PERSPECTIVES ON MARINE CARBON DIOXIDE REMOVAL FROM THE GLOBAL OCEAN ACIDIFICATION OBSERVING NETWORK

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ABSTRACT. Along with other carbon monitoring groups, the ocean acidification (OA) community has been observing, modeling, and projecting the impacts of changing carbonate chemistry for over two decades. The Global Ocean Acidification Observing Network (GOA-ON) has three key goals related to these issues: (1) improve understanding of global OA conditions, (2) improve understanding of ecosystem responses to OA, and (3) acquire and exchange data necessary to optimize modeling for OA and its impacts. GOA-ON and associated networks have a wealth of knowledge, data, models, and best practice guides on how to monitor global carbonate chemistry, and GOA-ON regional hubs collaborate at local scales to inform policy and action for coastal communities. Here, the GOA-ON community shares lessons learned relevant for marine carbon dioxide removal (mCDR) research and development. Understanding whether, how, and where mCDR approaches should be deployed will require knowledge of the carbonate system, robust observations, sensor technology, and modeling capacities. Ongoing monitoring, reporting, and verification during field trials and any eventual implementation of mCDR will again require these resources. The GOA-ON community's knowledge about environmental impacts, running laboratory and field experiments, and deriving biological indicators of change is of fundamental importance for assessing the environmental impacts of mCDR and of the potential for mitigating or exacerbating OA. Finally, we present recommendations for utilizing this OA experience toward mCDR research.

INTRODUCTION

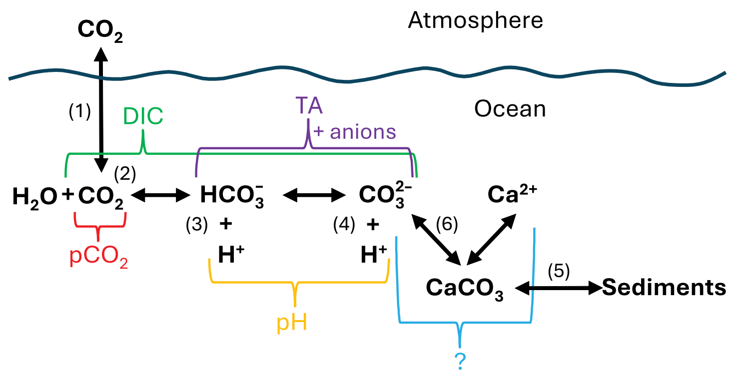
Due to human activity, carbon dioxide (CO_2) concentrations in the atmosphere continue to rise. The ocean is absorbing about 30% of the extra CO_2 and at present continues to store carbon (Friedlingstein et al., 2024). Because the rate of CO_2 uptake into the ocean is too fast for natural geological buffering processes to keep pace, the excess carbon alters the marine carbonate system and results in a measurable decrease in ocean pH, commonly referred to as ocean acidification (OA; see **Box 1**; Caldiera and Wickett, 2003). The changing chemistry is impacting important biological and biogeochemical processes that rely on stable pH or specific saturation state levels of important minerals such as aragonite or calcite (Kroeker et al., 2013). These impacts have knock-on consequences for the ecosystem and the services they provide (Hall-Spencer and Harvey, 2019).

The continuing rise in CO_2 emissions has also spurred interest in carbon dioxide removal (CDR) mechanisms that are now needed alongside continued emissions reductions to meet climate goals (Smith et al., 2024). Given the ocean's ability to take up and store CO_2, there is increased interest in exploring methods that could exploit these natural storage mechanisms, as so-called marine CDR (mCDR) approaches. All mCDR methods require additional research and development to determine carbon removal efficiency and potential environmental responses. If mCDR approaches are implemented at scale, they must have the potential to remove carbon durably (1,000+ years; Brunner et al., 2024) and without causing detrimental side effects. Unlike solar radiation management and other non-carbon removal geoengineering solutions, mCDR, alongside drastic emissions reductions, has the potential to mitigate climate change while also preventing further OA by capturing carbon. However, the ability to mitigate OA that has already occurred will depend on many factors, including the methods used and scales of application.

Some mCDR approaches are being pursued more seriously than others, as they have greater potential to remove carbon durably and at scale (NASEM, 2022). *Macroalgae cultivation*, involves rapidly growing marine seaweeds to fix carbon and store it as biomass. Subsequently, this biomass can either be harvested to produce long-lasting bio-products, including biochar, which can result in some passive carbon storage, or be deliberately sunk to the deep ocean for long-term carbon removal. Ocean *nutrient fertilization* enhances marine productivity by adding micronutrients essential for the growth of phytoplankton, thus stimulating primary production, whereby CO_2 is taken up from the surface water and stored in organic biomass that sinks out of the surface ocean. Surface productivity can also be stimulated through *artificial upwelling*, whereby deep, nutrient-rich waters are brought to the surface and utilized there by phytoplankton. *Ocean alkalinity enhancement* (OAE) involves the addition of alkalinity, either by adding crushed alkaline minerals or aqueous hydroxides, or by using electrochemical methods to generate base, which can then be added to seawater. This addition of alkalinity enhances the CO_2 uptake potential of the ocean. CO_2 is then stored within the ocean as part of the dissolved bicarbonate (HCO_3^-) pool for a longer timescale. *Direct ocean carbon capture and storage* (DOCCS) uses technological processes to extract CO_2 directly from the ocean, usually through electrochemical methods that create a pH swing and force all the dissolved inorganic carbon (DIC) into CO_2. The extracted CO_2 can either be stored in sub-sea geological formations or used in industrial processes (following known carbon capture utilization and storage pathways, or CCUS). Low-CO_2 water is then returned to the ocean where net carbon removal is only achieved after air-sea CO_2 (re)equilibration.

Research on mCDR can, and should, be informed by other adjacent, relevant fields, such as the work on OA, where there is a wealth of knowledge about the marine carbonate system and ecosystem responses to it. Together the OA and carbon communities have developed experimental and field-based methodologies, created best practices guides (Riebesell et al., 2011; Currie et al., 2024), and built carbon measurement observing capacity through a number of networks. One such network is the Global Ocean Acidification Observing Network (GOA-ON). GOA-ON was established in 2012 as a result of increased awareness and concern about OA from scientists who recognized the need for coordinated efforts to understand this global issue (Newton et al., 2015). Today, GOA-ON has >1,000 members from >115 countries and territories that are organized into 11 regional hubs (**Figure 1**). GOA-ON members also participate in other carbon-related international initiatives, including the Global Ocean Observing System (GOOS), the Scientific Committee on Oceanic Research (SCOR), the Commonwealth Blue Charter, the International Ocean Carbon Coordination Project (IOCCP), the Surface Ocean CO_2 Atlas (SOCAT), and the Global Ocean Data Analysis Project (GLODAP). This interaction is actively maintained through partnerships, joint initiatives, and GOA-ON secretariat members, the latter of which are financially supported by three partner organizations, the US National

BOX 1. CARBONATE CHEMISTRY AND OCEAN ACIDIFICATION



Ocean acidification is occurring because of (1) the rapid uptake of CO_2 from the atmosphere, which is causing a shift in marine chemistry: CO_2 reacts with seawater to become (2) part of the marine carbonate system, increasing the pool of dissolved inorganic carbon (DIC), and (3) causing an increase in bicarbonate ions (HCO_3^-)and hydrogen ions (H^+) (a decrease in pH—Equation 1) and (4) a decrease in carbonate ions (CO_3^{2-}).

$$pH = -\log[H^+] \qquad (1)$$

Total alkalinity (TA) is the sum of all the bases in seawater that are able to buffer hydrogen ions. TA does not change as a result of CO_2 addition but rather absorbs the additional DIC by shifting the equilibrium between CO_2, HCO_3^-, and CO_3^{2-}. Over geological time frames, mineral weathering of carbonate sediments (e.g., $CaCO_3$), but also silicates, plays an important role in buffering these shifts in chemistry by (5) adding alkalinity to the ocean.

