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Quo Vadimus

The importance of engagement with fisheries, aquaculture, and Indigenous communities in the planning and implementation of marine carbon dioxide removal (mCDR)

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Abstract

As climate change continues to increase in severity, the window of time available to achieve climate stabilization decreases. In addition to reducing emissions, climate solutions such as marine carbon dioxide removal (mCDR) are being considered. If mCDR is to scale from research to implementation it will impact various sectors including fisheries and aquaculture. Well-coordinated, co-developed deployments along with meaningful and early engagement between the mCDR and fisheries, aquaculture, and Indigenous communities can maximize opportunities to avert zero-sum trade-offs and increase the potential for mutually beneficial synergies between the various groups. Limited engagement with fisheries, aquaculture, and Indigenous communities may enhance the likelihood of community opposition, misinformation, potential ecosystem harm, and/or difficulty in weighing cost-benefits of mCDR approaches. At this early stage of research and development, mCDR initiatives can learn from other sectors and existing networks about best practices for engagement; however, this effort requires prioritization of intentional conversations. This perspective paper offers a brief overview of mCDR overlaps with fisheries and aquaculture, followed by insights about the current state of mCDR engagement with fisheries, aquaculture, and Indigenous communities. From our perspective as an interdisciplinary co-authorship team including members from academic and government sciences, Indigenous communities, and commercial fishing communities, we offer the following high-level recommendations for engagement across mCDR and fisheries, aquaculture, and Indigenous communities that are based on lessons learned in other sectors and research areas: synthesize and expand current state of knowledge; conduct early and meaningful engagement; leverage existing networks; establish strong interdisciplinary collaboration; co-design projects with communities; and develop frameworks and best practice guides.

Keywords: mCDR; carbon drawdown; emerging industry; coordination; ocean climate solutions; co-design science; inter-sectoral

Introduction

Fisheries and aquaculture globally support a thriving marine economy for many coastal communities. Eighty-nine % of fishery and aquaculture harvests are used for direct human consumption, contributing 15% of animal proteins and six % of total proteins to diets worldwide (FAO 2024). While food systems as a whole are responsible for about a third of global greenhouse gas emissions (Crippa et al. 2021), wild seafood and farmed shellfish generally have a low carbon footprint relative to land-based protein and farmed finfish (Hilborn et al. 2018). Consequently, sustaining seafood production can be seen as an important societal objective for the sake of the food and climate systems as well as from the vantage point of supporting fisheries and aquaculture. Fisheries and aquaculture are a major source of employment within the marine sector (in 2022 an estimated 61.8 million people were engaged in commercial fisheries, FAO 2024) and coastal communities depend on fishing and seafood for income, recreation, and cultural continuity. Climate change impacts, including ocean warming and ocean acidification, will affect the health of marine ecosystems, fisheries, and aquaculture if carbon dioxide (CO_2) emissions are not drastically reduced.

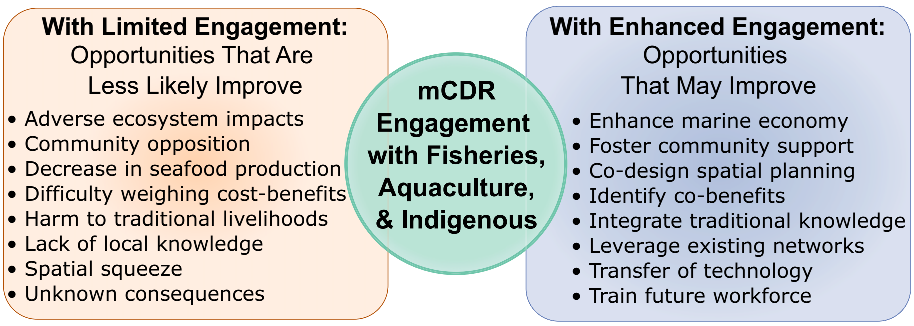

Figure 1. Diagram displaying opportunities that may be impacted by engagement between the mCDR and fisheries, aquaculture, and Indigenous communities. This figure highlights potential situations that are less likely to improve if engagement is limited (left box), compared to potential opportunities that may improve if there is enhanced engagement (right box). These opportunities are not comprehensive or a guaranteed outcome from engagement with the fisheries and aquaculture communities.

