public comment. We suggest adopting processes laid out in this framework to decide where, when, and how additional measurements, such as chlorophyll *a*, phytoplankton community composition, total metals concentration in sediments, and benthic community impacts, should be undertaken. The spectrum of additional measurements that may be beneficial, and their use cases, are laid out in detail in Table 5 of the framework.

Dissolution of mineral powders

For technologies adding alkaline mineral powders to fresh- or salt-water outfalls or open waters, the amount and rate of dissolution of these additions is critical for quantification of carbon removal. Characterizing the feedstock is critical for understanding its dissolution rate, expected CDR potential, and presence of impurities such as trace metals, which may have environmental effects.

Expected CDR potential is based purely on chemistry (if all reactions were allowed to play out until equilibrium), whereas the realized alkalinity increase is a function of the dissolution rate, the chemistry of the receiving waters, and potentially other processes that can influence it. The dissolution rate itself is a function of the receiving water's carbonate chemistry state and other factors like temperature, salinity, etc.

Quantifying dissolution rates

Dissolution rates are usually derived from laboratory tests, but a consistent standard for deriving these rates would be beneficial for easier comparison among projects. Laboratory dissolution rates should be confirmed in-situ through proxy measurements, such as dissolved and particulate total alkalinity, pCO2, total suspended solids, or turbidity, although this is limited by signal-to-noise ratios especially in early, smaller trials.

While dissolution on short timescales can vary, it is important to note that scientific understanding is that eventually most of the feedstocks will dissolve, and can lead to atmospheric drawdown as long as decarbonized water comes in contact with the atmosphere.
That is not to say that estimating dissolution rates is unimportant, but rather that these estimates must be coupled with strong estimates of the transport of alkalized seawater and, for non-equilibrated OAE approaches, air-sea gas exchange equilibration dynamics, to get the full picture of carbon removal. Alkalized water transport quantification is needed whether or not feedstocks are dissolved in situ, pre-dissolved before discharge, or when the discharge is of seawater made more alkaline via electrochemical processes.

To increase confidence in open-system OAE, quantification reports by projects seeking certification should include a prominent summary that links lab-based feedstock characterization if a mineral feedstock is used, evidence of dissolution and alkalinity increase from the field, and assumptions made in models that serve as critical input to the overall quantification. Certification protocols would benefit from a clear explanation of the role of required measurements, distinguishing between their role in operational evidence, model validation, and environmental impact assessment. The review paper provides an insightful explanation of the importance and roles of observations in meeting baselining and certification needs at section 2.4.1. Protocols should also specify, and potentially increase, the scale and frequency of measurements to provide operational evidence of alkalinity addition.

Addressing dissolution uncertainty

For OAE pathways that use solid mineral feedstocks, confidence in the dissolution rate is a prerequisite for quantification and merits clear requirements by certifiers as outlined above. But if those requirements can be met, adding undissolved minerals is an effective OAE pathway depending on economic, operational, and site-specific oceanographic goals of a project operator. We believe that uncertainty associated with in situ dissolution of mineral powders can be reasonably quantified and managed, and above we suggest several steps that can be taken to improve confidence in dissolution rates and reduce their associated uncertainty. As a result, we consider two of the three solutions proposed in the review paper at section 4.1.1—requiring pre-dissolution of feedstocks or requiring their dissolution on time scales of days to weeks—unnecessarily restrictive.

Pre-dissolution of feedstocks addresses one problem but potentially creates others. While it removes uncertainty about the amount of added alkalinity, it results in more alkalized effluents with potentially higher risks of triggering regulatory thresholds and inducing secondary precipitation. While this can be managed by reducing dosing levels, it introduces constraints not present in other approaches. Requiring pre-dissolution as a condition of certification may impose prohibitive costs and technology challenges, unnecessarily limiting the range of OAE technologies available to assist in meeting EU climate goals.