The saturation state (Ω) of minerals, such as $CaCO_3$, is important for determining the stability of the mineral in a solution (Equation 2). As Ω increases, seawater becomes increasingly saturated (Ω > 1) and minerals are more likely to precipitate; as Ω decreases and eventually becomes undersaturated (Ω < 1), minerals are more likely to dissolve.

$$\Omega = \frac{[CO_3^{2-}]\,[Ca^{2+}]}{K_{sp}}, \qquad (2)$$

where K_{sp} is the solubility product constant.

Calcification and dissolution can also (6) alter the DIC and TA by the following reactions (Equation 3):

$$2HCO_3^- + Ca^{2+} \leftrightarrow CaCO_3 + CO_2 + H_2O \qquad (3)$$

Oceanic and Atmospheric Administration (NOAA) Ocean Acidification Program (OAP), the International Atomic Energy Agency Ocean Acidification International Coordination Centre (IAEA OA-ICC), and the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO). Furthermore, the GOA-ON Executive Council consists of representatives identified for their topical, regional hub, institutional, and/or early-career status. Early-career researchers are also members of the International Carbon Ocean Network for Early Career (ICONEC), which was established by GOA-ON in 2023.

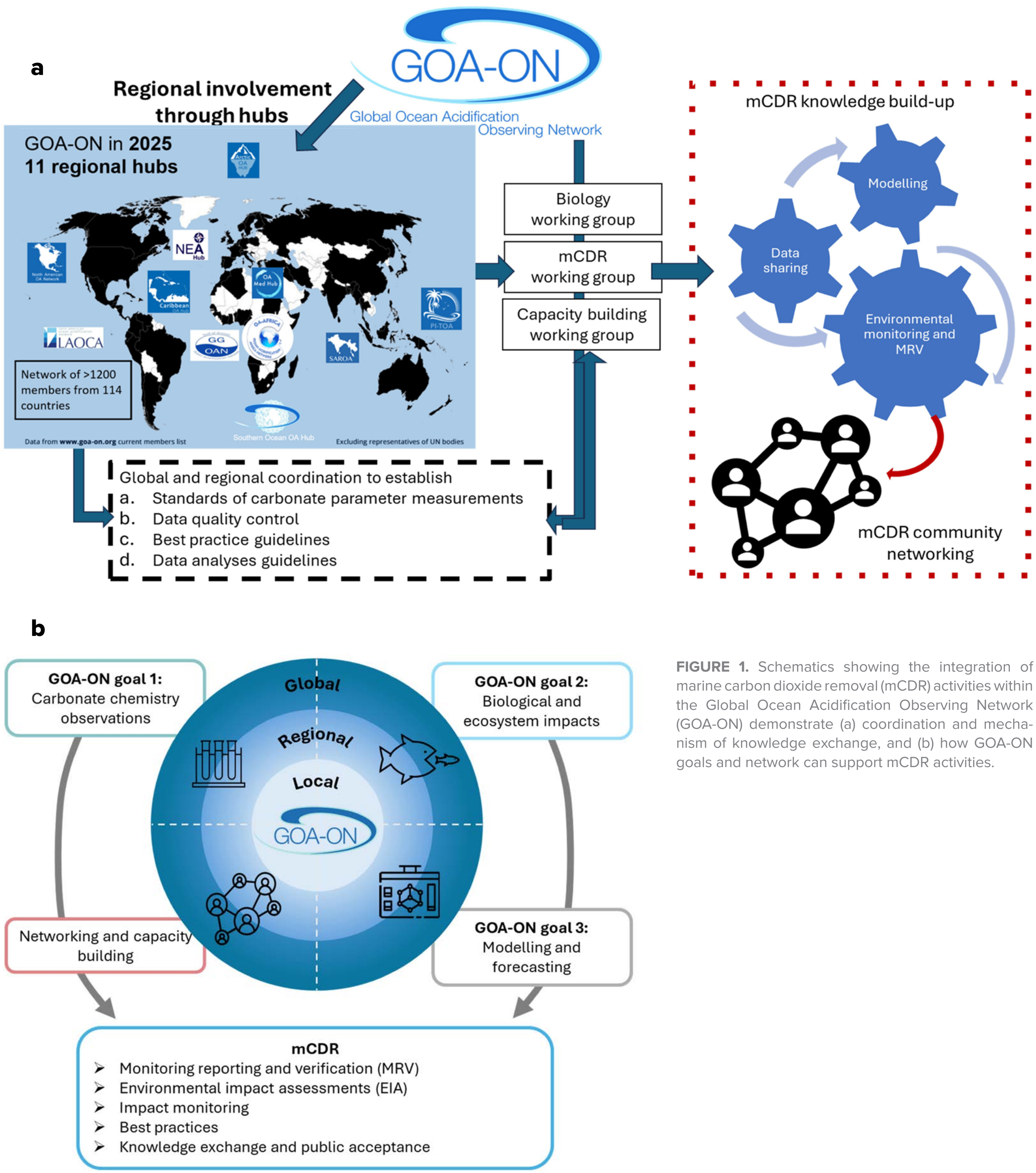


FIGURE 1. Schematics showing the integration of marine carbon dioxide removal (mCDR) activities within the Global Ocean Acidification Observing Network (GOA-ON) demonstrate (a) coordination and mechanism of knowledge exchange, and (b) how GOA-ON goals and network can support mCDR activities.

As mCDR becomes increasingly investigated as a potential tool to help mitigate climate change, understanding how GOA-ON's goals intersect with and support mCDR initiatives is crucial. GOA-ON's three high-level goals are: (1) improving understanding of global OA conditions; (2) improving understanding of ecosystem responses to OA, and (3) acquiring and exchanging data necessary to optimize modeling for OA and its impacts (Figure 1). Here, we explore the GOA-ON community perspective for informing and supporting mCDR activities in relation to the GOA-ON goals. The aims of this paper are to consider how mCDR could interact with OA, either by mitigating or exacerbating it; to identify what knowledge gaps exist; to consider lessons learned from OA research when approaching mCDR; and finally to make recommendations about how OA knowledge and the GOA-ON community can support mCDR research.

POTENTIAL FOR mCDR TO MITIGATE OR EXACERBATE OA

In order to reverse the OA that has already occurred without further manipulating other components of the carbonate system, CO_2 needs to be removed from the ocean while maintaining alkalinity (reverse of "Continued CO_2 emissions" line in Figure 2). As the end goal of mCDR is to remove carbon from the atmosphere and lock it away in long-term storage, all mechanisms have the overall potential of preventing further OA in the future. However, depending on where the carbon is stored in the ocean and the manipulation involved, ongoing OA and/or its impacts could either be ameliorated or exacerbated at different scales, and we discuss these here (see Figures 2 and 3).

Given the chemical equilibrium underpinning the carbonate chemistry in seawater during OAE, the reduction of H^+ following alkalinity injection or mineral dissolution would lead to an increase in