Climate solutions such as carbon dioxide removal (CDR) are now gaining interest alongside necessary greenhouse gas emissions reductions (IPCC 2023). Marine CDR (mCDR) utilizes the ocean's vast natural capacity to draw down CO_2 from the atmosphere and lock it away for climate-relevant timescales; ideally 1000 years or more (Brunner et al. 2024) (See "Current state of mCDR and potential overlaps with fisheries and aquaculture" section for additional details). Ideally, carbon removal is not a substitute, but rather a complement to emissions reductions, and it is possible that mCDR may do more harm than good if emissions are not drastically reduced (Nawaz et al. 2024a). Pilot and research-scale mCDR projects are currently being led by academic, government, non-governmental, and private industry entities, and the transition of mCDR from a research to commercial development phase has potential to be a part of a larger energy transition portfolio (Smith et al. 2024). If mCDR is effective, fisheries, aquaculture, and Indigenous communities (as well as the rest of the planet) could experience positive effects of mCDR's climate change mitigation for decades to come through the reduction of threats from rising temperatures, deoxygenation, and acidification. However, as mCDR technologies scale, fisheries are increasingly likely to experience a mixed bag of neutral, positive, and/or negative impacts, some of which may further exacerbate climate change pressures on ecosystems (Tagliabue et al. 2023).

mCDR deployments co-developed through meaningful engagement with researchers, fisheries representatives, local and Indigenous communities, and resource managers have a higher likelihood of considering and preemptively addressing potential benefits and risks. Engagement includes structured interactions between decision makers and potentially affected parties, with explicit attention to power, representation, and reciprocity (IAP2 2024, See *Terminology and Phrases Box*). Decision makers can be public or private actors, and engagement can take place at any level of decision making, from project-specific planning to the setting of national and international policies. Projects that properly engage are more likely to reduce potential conflicts before they might arise, while supporting enhanced marine economies, co-design of spatial planning, and integration of traditional knowledge (Fig. 1). The absence of genuine engagement may increase the likelihood of community opposition to mCDR deployments, potential harm to ecosystems on which traditional livelihoods depend, lack of access to local baseline knowledge and data, and difficulty in weighing the costs and benefits of mCDR approaches (Fig. 1).

From our perspective as an interdisciplinary co-authorship team including members(s) from academic and government sciences, Indigenous communities, and commercial fishing communities, we explore how fisheries (including Indigenous fisheries) and aquaculture communities, as key historical users of coastal and ocean spaces, can be included now in the research stage to enhance and benefit from mCDR and help support informed decision making about planning and potential large-scale implementation. This can help identify benefits and minimize risks for most coastal users. Here, we present a brief overview of mCDR and overlaps with fisheries, aquaculture, and Indigenous communities, including the current status of engagement. We conclude with high-level recommendations for engagement based on lessons learned from economic sectors, like offshore wind and oil and gas, and other scientific disciplines, such as ocean acidification (OA) research (Arbo and Thuy 2016; Pol and Ford 2020, Findlay et al. 2025). These recommendations include:

1. Synthesize and expand current state of knowledge related to fisheries and aquaculture
2. Conduct early and meaningful engagement with transparent collaboration
3. Leverage existing networks
4. Establish strong interdisciplinary collaboration with communication conduits
5. Co-design projects with local and Indigenous fisheries
6. Develop targeted engagement frameworks and best practice guides

While many of the concepts presented here can be applied to other climate solutions, general CDR, and other ocean-based sectors, we focus this manuscript on mCDR specifically and engagement with fisheries, aquaculture, and Indigenous communities, given the relevant connection between mCDR and these communities through marine systems.