All things being equal, the use of rapidly dissolving feedstocks is advantageous, as calculating dissolution rates becomes more difficult over greater temporal and spatial scales. However, we suggest that project developers should be given the opportunity to assess the uncertainties associated with their preferred technology and see if they can satisfy standards for uncertainty quantification and management in relevant certification protocols. For a thorough discussion of the tradeoffs presented by different technological pathways, see this review on CTS's website.

The need for multi-scale, coupled models of dissolution and transport

In section 4.1.1, the review paper states that models of particle dissolution and transport are "currently immature... making OAE mineral addition without pre-dissolution the least certifiable of the OAE methods currently." This assertion does not seem to acknowledge that Isometric issued credits to Planetary which utilizes mineral feedstock that dissolves largely in situ.

We agree that better, and better-coupled, models are needed and CTS is investing in research in this area. But we do not feel that this poses an obstacle to certifying high-quality CDR credits from technologies utilizing this approach, if they provide:

1) a verifiable characterization of feedstock CDR potential and dissolution rate
2) a reproducible and thoroughly documented approach to provide particle information (i.e., particle size distribution, shape, density; and modeled dissolution rate, as outlined by Isometric's Appendix 2, Table A2-3) that is input into mixing zone and coastal dynamics models used for quantification (e.g., through small-scale models adequately reflecting dissolution on meter scales, or other modeling approaches to represent alkalinity addition into models used for quantification) and adheres to the same model sharing requirements as other models used
3) operational evidence of in situ feedstock dissolution such as via proxy measurements and an assessment of how those field measurements compare with modeled dissolution.

These are significant challenges, but we feel they can be appropriately managed. For instance, standards can be developed for feedstock characterization approaches, uncertainties of dissolution models can be quantified, and approaches to provide in-situ evidence of dissolution are currently tested. As stated previously, to ensure quality of the resulting credits, these aspects of dissolution modeling should be adequately accounted for in comprehensive uncertainty assessments that each project should be required to complete. For all OAE approaches, this assessment should be used to assess a discount on any resulting credits and/or consider a contribution to a buffer pool. Offering a full or partial refund of credits from the buffer pool if a project subsequently demonstrates a substantial reduction in uncertainty surrounding its removal estimates would create a powerful incentive to do so.

Moral hazard if calculated removals (using modeled rates of particle dissolution) are not directly dependent on the actual quality of feedstock and its successful dissolution.

We agree this would be a problem if unaddressed, but the solution seems to lie in the statement of the problem:

- develop and implement standards for feedstock characterization and monitoring (including standardized best practices for determining the feedstock's CDR potential and dissolution kinetics)
- require specific in situ measurements to show or be a proxy for dissolution

- require rigorous LCA assessments that account for feedstock origin

Secondary precipitation and inhibition of natural alkalinity inputs

These are potentially important phenomena affecting both the efficiency of OAE and its environmental impacts. CTS's blog post on open-system OAE reviews the most recent literature and factors affecting its efficiency. More concentrated introduction of alkalinity, such as from electrochemical approaches or pre-dissolution of feedstocks, may increase the risk of secondary precipitation. On the other hand, use of slowly dissolving feedstocks that sit on the seafloor (or sustained benthic contact with alkalized seawater from other OAE approaches) may result in inhibition of natural sediment alkalinity fluxes.

Current science provides a good indication of what environmental thresholds are for secondary precipitation via measurements such as pH and aragonite saturation. Since we know at what pH and aragonite saturation levels this occurs, projects can avoid exceeding these thresholds through careful management and engineering. Project experience to date indicates that existing regulatory thresholds (for example, in the United States and Canada) are already below secondary precipitation thresholds, allowing projects to proceed without compromising operational goals, albeit for small-scale, short-term alkalinity additions. There is ongoing research to develop approaches to directly quantify secondary precipitation. For example, the use of optical sensors is being explored to detect the formation of $CaCO_3$ or brucite particles via optical fingerprinting

Less is known about the potential for OAE to inhibit natural alkalinity fluxes, which could offset some of the OAE CDR potential. Current research suggests that some pathways such as coastal enhanced weathering have more potential to inhibit these natural fluxes, but also that one could manage for this by avoiding areas where this suppression would occur. More research is clearly needed to explore longer-term and larger-scale interactions of OAE with natural biogeochemical processes, in terms of both efficiency of carbon removal and ecosystem effects. For certification, as well as regulation, site-, technology-, and feedstock-specific rules will be needed for commercial-scale projects to avoid overloading sediments with slow-dissolving alkalinity sources.