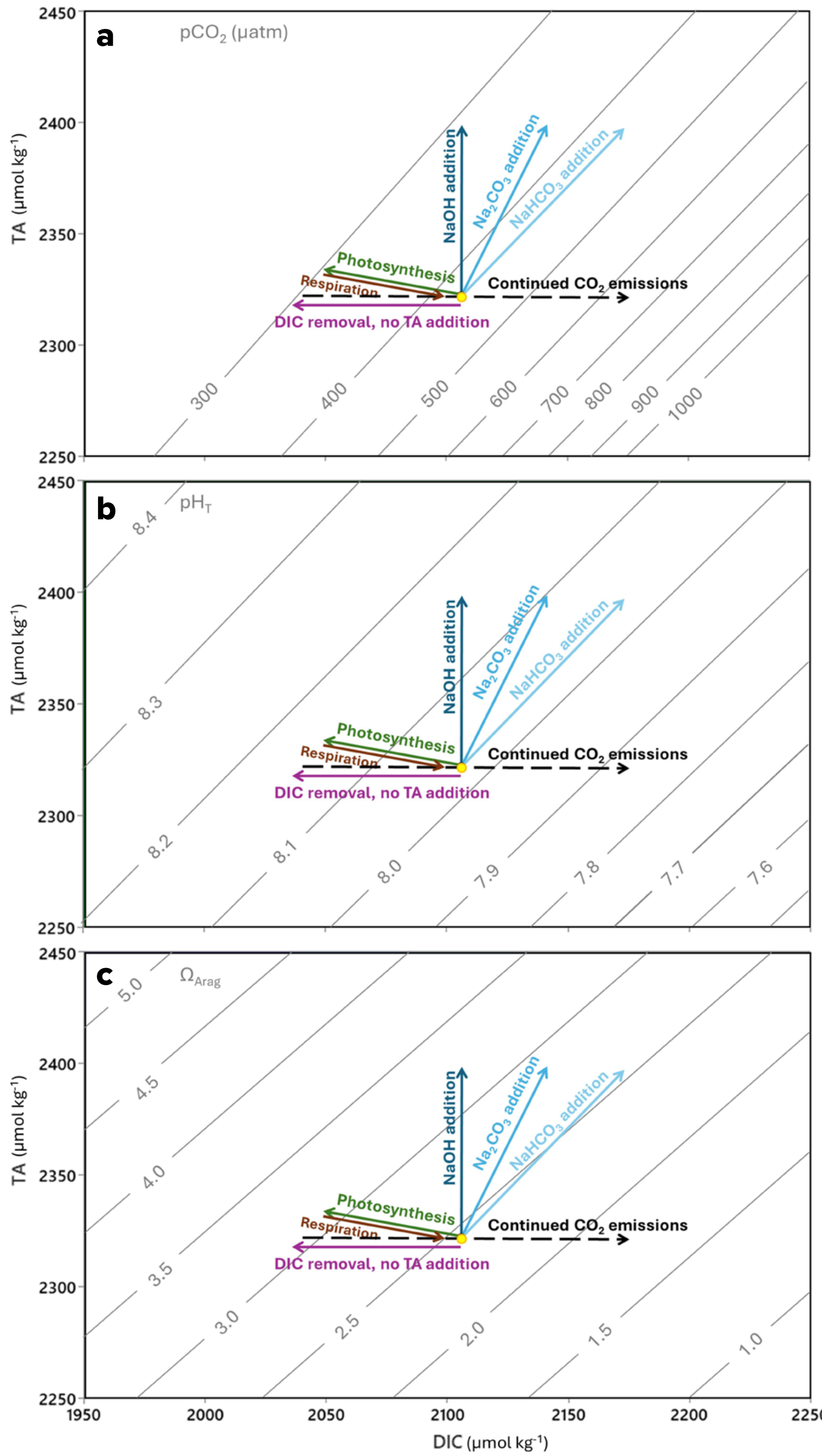


FIGURE 2. Dissolved inorganic carbon (DIC)–Total alkalinity (TA) plots showing (a) pCO_2, (b) pH, and (c) aragonite saturation state. [Overlaid trajectories indicate when different mCDR approaches are applied in their unequilibrated phase] [Overlaid trajectories indicate effects of applying different mCDR approaches in their unequilibrated phases?]. The relative concentrations of these variables apply only to a specific temperature and salinity (here T = 15°C, S = 34); the absolute values will change at other combinations of temperature (T), salinity (S), dissolved inorganic carbon (DIC), and TA. In this example, present day is represented with a pCO_2 of 420 µatm and shown as the yellow dot in each panel. At some point along the "continued CO_2 emissions" trajectory, the mCDR approaches are applied, noting that the closer to present day CO_2 levels they are applied, the less mCDR will be needed to return to present day or historic levels, and that without continued emissions reductions no mCDR approach will work. The mCDR approaches include: "DIC removal, no TA addition" (purple), which represents direct ocean carbon capture and storage (DOCCS); three ocean alkalinity enhancement (OAE) options as represented in Schulz et al. (2023): "NaOH addition" (dark blue), which adds TA and not DIC; "Na_2CO_3 addition" (mid blue), which adds TA and half as much DIC; "$NaHCO_3$ addition" (light blue), which adds equal amounts of TA and DIC; "Photosynthesis" (green), which is all photosynthetically driven mCDR (e.g., macroalgae growth, nutrient fertilization, artificial upwelling; these may have additional impacts on alkalinity depending on the form of nutrient additions and the type of photosynthetic organism). Also shown is "Respiration" (brown), representing eventual remineralization of organic matter. Here, photosynthesis and respiration are assumed to occur as a result of nitrate or nitrite being the N source and product, respectively (as opposed to ammonia). See Wolf-Gladrow and Klaas (2024).