Current state of mCDR and potential overlaps with fisheries and aquaculture

What is mCDR?

mCDR approaches aim to decrease atmospheric and/or surface ocean CO_2 concentrations and enhance the ocean's natural absorption of CO_2 by either altering the ocean's biologi-

Terminology and phrases box:

Below are terms and phrases that we use throughout the paper. While these terms can have many meanings and applications, we define them here for use within this manuscript. Overall, we treat communities, such as the mCDR, industry, fisheries, and aquaculture communities, as composed of self-identifying actors. It is important to remember that these communities and their representatives are heterogenous, fluid, and non-exclusive with diverse opinions, priorities, and approaches. Therefore, we refer to these communities and their representatives from a high-level, which will require interpretation for specific situations, taking into account community composition and local nuances.

- **Engagement**: Includes structured interactions between decision makers and potentially affected parties, with explicit attention to power, representation, and reciprocity (IAP2 2024). Decision makers can be public or private actors, and engagement can take place at any level of decision making, from project-specific planning to the setting of national and international policies (Fig. 2).
- **mCDR community**: Practitioners and entities that engage in mCDR research, development, and other related activities. This may include actors from academia, government, industry, non-profits, and other entities engaging in mCDR activities.
- **Fisheries and aquaculture community**: Fishers, farmers, managers, representatives, and other actors who depend on fishing or aquaculture for their social, economic or nutritional needs. This may include industrial, recreational, and Traditional fishers and farmers as well as those that identify with these groups.
- **Indigenous community**: Following the UN-system body, a specific definition has not been adopted for "Indigenous," but a modern understanding of the term is based on the following (UN 2025):
    - Self-identification as indigenous peoples at the individual level and accepted by the community as their member.
    - Historical continuity with pre-colonial and or pre-settler societies
    - Strong links to territories and surrounding natural resources
    - Distinct social, economic and political system
    - Distinct language, culture and beliefs
    - Form non-dominant groups of society
    - Resolve to maintain and reproduce their ancestral environments and systems as distinctive peoples and communities
- **mCDR Industry**: Actors or entities that are gaining, or will gain, direct profit from goods or services, such as the removal, or potential future removal, of carbon.
- **Social license**: While social license is not universally defined, here we adopt the definition from Kelly et al. 2017 as "an unwritten social contract" that reflects opinions and expectations of the broader community on the impacts and benefits of industry and government practices.
- **Mitigation deterrence**: Broadly defined as "the prospect of reduced or delayed mitigation resulting from the introduction or consideration of another climate intervention," such as the introduction of mCDR (Markusson et al. 2018)

cal processes (e.g. macroalgal cultivation and sinking; nutrient fertilization including artificial upwelling/downwelling) or inorganic processes (e.g. ocean alkalinity enhancement, OAE; direct ocean carbon capture and storage, DOCCS) (NASEM 2022). Here we provide a high-level introduction to some of the most commonly considered mCDR techniques that are considered to have potential to remove carbon at scale (Cross et al. 2023, NASEM 2022, Smith et al. 2024). For more in depth information about the techniques' methodology and current knowledge about the feasibility, advantages, and challenges, references are included. For biological methods, CO_2 in surface waters is taken up by increasing photosynthetic processes during micro/macroalgae production, which can be enhanced with nutrient fertilization or artificial upwelling (Cross et al. 2023, NASEM 2022). For mCDR efforts to be successful, the biomass produced during these processes then has to be durably stored, with suggestions for such storage being the deep ocean (Cross et al. 2023, NASEM 2022). OAE removes CO_2 by increasing total alkalinity (through mineral, chemical, or electrochemical processes), which converts CO_2 into carbonate and bicarbonate ions (Oschlies et al. 2023, Cross et al. 2023, NASEM 2022, Bach et al. 2019). DOCCS directly removes CO_2 from seawater through membranes or by altering pH, then returning CO_2-depleted seawater back to the natural source (Cross et al. 2023, NASEM 2022, Digdaya et al. 2020) and allowing the ocean to take up more CO_2 from the atmosphere. Emerging research is investigating mCDR techniques' carbon removal and storage potential as well as possible biological and ecosystem co-benefits and adverse impacts.