Effects of OAE on biological calcification

At section 4.1.2.1, the review paper states that biological calcification is known to be enhanced by increased alkalinity but the effect is likely small and hard to quantify for individual projects. Our understanding of the science in this area is that a paper by Lennart Bach theorized this effect, and it has been shown in the lab for some single species, but has not been demonstrated in mesocosm studies. Thus, while there is reasonable theory behind this assertion, it has not been demonstrated to occur as a result of OAE in the field. We agree that any effects are likely to be modest and that cumulative effects of OAE at scale will need to be assessed and considered.

Equilibration with atmospheric CO_2

OAE efficiency modeling suggests that, for most places around the world, the full CDR potential is reached after 10-15 years, considering varying dissolution, subduction, and equilibration rates (Zhou et al., 2025). Unequilibrated alkalinity is a major constraint on the efficiency of OAE. Other major drivers, or constraints, on efficiency include dissolution rate and secondary effects, like precipitation. But Zhou and colleagues also suggest that the majority of the uptake takes place in the first five years. Credible certification schemes would only award credits after air sea exchange has taken place, so projects should be able to receive credit for the portion of the total added alkalinity modeled to have equilibrated during intervals less than required for full equilibration.

Scale and reliance on models for quantification of removals

The large spatial and temporal scales of equilibration with the atmosphere necessitate reliance on models and are a central challenge for quantifying carbon removals from OAE and their certification. Nonetheless, we agree that the physical representation of transport is probably the best constrained of the modelling needs for MRV for OAE. Therefore, as mentioned above, project CDR credits can legitimately be taken at shorter time intervals for a portion of the added alkalinity, so long as there is confidence in the portion of total added alkalinity that remains unequilibrated for each crediting interval, including comprehensive uncertainty assessments.

Early partial crediting efforts can significantly reduce uncertainty by running hindcasts of models with actual observed atmospheric forcing conditions (i.e., weather)—a large driver for air/sea gas exchange. This is computationally expensive but may be worth the effort for trust gained in return. For example, Planetary had an 8% uncertainty due to interannual variability (how weather affects CDR in their models) in their first crediting instance, but by running the model with actual weather data for the crediting period, they were able nearly to eliminate this component of uncertainty in the second crediting round. That said, some systemic uncertainties (i.e., how well models represent underlying processes and the real world) remain and cannot be addressed by individual projects. Model intercomparison exercises, parametric sensitivity analyses, perturbed parameter ensembles, etc., are some of the ways to quantify them. Generally, all uncertainties would benefit from shared taxonomies and best practices to quantify them.

Regarding the reference to Ho et al. (2023), indicating that application of ocean biogeochemical models to estimate CO_2 uptake from alkalinity enhancement “remains largely unvalidated”, we believe there have been significant advancements in the field since that time that raise our confidence in their use for this purpose. Notably, model capabilities can only be tested and their representation of real-world OAE additions can only be improved when actual data from such additions exist for comparison, as stated elsewhere in the consultants' report. Uncertainties arising from these representations must be accounted for in the interim.

Addressing model uncertainty

Models inherently carry uncertainty from varying sources as they aim to represent the real world in a simplified way. Generally, we agree with the report's recommendation to conduct comprehensive uncertainty estimates. For early projects such as the ones currently undergoing or preparing for certification, it is important to recognize that some ambiguity remains around what constitutes sufficient and "comprehensive" uncertainty estimates and how confident projects are in these estimates.