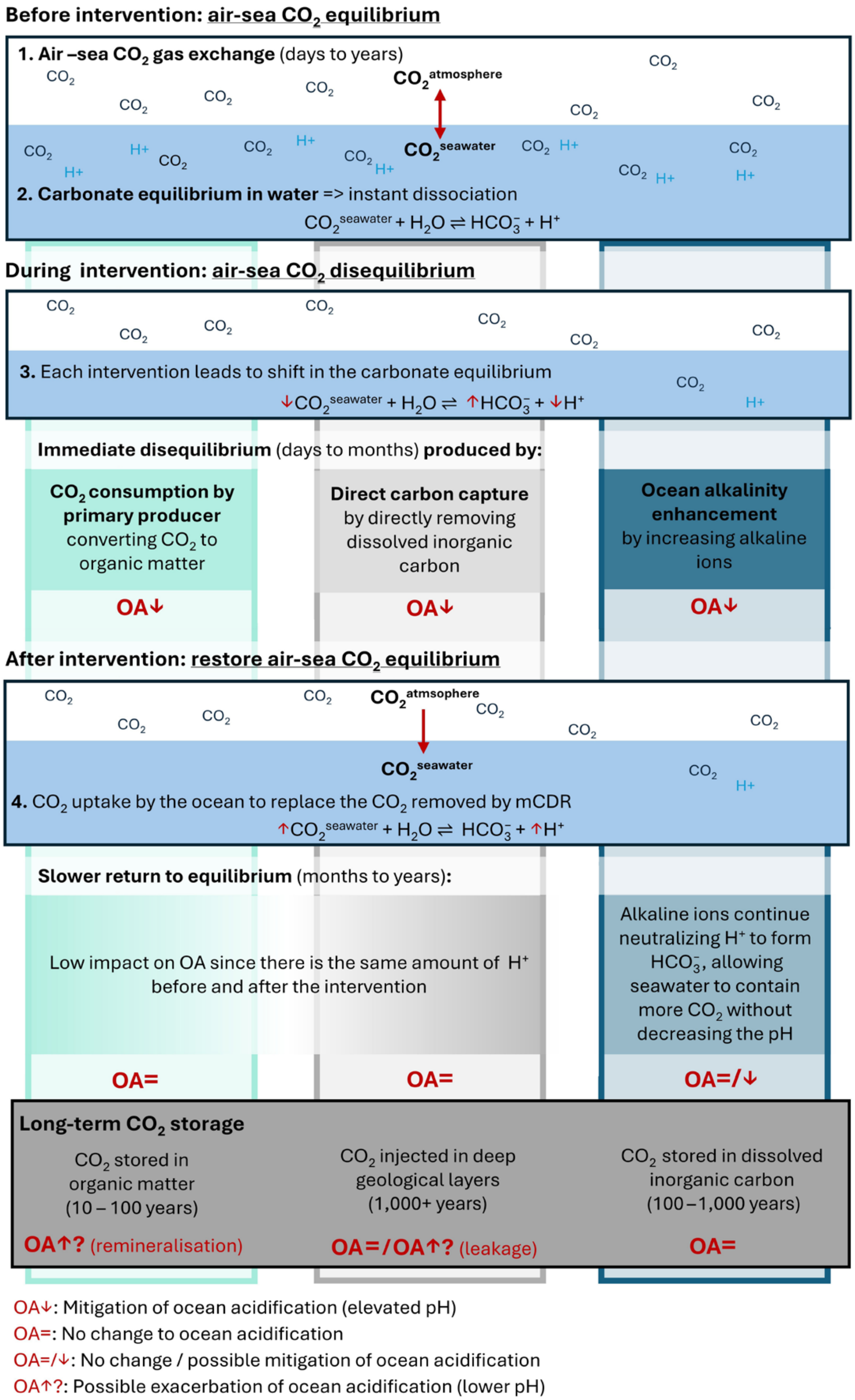


FIGURE 3. Schematic of the air-sea equilibrium and carbonate chemistry of seawater before, during, and after mCDR interventions, highlighting potential connections to ocean acidification (OA) as indicated by the dark red annotations. "OA↓" indicates mitigation of OA (elevated pH), "OA =" indicates no change in OA, "OA=/↓" indicates no change/possible mitigation of OA (elevating pH), and "OA↓?" indicates possible exacerbation of OA (lower pH). For the biological mCDR column, long-term storage is dependent on the vertical partitioning of the biological carbon pump, and where the organic matter finally ends up. It is highly likely that the organic matter remineralizes back to CO_2 in the deep ocean, then potentially exacerbates OA. For the other two columns, long-term storage is likely to be stable in DIC form (OAE) or in geological storage (DOCCS), where there is low likelihood of leakage back into the marine system as CO_2 (which could then exacerbate OA).

pH and therefore a potential mitigation of OA (Doney et al., 2024; "NaOH addition," "Na_2CO_3 addition," and "$NaHCO_3$ addition" lines in Figure 2; see also Figure 3). To date, modeling studies have suggested large uncertainty in the OA mitigation potential of OAE (Butenschön et al., 2021; Palmiéri and Yool, 2024). On a local scale, OAE might prove to be beneficial for mitigating the impact of OA, especially in environments with less water exchange (Khangaonkar et al., 2024). However, this approach greatly depends on the spatial and temporal scales and evolution of the perturbed alkalinity (Suitner et al., 2024). A recent study suggests that connecting OAE efficiency, air-sea gas exchange, and ocean circulation could be a useful tool for considering local implications for OA (Zhou et al., 2025). Once equilibrated, the only benefit to OA is an offset from further acidification from continued CO_2 uptake (i.e., more CO_2 can go into the ocean without causing further OA), rather than a reversal (i.e., removing CO_2 and increasing pH back to historic levels) (Mongin et al., 2021). Interestingly, if OAE improves the seawater chemistry for shell-building organisms through raising calcium carbonate saturation states, increased net calcification rates (one of the key ecological processes impacted by OA) would consume alkalinity and increase seawater pCO_2, thus potentially negating any carbon removal efforts at local (habitat) scales (Renforth and Henderson, 2017). The type of alkalinity used, and the method and rate of OAE addition, will all determine OAE's ability to mitigate OA (Figure 2). Furthermore, if OAE is carried out incorrectly (i.e., adding too much alkalinity too rapidly), it could increase the carbonate mineral saturation state and stimulate precipitation (Renforth and Henderson, 2017), thereby consuming alkalinity and increasing pCO_2 levels. In this scenario, OAE could exacerbate OA by reducing seawater's buffering capacity. Although most recent scientific research has focused on the impact of OA and low pH on marine species, high pH can also significantly impact them (Pedersen and Hansen, 2003; Mos et al, 2020; Bednaršek et al., 2025). Further research is needed to confirm the safe levels of alkalinity and pH that can be released without causing harm; such investigations would produce critical data for idealized dosing operations and identification of alkalinity addition limits in different oceanic regions.

DOCCS uses electrochemical processes to remove DIC from seawater by adding acid to convert all DIC into CO_2, and then using a stripping process to remove and capture the CO_2, before finally adding alkalinity back in to elevate total alkalinity (TA) to original levels (Karunarathne et al., 2025). This approach results in the discharge of treated seawater back into the ocean that now contains lower DIC, ambient alkalinity (noting the dominant alkalinity at the end of the process is OH^- rather than HCO_3^- and CO_3^{2-}), but higher pH. This low DIC, high pH discharge water has potential to mitigate OA in the direct vicinity of the discharge plume ("DIC removal, no TA addition" line in Figure 2; see also Figure 3). As atmospheric CO_2 re-equilibrates into the low CO_2 plume, the carbonate chemistry returns to the original values and therefore any mitigation effect is confined to small spatial and temporal scales. As with OAE, further research is needed to fully elucidate the potential of DOCCS to either mitigate OA or indeed have its own environmental impacts from aspects such as elevated pH or low CO_2 and bicarbonate water.

The biological mCDR approaches of ocean nutrient fertilization and macroalgal cultivation are considered to be CDR techniques because they directly remove DIC through biological primary production. The manipulation of seawater chemistry in these cases, as a result of photosynthetic activity, results in local drawdown of CO_2, elevation of pH, and consumption of nutrients (especially phosphate and nitrates, but also silica in diatoms and other minor nutrients), which has a small impact on alkalinity (Wolf-Gladrow and Klaas, 2024; "Photosynthesis" line in Figure 2; see also Figure 3). Thus, in the immediate surrounding surface waters, both macroalgal cultivation and nutrient fertilization have the potential to ameliorate OA. However, due to the smaller changes in alkalinity and its higher variability, the potential for co-benefit at a large scale seems limited (Berger et al., 2023). Some research has shown that macroalgal cultivation can mitigate the impact of OA on calcifying bivalves that are grown in close proximity to the macroalgae (Wahl et al., 2018; Young and Gobler, 2018). However, contrasting results suggest coral calcification decreases in the presence of macroalgae (Isaak et al., 2024). There is also evidence that, while macroalgae systems photosynthesize during the day (increasing pH), nighttime respiration produces CO_2, and decreases pH (Hirsh et al., 2020; Ricart et al., 2021), and the resulting diel variability in pH can be problematic for organisms not already adapted to this regime. More research is required to understand the potential impact at much larger scales.

Especially important to consider for these biological approaches, but indeed for all approaches that make use of storing carbon at depth in the ocean, is what happens to that carbon once in that location. The deep ocean already has higher concentrations of carbon than upper layers due to organic carbon remineralization and global circulation patterns. There is widespread evidence that OA is not limited to the surface. The ocean interior is also acidifying, with some areas acidifying at much faster rates than others (e.g., Fassbender et al., 2023; Müller and Gruber, 2024). This ocean interior acidification is resulting in an expansion of undersaturated conditions with respect to calcium carbonate (aragonite and calcite) minerals, which will impact calcifying organisms in the deep sea and throughout the water column (e.g., Feely et al., 2024). By intentionally adding more carbon, either directly as liquid CO_2 (a method not discussed in this paper) or indirectly as organic matter from phytoplankton or macroalgae (or land-grown biomass) that can be remineralized back to CO_2 ("Respiration" line in Figure 2), there is potential to increase this deep ocean interior acidification impact. Subsurface remineralization processes that are enhanced by eutrophication in coastal regions also contribute to interior acidification. Excess nutrients lead to rapid phytoplankton or macroalgal blooms in surface waters that then sink and are remineralized in subsurface waters, consuming oxygen and releasing CO_2. Remineralization can be amplified in estuaries and river plumes where mixing-induced minimum buffering zones can locally amplify OA signals (e.g., Van Dam and Wang, 2019; Cai et al., 2021). In the open ocean, the eutrophication phenomenon can result in large hypoxic and anoxic zones (e.g., Feely et al., 2024; Rose et al., 2024).

Artificial upwelling has the potential to both counteract the efficacy of its own mCDR mechanism and cause more surface OA, because the deep waters that are being brought to the surface, while rich in nutrients, are also rich in carbon. Natural upwelling events that occur off the west coasts of the continents (also known as eastern boundary upwelling systems) have demonstrated that upwelling can amplify OA (Feely et al., 2008, 2016) and impact organisms (Barton et al., 2015). Bringing carbon-rich water to the surface shortens the otherwise longer-term storage time of the carbon by exposing it to the atmosphere and potentially negates any uptake of carbon that occurs through enhanced biological productivity.