Scaling up from research to climate-relevant scales

Alongside steep emissions reductions, the amount of terrestrial and marine CDR necessary to achieve Paris Agreement climate goals (i.e. limit warming below 2 degrees Celsius) is projected to be an order of magnitude more than the current natural ocean sink (10 Gt CO_2 per year) by 2050, and would require an increase to about 1.7x the current ocean sink (17 Gt CO_2 per year) by 2100 (Smith et al. 2024). Accomplishing CDR to this scale requires utilizing a diverse portfolio of approaches, including novel land- and marine-based methods. The ocean will need to play a significant role in this portfolio approach, given that there are limitations on sustainably scaling many land-based techniques (Deprez et al. 2024). At present, marine approaches are at a lower technology readiness level than many land-based CDR approaches (Cross et al. 2023, Agbo et al. 2024), which presents challenges, as well as tremendous opportunity for existing marine sectors to inform and help shape research and development of the emerging mCDR field in an accountable manner.

Effective foundational research is critical given the economic potential of the carbon removal industry. In recent years, the voluntary carbon market has seen annual transactions of nearly US$2 billion, although scrutiny of decarbonization methods is increasing, thus pushing emerging CDR techniques, such as mCDR, to have higher standards to safely and durably remove carbon in a verifiable manner (Chu et al. 2024, Carbon Direct 2025). While uncertainties related to efficiency, durability, scalability, and environmental impacts of mCDR remain, evaluations indicate a growing global market demand for durable and verifiable CDR equating to anywhere between US$10 to US$135 billion depending on a number of factors including the price of carbon, commitment of investors, and developments in compulsory markets (Mistry et al. 2023). This large variability in price is driven by policy uncertainties at multiple political scales, and also closely intertwined with technical uncertainties in carbon removal efficiencies, possible environmental impacts, durability of storage, and ability to verify the carbon removed, which are necessary aspects to investigate through pilot and research-scale projects.

A current key objective of the mCDR field is to conduct research to inform future implementation decisions regarding climate-relevant mCDR. Field trials are moving forward (Ocean Visions 2025), yet it is likely that other ocean-based sectors, such as fisheries and aquaculture, ocean renewable energies, and shipping, are likely to be impacted as mCDR scales (Roberts et al. 2024, in review). Because mCDR only provides meaningful climate mitigation at larger scales (see *Potential footprint of climate relevant scale mCDR* Section), considering the possibility for expansion in the number of research-scale projects and/or industrial-scale developments during these early stages provides opportunities to address community concerns about future deployment as well as near-term research activities. Engagement with communities by projects at all scales is important since community impacts and attitudes towards mCDR may change in nonlinear ways as mCDR scales. For example, research has shown that public acceptance for OAE is more favorable for small scale, modular, and community-owned projects (Nawaz et al. 2024a, Cox et al. 2024), and it cannot be assumed that relationships of goodwill established in the course of a small-scale project will carry over to larger scale deployments.