While early projects can successfully quantify and report on uncertainties, open questions still remain about their size and contribution. Notably, this is expected but can be improved on over time and should not be considered a barrier to quantification because data from alkalinity additions are required to reduce these uncertainties Looking ahead, the risk lies in scaling up without adequately representing the limits of current knowledge.

Based on early certification experience, Carbon to Sea recommends that certification protocols seek to align uncertainty taxonomies and provide unambiguous guidance on the type of uncertainties that must be accounted for as well as confidence bounds in this uncertainty.Small-scale pilots may be overburdened when having to account for all uncertainty considerations. Challenges around systemic uncertainty quantification in particular cannot be resolved by a single project—and in some cases require complex intercomparison exercises. However, a pathway should exist to ensure conservative treatment in early certifications of systemic and other uncertainties alike, either through additional discounts or potentially through buffer pools.

Other marine carbon cycle feedbacks and reversals

CTS agrees that more research is needed to understand both short- and long-term effects of OAE on marine ecosystems. We're encouraged that decades of work on ocean acidification, nutrient dynamics and toxicology provide a decent idea of the direction of such effects. The magnitude will, of course, depend on dosage, and site-specific factors, and is therefore less certain. For example, if heavy metals are introduced at levels that are toxic to plankton, this could reduce the biological carbon pump. If feedstock contains nutrients such as iron, on the other hand, it could stimulate growth and affect the biological carbon pump in other ways.

These processes should be understood and accounted for in assessing environmental impact and the efficiency of carbon removal from OAE. But they are unlikely to rise to a level at which they create reversals. We've learned a lot by now in the lab and in mesocosms. Now demonstrations in the ocean are required to advance our understanding. While this research may pose some environmental risks, we believe those can be managed through appropriate regulation and oversight by regulators during the permitting process.

Acid disposal

Acid, and any other byproducts, resulting from electrochemical OAE, should be utilized or disposed of sustainably. We don't expect this to be a significant problem unless/until such approaches reach a large scale. For purposes of certification, such considerations should be addressed in life cycle analyses to ensure removals are properly discounted for acid neutralization and in environmental sustainability requirements.

While electrochemical OAE pathways are the most constrainable with respect to quantifying how much alkalinity is added to the water, open-system electrochemical technologies have the same challenges in modeling transport and equilibration, and assessing the associated uncertainties, as do technologies using mineral feedstocks.

MRV model refinement

In section 4.1.6, the review paper states that "it will be important to recognise that early OAE activities will have greater uncertainties around carbon removed but will add the greatest value to the process of constraining and improving model-based MRV for future OAE deployments." We agree early activities are required to reduce uncertainties. As a result, it will be important that certification schemes are sufficiently flexible to accommodate greater uncertainty in early-stage, small-scale projects. Procedural transparency, data sharing, rigorous accounting for uncertainty, and appropriate discounting of credits are important for projects at any scale but are particularly vital for the early-stage, small-scale projects that will deliver key information about the safety and efficacy of individual technological approaches.

Certification methodologies can unlock both public and private capital to advance the technological readiness of approaches that prove to be safe and effective. Private investors, philanthropies, and government entities seeking to advance responsible OAE will all look to high-quality certification protocols for signals about where to invest. Availability of diverse sources of funding is critical for companies undertaking the kind of small-scale projects that are needed to provide information to assess the safety and efficacy of different OAE approaches.

Importance of transparency and data-sharing

In section 4.1.6, the review paper highlights provisions of Isometric's protocol for collection and accessibility of data, and their importance for advancing technology. We certainly support these aspects of the Isometric protocol and their incorporation by reference of the FAIR data principles and best practices for OAE research put forward by Oschiles et al. (2023). Perhaps it is beyond the scope of the consultants' report, but CTS feels it is vitally important that any CRCF certification protocols be clear about required levels of data sharing and accessibility.