Any impact of mCDR on marine organisms or ecosystems could also have knock-on consequences for the carbon cycle, including direct implications for CO_2 sequestration, but also for indirect feedbacks to OA. This is a knowledge gap that needs to be addressed within the mCDR research effort. These potential impacts include the broader alterations in seawater chemistry whose impacts on marine life are not fully understood (Meyer and Spalding, 2021; Bednaršek et al., 2025). For example, shifts in nutrient biogeochemical cycling, production of climatically important gases, and particle flux dynamics can play significant roles in changing the speciation of the carbon system in seawater

(Gruber et al., 2023; Vivian et al., 2024). While much more research is needed, a few examples are emerging: recent modeling work suggested that using macroalgae as an mCDR approach had limited potential because of ocean circulation and biological feedbacks that resulted in reduced efficacy of carbon sequestration (Berger et al., 2023). Other modeling work has shown that when iron fertilization was considered as an mCDR approach alongside ongoing climate change, phytoplankton growth resulting from the iron addition led to extra climate-induced stress on the growth of other organisms (consumers), and limited CO_2 sequestration (Tagliabue et al., 2023).

In summary, the mCDR approaches discussed here have the potential to prevent further OA by their very nature, in that they aim to remove CO_2 from the atmosphere. However, atmospheric equilibrium processes and possible remineralization add uncertainty as to their effectiveness at either reversing OA or alleviating it at global scales, especially as mCDR methods are, by design, using the ocean to store the extra carbon from the atmosphere. Therefore, the location of the stored carbon and the stability of the store will ultimately determine whether or not the problem of OA is alleviated or just transferred to another part of the ocean.

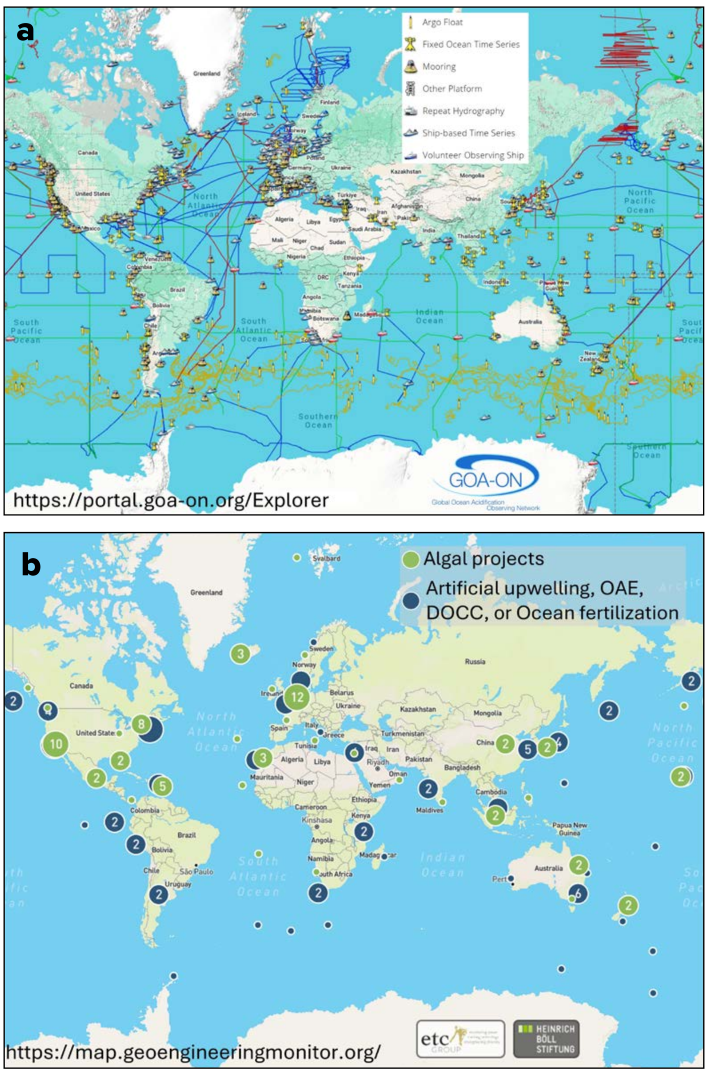


FIGURE 4. Maps show (a) OA-relevant monitoring, taken from the GOA-ON Data Explorer (correct as of January 2025), and (b) mCDR activities between 2000 and 2025 (numbers in circles indicate number of projects in that area), taken from the Geoengineering Map (correct as of January 2025).

GOA-ON GOALS AND mCDR RESEARCH

As an established network of international scientists and ocean professionals, GOA-ON offers a wealth of knowledge to the mCDR community. Here we explore the three goals of GOA-ON and how they offer lessons learned by the OA community that are relevant to mCDR and how each of these goals could support mCDR research.

GOA-ON GOAL 1: IMPROVE UNDERSTANDING OF GLOBAL OCEAN ACIDIFICATION CONDITIONS

GOA-ON's first goal is to enhance global monitoring of ocean carbonate chemistry, with key observations being pCO_2, pH, alkalinity, and DIC (Newton et al., 2015). This monitoring is achieved by establishing and supporting standardized observation protocols, as well as increasing the spatial and temporal coverage of OA monitoring efforts through capacity building activities. By improving our understanding of the spatial and temporal variations in carbonate chemistry, GOA-ON provides the scientific baseline necessary for evaluation of any large-scale marine intervention, including mCDR.

GOAL 1 LESSONS LEARNED RELEVANT FOR mCDR RESEARCH AND CURRENT STATE OF OBSERVATIONS

Early OA monitoring was mostly carried out in open ocean systems where variability is relatively low. However, increasingly, observations show higher variability, especially in coastal areas. Carbonate chemistry is influenced by a complex interaction between physical, chemical, and biological processes, sediment-seawater interactions, and proximity to coastal and land-based inputs (e.g., Cai et al., 2021). Static, long-term observations (such as moorings or repeat hydrographic transect sections) and underway systems such as on ships and uncrewed systems that provide broader spatial coverage, including throughout the water column, are fundamental for understanding OA. However, there have been challenges because researchers lack reliable, cost-effective sensors and readily available reference materials for calibrating measurements, and OA observations have limited spatial coverage. To address these challenges, GOA-ON and other networks have supported capacity development (see later section on GOA-ON's Network and Capacity) that has expanded observations across the globe. To facilitate awareness of existing data and platforms, GOA-ON created an online data explorer (**Figure 4a**) that displays >750 assets and is a first port of call for anyone trying to understand where carbonate chemistry monitoring activities are being conducted and who is leading those activities.

Ocean carbon data archiving is now being streamlined, with general consensus among scientists globally that individual archiving centers need to be connected and interoperable, so as to essentially create one location for all the data, thus making data discovery, sharing, and use easier. For example, a large portion of the quality-controlled ocean carbon data from across the globe is, by community agreement, archived in the United States at NOAA's Ocean Carbon and Acidification Data System, although many countries have their own national data centers. This data sharing facilitates use of the data beyond their immediate applications, resulting in products such as SOCAT and GLODAP. Requirements for reporting on OA are now being implemented at an international policy level through the UN Sustainable Development Goal (SDG) 14.3 target designed to "minimize and address the impacts of ocean acidification," which is also driving the development of standardized metadata formats, common language, and a federated data system. However, there are still many challenges in data sharing and reporting. In 2024, only 42 of 193 UN member states reported OA observations to the IOC-UNESCO in support of SDG 14.3. The SOCAT community also highlighted a decline in surface pCO_2 observations over recent years that is resulting in enhanced uncertainties when these data are used for calculating the global carbon budget (Dong et al., 2024).