Toward these ends, CTS has funded development of OAE Data Management Guidelines and an OAE Data Management Protocol to enable OAE data collected from academia, government, non-profit, and industry to be documented in a consistent way, and make them findable and discoverable from shared data repositories to facilitate future data synthesis efforts.

More broadly, the European Commission should consider creating and maintaining adequate and accessible data repositories for this information. Such real and virtual infrastructure will facilitate the kind of rapid advances that will be needed if OAE, and other CDR technologies, are to rise to the scale needed to support achievement of Europe's ambitious climate goals.

Durable storage

The first bullet in the summary of the scoping paper says that the residence time of alkalinity in the ocean is of the order of hundreds of millennia, but the review of potential certification issues, at section 4.2, presents a much more conservative view: "...a timescale of at least several centuries." While these statements are not technically at odds–hundreds of millennia are indeed *at least* several centuries—they will be confusing to policy makers considering next steps on OAE certification. We believe that a careful review of the science will show that both carbon and alkalinity have a residence time in the ocean of about 100,000 years, plus or minus 20,000 years. The larger point is that storage as dissolved inorganic carbon (DIC) in the ocean is highly durable and at low risk of reversal. The main challenge, therefore, is determining to a reasonable degree of certainty how much carbon is added to DIC by OAE on a project-by-project basis.

It is true that future changes to the concentration of CO_2 in the atmosphere will affect the efficiency of OAE, and all forms of CDR, to some degree. Such changes are, for better or worse, likely to be slow and small. But they will make estimates of removals conservative during the period of increasing pCO_2 in the atmosphere. If/when we are fortunate enough to have to confront the problem of the declining efficiency of CDR due to dropping atmospheric concentrations of CO_2, these changes can be factored into the baseline for crediting at that time.

Sustainability

We concur with the general thrust of section 4.3 of the review paper that some aspects of effects of OAE on marine organisms and ecosystems are poorly quantified at present, and that more research is needed to understand the extent and magnitude of such effects. We are beginning to understand how changes in carbonate chemistry, i.e., alkalinity and pH, affect plankton. These impacts are likely to be small or non-existent at realistic levels of OAE. Impacts on higher trophic levels (e.g., fish) are poorly quantified, but if plankton are not affected there is little reason to think that higher trophic levels would be more impacted based on organism physiology. Other poorly quantified impacts are feedstock and pathway specific, e.g., from the introduction of particles or trace elements. A special issue of Biogeosciences provides detailed insights on these matters.

To understand these effects at scale, as well as cumulative or delayed impacts, it will be necessary first to thoroughly monitor and study early, small projects. To accomplish this, environmental monitoring will need to be expanded beyond what is required by the Isometric protocol and what we have seen so far in government permit requirements, so that early OAE projects establish strong baselines and protocols for assessing any short- and long-term effects. The importance of these additional requirements is discussed in detail above under Quantification/MRV. Here we refer again to the Environmental Impact Monitoring Framework, which can assist in the design of monitoring programs to avoid harmful effects, while ensuring data collection and analysis that will improve our understanding of these issues.

Regarding specific effects cited in the review paper:

- Changes in DIC speciation—For realistic levels of OAE, we agree that effects are likely to be small, albeit in a beneficial direction given the known effects of ocean acidification.
- Changes in silica concentration—Where silica is a limiting nutrient, this will tend to favor silicifying plankton over calcifiers. But silica may not be limiting in coastal areas. The magnitude of effect also depends on the bioavailability of silica from OAE.
- Changes in calcium and magnesium cation concentrations—Elevated calcium concentrations will tend to favor calcifiers but magnesium silicates and hydroxides may inhibit calcification. However, we really don't know much about these dynamics.

For all the potential impacts, baselining and monitoring (including concentrations of calcium, silicate, magnesium, and other metal ions) will help to elucidate dynamics. Such intensive monitoring is likely more important in early OAE development to build knowledge and understanding. Lastly, environmental effects incidental to OAE must ultimately be weighed against the benefits of carbon removal for climate change mitigation, and the harm done to marine life and ecosystems caused by climate change.