HOW GOAL 1 SUPPORTS mCDR RESEARCH

Strategies for mCDR rely on a thorough understanding of the current state of the ocean's carbonate chemistry. The data generated by the GOA-ON community, alongside other important, connected observing networks and efforts, provide background information on the state and dynamics of the carbon system that is essential for identifying whether and where mCDR technologies would be most effective, whether there is a meaningful perturbation from the baseline condition, and what risks might arise from anthropogenic alteration of local chemistry. Mapping of OA monitoring activities against mCDR efforts already provides some insight into what observational capacity may be available to support mCDR (**Figure 4a *cf.* 4b**). Understanding where OA is proceeding most rapidly, or what areas are at higher risk from OA, can also inform where mCDR could be deployed, especially if co-benefits or the ability to mitigate against the impacts of OA have been identified.

Monitoring carbonate chemistry before, during, and after mCDR interventions is critical to assessing their efficacy and to minimizing unintentional harm to marine ecosystems. Availability of observation technology and resulting data will be fundamental for assessing how much carbon can be feasibly extracted without disturbing the natural balance of ocean chemistry and for ensuring that these interventions remain safe and effective. In the mCDR community, this is referred to as monitoring, reporting, and verification (MRV). There is also a clear requirement to standardize and report MRV measurements using agreed upon methodologies and best practices (Boyd et al., 2023; Oschlies et al., 2023). Further work is required to integrate observational data with the OA and carbon communities' data for full data equity.

Only limited numbers of carbon system sensors are commercially available with both the precision and accuracy needed to detect an mCDR perturbation against the large background ocean variability. The carbon community maintains a directory of these systems (IOCCP hardware directory); however, there is an ongoing need to continue to develop, maintain, and distribute low-cost, high-accuracy sensors and autonomous platforms to increase observational capacity for monitoring mCDR (Pardis et al., 2022; Li et al., 2023). The GOA-ON community's experience in building cost-effective, fit-for-purpose observing platforms is ideally matched toward understanding how global climate change measurements and monitoring for MRV can dovetail effectively.

The combination of both large- and small-scale monitoring that is essential for understanding the overall impact of mCDR will require enhancement of the existing ocean carbon observing infrastructure at both global and regional scales (**Figure 4**). While it may be opportune to use well-established climate time series as measurement baselines for small-scale mCDR projects in some regions, limiting the amount of direct perturbation against these baseline network stations will also be necessary to maintain the integrity of the globally important climate time-series observing assets.

GOA-ON GOAL 2: IMPROVE UNDERSTANDING OF ECOSYSTEM RESPONSES TO OCEAN ACIDIFICATION

The second goal of GOA-ON is to understand how marine ecosystems, ranging from microscopic plankton to large coral reefs, respond to OA. Members of GOA-ON have been studying the biological impacts of acidified conditions on various key species and ecosystems in the laboratory, within mesocosms, and in the field, using a wide range of techniques and skills. There are also efforts to standardize protocols for laboratory experiments (Riebesell et al., 2011) and for observing and monitoring impacts in the field (Widdicombe et al., 2023; Currie et al., 2024).

GOAL 2 LESSONS LEARNED RELEVANT TO mCDR AND CURRENT STATUS OF BIOLOGICAL UNDERSTANDING

Initial concern about the impact of OA was primarily related to the reduction in calcium carbonate saturation state and the impact this would have on calcium carbonate-forming (or calcifying) organisms. Early laboratory and field studies demonstrated that increased CO_2 could lead to a 10%–50% reduction in calcification rates of pteropods, oyster larvae, reef-building corals, and coralline algae (e.g., Kleypas et al., 2005; Doney et al., 2009). However, further laboratory work showed that many organisms could still calcify but often with some energetic trade-offs (Wood et al., 2008). Since this realization, many non-calcifying organisms have also been shown to respond to OA, including phytoplankton (e.g., Hutchins et al., 2009; Dutkiewicz et al., 2015), zooplankton (e.g., Keil et al., 2021; Thor et al., 2022), benthos (e.g., Birchenough et al., 2015; Bednaršek et al., 2021), and fish (e.g., Heuer and Grosell, 2014; Sundin, 2023). OA has been shown to impact physiology, growth, reproduction, photosynthetic efficiency, behavior, predator-prey interaction, chemical signaling and sensing, epigenetics, and much more. There have been a number of attempts, using meta-analyses, to group responses by organism type (Kroeker et al., 2013; Alter et al., 2024), trophic level, and/or geographic location (Busch and McElhany, 2016; Hu et al., 2024). These results have been used to discuss socioeconomic impacts, such as those on fisheries and aquaculture (Barton et al., 2015; Narita and Rehdanz, 2017) as well as on human health (Falkenberg et al., 2020).

Some of the varying responses to OA can be accounted for by experiment duration (short-term experiments having more of an acute effect than longer-term acclimation experiments; e.g., Form and Riebesell, 2012) or by the method of acidification used (Hurd et al., 2009). These inconsistencies led to the development of community best practice guides (Riebesell et al., 2011) designed to promote more robust ongoing and future research that would be repeatable and useful for meta-analysis. It also led to the OA-ICC providing two online databases: a bibliographic database that can be shared using Zotero or pCloud, and a database on the impacts of ocean acidification on marine organisms.

Researchers also need to consider spatial variation in marine ecosystems: how organisms have acclimated and adapted to their environments, and what this means for their responses to future change (e.g., Lewis et al., 2013; Vargas et al., 2022). Short-term, local fluctuations can result in different responses for marine organisms that are exposed to them compared to organisms exposed to less variable environments (e.g., Mangan et al., 2019; Lowder et al., 2022).

HOW GOAL 2 SUPPORTS mCDR RESEARCH

Understanding ecosystem responses is fundamental for evaluating the ecological implications of mCDR techniques. Research on OA provides insights into the vulnerabilities of various species and habitats to changing carbonate chemistry, helping to predict which life stages, species, or habitats to focus on first in mCDR impact studies, or helping to generate risk analyses for species responses (Bednaršek et al., 2025). For example, early life stages are likely to be most sensitive, and both calcifying and photosynthetic organisms have additional energetic requirements for maintaining internal physiology against shifting carbonate chemistry in surrounding seawater. Calcifying and photosynthetic organisms may respond to mCDR conditions, especially at the point source of the activity, because of their direct reliance on components of the carbonate system. Understanding the dynamics of any discharge plume and its dilution moving away from the source will be important for determining the exposure, and therefore the vulnerability, of organisms and ecosystems. Additionally, fluctuating exposure to plumes could result in different responses than continued exposure.

In the case of seaweed cultivation and nutrient fertilization, it will be critical to understand how large-scale farming or nutrient additions or removals might affect a variety of ecosystems, not just the immediate ecosystem being manipulated. Large-scale cultivation or nutrient addition could alter habitats and biodiversity, shift nutrient availability (cause nutrient "robbing"), and alter the deep-sea environment. The GOA-ON community is again useful here as it is not solely focused on the surface ocean, but members also study the interior and deep ocean and their ecosystems. Use of the latest biological mapping methods combined with sensitivity analysis from the OA community could be transformative in assessing potential habitat and ecosystem vulnerabilities to different mCDR interventions.

Clarity in the methods used to change the carbonate chemistry, as well as how impacts to organisms are measured, is vitally important to make sure experiments and field studies are comparable. A highlight from the OA community has been the principle that experiments should be reported clearly and conducted according to published best practices, allowing results to be collated for data transparency (OA-ICC, 2023) and metadata analyses. The production of a guide to best practices for ocean alkalinity enhancement (Oschlies et al., 2023), with input many GOA-ON members, is a positive step toward creating a coordinated research effort. While there is an understandable need to focus on key marine organisms for experimental purposes, understanding the consequences of any ecosystem-scale impacts is more complex and ties into the need to co-develop modeling and monitoring processes. Determining these complex interactions exemplifies the need for a community approach to consider impacts from multiple angles using multiple techniques.

Organisms are exposed to multiple stressors, and changes in carbonate chemistry can act with other variables synergistically, additively, or antagonistically (Secretariat of the Convention on Biological Diversity, 2014). For mCDR research, key questions in preparation for experimentation will be whether to test impacts individually or in combination with other stressors, which can be informed by the existing body of OA research, such as that developed by the SCOR Changing Ocean Biological Systems working group.

Finally, the biology working group of GOA-ON has developed a conceptual framework for the biological monitoring needed to be able to attribute observed changes in the field to OA (Widdicombe et al., 2023). In addition to the GOA-ON biological working group, a number of other groups are looking at establishing biological indicators for OA (e.g., Bednaršek et al., 2019). These activities are useful to consider for mCDR, in particular for identifying potentially vulnerable species, which can then be mapped to determine where they may be at risk of impact or benefit from mCDR. For instance, for environmental MRV, considering specific biological indicators that are known to respond to changes in carbonate chemistry could be useful for monitoring impact at mCDR field trials (and if mCDR techniques are scaled).

GOA-ON GOAL 3: DATA AND KNOWLEDGE EXCHANGE TO OPTIMIZE MODELING

GOA-ON's third goal emphasizes the importance of data sharing and collaboration to improve modeling efforts. The network facilitates the exchange of knowledge between observational, experimental, and modeling scientists, as well as their access to data, to enable the development of more accurate and comprehensive models that can both hindcast and project the future trajectory of OA, and to investigate its effects on marine ecosystems.

GOAL 3 LESSONS LEARNED RELEVANT TO mCDR AND CURRENT STATUS OF PRODUCTS AND MODELING EFFORTS

The collective OA knowledge gained through observing systems and experimental studies encompasses critical and necessary preliminary steps toward informing, improving, and validating models as well as toward developing products that can be used beyond the scientific community. For instance, increased understanding together with accumulation of data has allowed the development of empirical relationships for estimating DIC and alkalinity (e.g., Fassbender et al., 2017; Land et al., 2019; Carter et al., 2021), and for creating climatologies of OA-relevant parameters across the global ocean (e.g., J. Jiang et al., 2023). More recently, machine learning and AI are aiding the development of new products that can derive OA-relevant parameters from in situ and remote sensing observations (e.g., Gregor et al., 2024). These products are being made available in various forms (Box 2), including netCDF (e.g., Gregor and Gruber, 2021), static maps (e.g., L.Q. Jiang et al., 2022), visualization platforms (e.g., the OceanDataLab acidification platform), and the #OceanAcidificationStripes website.

In addition to these data products, available numerical models that complement observation-based expertise can track biological and biogeochemical interactions and predict a range of potential OA trajectories (Boyd et al., 2023). The GOA-ON community has critically invested in these developments, including by publishing best practices for parameterizing marine carbonate chemistry (Orr et al., 2018; Carter et al., 2021). Both global (including Earth system, e.g., Palmiéri and Yool, 2024) and regional (e.g., Artioli et al., 2014, 2012) implementations demonstrate reasonable skill and deliver predictive capabilities. These models are widely used to assess impacts of OA on both scientific and policy levels, for example, in reports for the IPCC (IPCC, 2021), such national and regional bodies as OSPAR[1] (McGovern et al., 2023), or the UK Marine Climate Change Impacts Partnership (Findlay et al., 2025). However, numerical models are limited by their parameterization and vary in sophistication due to necessarily simplified marine biogeochemistry and ecosystem descriptions (Fennel

[1] The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") was open for signature at the Ministerial Meeting of the Oslo and Paris Commissions in Paris on September 22, 1992. See https://www.ospar.org/convention.

BOX 2. mCDR-RELEVANT OCEAN ACIDIFICATION RESOURCES

- **Global Ocean Acidification Observing Network (GOA-ON)**
  (see also https://www.goa-on.org/news/news.php)
- **Surface Ocean CO_2 Atlas (SOCAT)**
- **Global Ocean Data Analysis Project (GLODAP)**
- **International Ocean Carbon Coordination Project (IOCCP)**
- **International Atomic Energy Agency (IAEA) Ocean Acidification International Coordination Centre (OA-ICC)**
- **Intergovernmental Oceanographic Commission (IOC-UNESCO)**
- **Global Ocean Observing System (GOOS)**
- **Scientific Committee on Ocean Research (SCOR)**
- **International Carbon Ocean Network for Early Career (ICONEC)**
- **GOA-ON data explorer**
- **NOAA Ocean Carbon Acidification Data System (OCADS)**
- **UN Sustainable Development Goal (SDG) 14.3.1 data portal**
- **IOCCP hardware directory**
- **OA-ICC bibliographic database**
- **OA-ICC portal for OA biological response data**
- **SCOR Changing Ocean Biological Systems (COBS) Working Group**
- **GOA-ON Biology Working Group**
- **GOA-ON mCDR Working Group**
- **Global Surface Ocean Acidification Indicators**
  (L.Q. Jiang et al., 2022)
- **OceanSODA-ETHZ data product**
  (Gregor and Gruber, 2022)
- **Ocean Data Lab (ODL) Ocean Health – Ocean Acidification portal**
- **#OceanAcidificationStripes**
- **SCOR MarChemSpec Working Group**
- **GOA-ON Pier2Peer program**
- **GOA-ON in a Box kits**
- **Example GOA-ON and IAEA OA-ICC training event**
- **OceanTeacher Global Academy (OTGA) OA course**
- **Ocean Acidification Research for Sustainability (OARS) Programme**
  (see also https://www.goa-on.org/oars/overview.php)

et al., 2023), as well as incomplete understanding of the carbonate pump in Earth system models (Planchat et al., 2023).

Some model approaches go beyond biogeochemistry and attempt to model impacts on species and ecosystems. However, the complexity and uncertainty of responses to OA, coupled with lack of representation of biodiversity in numerical models, make them generally less certain, but still informative. For instance, pelagic calcification is included in several models as a back-calculation from particulate organic carbon production (e.g., Aumont et al., 2015; Yool et al., 2015). Few models explicitly represent calcifying plankton functional types (e.g., Krumhardt et al., 2019), and the benthos is usually represented in a very simple manner focused on the recycling of organic matter into nutrients and CO_2. Feedbacks on pelagic carbonate systems are represented in some models (e.g., DIC and TA fluxes associated with remineralization of organic matter), but benthic calcification is not usually represented.

The implementation of these coupled physical-biogeochemical-ecosystem models has allowed identification of further areas of uncertainty that require both deeper understanding of processes and further model development to improve the representation of the carbonate chemistry system. For example, improving representation of freshwater input of DIC and TA and providing better constraint of the continuous representation of the carbonate system along the salinity gradient are particularly important for simulating the spatial and temporal variability in coastal environments. Including the impact of sediment processes on carbonate chemistry dynamics is similarly important for reducing uncertainty in the coastal environment.

HOW GOAL 3 SUPPORTS mCDR

Data and knowledge synthesis for use in products and models is essential for mCDR. Before deployment (i.e., in the research stage), they are needed to predict feasibility, scalability, efficiency, ecosystem response, and impact, and thereby to support decision-making to optimize mCDR approaches. If the mCDR activities are taken forward beyond the research and development stage to deployment (i.e., field trials and commercialization), these tools are needed to evaluate MRV, carbon accounting, and environmental monitoring, therefore supporting the regulation and implementation of safe and sustainable practices.

The spatial and temporal scales over which mCDR may ultimately be deployed may be very large, making observational monitoring potentially (even prohibitively) expensive. A joint model-observation approach to MRV is therefore recommended, especially to assess alterations to ecosystems that may be too small to measure observationally. Uncertainties associated with both models and observations will still limit accurate prediction (Bach et al., 2023) and provide challenges for governance and social license to operate, thus requiring interdisciplinary, collaborative approaches.

Models that already incorporate carbonate chemistry and biological response provide the foundation for the mCDR community to build upon. However, some of the mCDR methods could push the chemical composition of seawater outside of the normal range and therefore could require a more detailed approach like the one developed in the SCOR working group Modelling Chemical Speciation in Seawater to Meet 21st Century Needs (MarChemSpec; Clegg et al., 2023). In relation to OA, models can help to predict how different mCDR strategies will interact with OA processes and ultimately whether they will result in long-term benefits or result in disruptions to marine ecosystems.

Models provide a reliable basis for assessing the long-term effectiveness of upscaled CDR as governed by macroscale hydrodynamics and the biological pump, which operate on decadal to millennial timescales. While large-scale approaches provide the climate context for mCDR impacts and benefits, the efficacy and impacts of mCDR at local to regional scales can only be conveyed through higher-resolution and local-scale modeling. Such models often have sub-kilometer resolution and can be adapted to address individual or clusters of CDR deployments, assessing environmental impact, dispersion of chemical and biological particles and plumes, local sequestration, and export. These models will require validation studies to demonstrate that they are fit-for-purpose, and local model approaches will need to be site-specific (Khangaonkar et al., 2024).

Modeling is already offering a holistic picture of different mCDR deployment scenarios; for example, regional simulations (Wang et al., 2023) and century-long simulations (González and Ilyina, 2016) show artificial OAE can effectively remove atmospheric CO_2 and alleviate OA. However, emissions-driven Earth system modeling demonstrates that an abrupt ending of OAE might act to accelerate OA and atmospheric warming, thus threatening vulnerable ecosystems that are struggling to adapt to existing environmental pressures (González et al., 2018).

The community has already made critical investments in ocean biogeochemical and ecosystem models. Such models are crucial for simulating present-day and future predictions of mCDR impacts and ecosystem consequences. Better understanding of the implications of greenhouse gas emissions and CDR for the coupled carbon climate system is essential for providing reliable guidance to policymakers and other stakeholders. While such global-scale approaches provide the climate context for CDR impacts, answering questions about the effectiveness and ecosystem impacts of local to regional-scale CDR approaches may require both higher-resolution and regional-scale modeling as well as incorporation of additional modeling strategies. These tools will allow the combination of CDR scenario assessment, detection, and attribution; observation system simulation; and process studies to increase understanding and inform sound management decision-making.

GOA-ON'S NETWORK AND CAPACITY

GOA-ON has fostered collaboration among researchers, Indigenous Peoples, local communities, the wider public, and policymakers. The network allows for diverse expertise in areas such as oceanography, biology, climate, policy, law, Indigenous knowledge, and social science to converge, leading to more holistic and regionally tailored mCDR application. Capacity building has been a core pillar of GOA-ON, and a recent publication highlights the lessons learned, the increasing need for capacity, and a vision for the future (Newton et al., 2025). GOA-ON also serves as an example of an independent body that drives broader OA engagement; a similar entity has been called for within the mCDR community to lead broad scientific engagement that is fully independent in its research, but engaged with all relevant interested parties (Nawaz et al., 2024).

The OA community, supported by intergovernmental bodies (e.g., IAEA OA-ICC, IOC-UNESCO), nonprofits (e.g., The Ocean Foundation), and government agencies, has been advancing global capacity and supporting the development of early career ocean professionals (ECOPs) by providing training at multiple technical levels, equipment, approachable methodologies, networking, and research support (Lang et al., 2024; Dupont et al., 2025; Kitch et al., 2025; Newton et al., 2025; Valauri-Orton et al., 2025). For example, the GOA-ON Pier2Peer program allows ECOPs from anywhere in the world to apply for mentoring in OA. GOA-ON in a Box kits (Valauri-Orton et al., 2025) were specifically designed to allow scientists from lesser-resourced regions to initiate OA monitoring activities that often comprise the first efforts in their countries. GOA-ON scientists teach best practices through worldwide workshops hosted in well-resourced countries as well as in targeted locations, often using regional partners, and virtually and online through the Ocean Teacher Global Academy course on OA.

The emergence of interest in mCDR from both nongovernmental (e.g., Ocean Visions, Carbon to Sea) and philanthropic (e.g., Ocean Resilience and Climate Alliance, or ORCA) organizations could provide a basis for developing these efforts. A similar capacity-building strategy, learning from efforts in OA, would benefit mCDR by preparing scientists with the skills and knowledge needed to implement, monitor, and evaluate the effects of mCDR approaches in diverse oceanic contexts. Consistent data collection and analysis across various ecosystems, made possible through a well-equipped and trained global network, as well as standardized measurement methodologies and data sharing, would ensure that mCDR research is comparable and reliable across different regions, facilitating the development of robust mCDR guidelines and practices that can be scaled globally. Given the global scale of mCDR that will be required to achieve relevant levels of carbon removal, tailored capacity building efforts will help ensure equitability so that researchers along every coastline have the resources to assess proposed projects and contribute to the growing body of knowledge in the mCDR field. The IAEA OA-ICC has already expanded its capacity building program to support training in mCDR, recently offering a training course in "Ocean Alkalinity Enhancement—Assessing the Impacts on Marine Organisms" (Monaco, April 2025). Led by several GOA-ON experts, the course built on best practices and lessons learned from OA research adapted to OAE, notably on experimental design.

For any mCDR activity, involvement of local communities is required to assess potential ecosystem impacts, conflicts, or opportunities with local industry (e.g., Grabb et al., 2025) and infrastructure, and socioeconomic spin-offs for the local communities. Engagement with local communities is critically important through initiatives involving communication, education, outreach, and co-design. Globally, the OA community recognizes that co-developed strategies are key for reef restoration, fisheries resilience, nature-based projects, carbon strategies, pollution control, and climate-responsive planning (Dobson et al., 2023; IOC-UNESCO, 2024).

Transparent data and information reporting, particularly with respect to successes and pitfalls, are essential in order to maximize the potential for significant progress and ongoing social license in this field. Carefully designed efforts to encourage strong collaboration and cooperation will help ensure that the critical components of mCDR approaches, such as MRV and environmental impact assessment, are optimized. The recently established GOA-ON mCDR working group will play a key role in bringing these research areas together, helping to ensure that data and lessons learned from OA will inform mCDR research.

CONCLUSIONS

GOA-ON's three high-level goals—understanding global ocean acidification conditions, improving knowledge of ecosystem responses, and optimizing modeling through data and knowledge sharing—are also essential to the development and success of mCDR research. These goals provide the foundational knowledge and tools needed to ensure that mCDR efforts are environmentally responsible, scientifically rigorous, and sustainable over the long term. By contributing to better monitoring of marine carbonate chemistry, ecosystem assessments, and predictive modeling, the GOA-ON community facilitates safe development of mCDR technologies that mitigate climate change while safeguarding marine ecosystems from unintended harm. This makes GOA-ON a vital partner in the global effort to combat both OA and atmospheric CO_2 accumulation.

Key recommendations for mCDR research from the GOA-ON community:

- Acknowledge that achieving precise estimates of changes in the ocean carbon cycle remains difficult and necessitates access to high-quality data and instrumentation, in terms of both precision and accuracy, and requires skilled practitioners.
- Invest in development of accessible, low-cost tools, as well as human resources, to expand carbonate chemistry and biological monitoring globally.

- Develop overall sampling strategies from the ground up, utilizing the best available practices and technologies to respond to changing local conditions while still providing quality results.
- Support high-quality observation platforms that provide historical and ongoing observational context to mCDR activities, including MRV and environmental impact assessments.
- Utilize and leverage existing monitoring platforms for mCDR research, with care not to disrupt long-term "climate" time series.
- Ensure monitoring systems provide highly resolved temporal and spatial variations to determine the relevant changes in physical, chemical, and biological conditions.
- Co-develop biological indicators with both OA and mCDR applications in mind.
- Encourage chemists and biologists to co-design mCDR research to facilitate the understanding of environmental impacts and monitoring requirements.
- Make data visualizations available in as near-real time as possible so that sampling efforts can be modified as needed to meet the needs of field trials.
- Use existing data archive centers for both carbon and biological data to contribute to open-access data sharing.
- Recognize that data management and quality assurance are important contributions to mCDR: utilize existing best practices, provide metadata, and use quality assurance practices.
- Capitalize on modeling tools and expertise that have already been developed across the necessary spatial scales.
- Provide local communities with opportunities to contribute to monitoring their regions, allowing them to be informed and involved in planning decisions.
- Collaborate across communities—co-develop mCDR research with a range of interested parties from the beginning.

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