Frameworks to guide responsible, effective, and safe research that adequately accounts for possible environmental and social impacts for mCDR research, including codes of conduct and best practice guides (Aspen Institute 2023, Lebling et al. 2022, Ocean Conservancy et al. 2023, Oschiles et al. 2023, Satterfield et al. 2023), have been developed by mCDR practitioners and observers. These sources emphasize the need for inclusive decision making processes, meaningful engagement of affected communities, and the need to conscientiously address imbalances in power, resources, economic benefits, knowledge, and capacity that could undermine the goals of effective engagement. While these frameworks are a useful start, some emerging efforts (e.g. International Council for the Exploration of the Sea, ICES, Themed Set on mCDR and Fisheries: *mCDR and its interactions with ecosystems, fisheries and aquaculture*, 2025-2026) aim to address the need to develop accessible frameworks that are tailored for practitioner-focused resources (i.e. for fisheries and aquaculture communities) that draw from the environmental social sciences to specifically address the unique ethical and social challenges of mCDR development. Recognizing the gap in practitioner-focused resources centered on the fisheries and aquaculture communities in mCDR, a fishing industry-led project in the U.S. is currently working to develop guidance memos on: (1) the involvement of fishermen as co-producers of knowledge in an mCDR context, (2) core elements of fishery-sensitive mCDR governance, and (3) best practices for engaging the fishing community (NOAA OAP 2025a, Fishery Friendly Climate Action Campaign, 2025).

Although it is beyond the scope of this manuscript, in addition to engaging with communities, it is also critical for pilot and research-scale projects to conduct full life-cycle analysis (LCA) for any project proposed to be conducted at scale. LCA can include considerations related to ecosystem impacts, energy use, feedstock generation and production, byproduct generation, physical footprint, and coastal community influences (Bauer et al. 2024).

Potential footprint of climate relevant scale mCDR

Research and pilot stage mCDR projects may be able to co-locate with existing infrastructure (e.g. desalination, wastewater treatment, etc.), occupy space for a short amount of time, and/or use renewable energy to minimize project footprint. However, previous studies have estimated relatively high amounts of energy, space, and other resource demands for some scaled mCDR approaches for climate-relevant removal of one Gt CO_2 per year, which is 10% of global CDR targets by 2050 (Caserini et al. 2021, NASEM 2022, Yao et al. 2025). For example, at climate-relevant scales, growing macroalgae and sinking it in the deep ocean is estimated to require an area of kelp production equivalent to a 1 km wide swath along 63% of the global coastline (NASEM 2022). Comparably, methods of OAE that use mineral addition require substantial volumes of minerals to be dispersed on or near the ocean (NASEM 2022), thus significantly increasing shipping demands for dispersal and mining demands for minerals (Caserini et al. 2021). Current electrochemical techniques at scale would use ~2 000 TWH/yr (NASEM 2022), which is ~50% of the current total U.S. electricity production, or ~twice the total U.S. renewable energy production in 2023 (U.S. EIA 2025). Total resource demands are hard to predict at present, could vary substantially across projects and mCDR techniques, and may shift as different techniques are used separately or in combination to remove various amounts of CO_2 within the climate mitigation portfolio. Projecting potential resource demands for individual projects at scale early in the planning process can help prepare for and mitigate potential conflicts, such as spatial squeeze.

Although there have only been a few research-scale mCDR field trials executed, they have received mixed reactions from local communities (Nawaz and Belotti 2025). Therefore, projects considering climate-relevant scales would benefit from deliberate coordination and responsible planning with other marine users to minimize their impacts on current marine-based industries and communities, such as those interacting with fisheries and aquaculture (Chollett et al. 2022). Considering the potential scale of climate-relevant mCDR deployment, purposeful coordination can minimize spatial impacts through co-location and coordination of strategic geographic and temporal choices. The potential to co-locate

Table 1. Potential climate and ecosystem co-benefits and adverse impacts (indicated in white and black, respectively at the top of the columns, with those that could either be benefits or impacts indicated in grey) related to fisheries and aquaculture.

mCDR Technique	Potential Climate Mitigation ($Gt\ CO_2$/year)a	Ocean Acidification Mitigation	Co-location Potential	Direct Carbonate Chemistry Alteration	Fertilization/ Alteration of Primary Production	Habitat Alteration	New Infrastructure Needs	Direct Entrainment/ Mortality	High Energy Requirements	Increased Ship Traffic	Introduced Species	Nutrient Robbing	Potential for Ecotoxicity	Spatial Competition with Fisheries/Aquaculture
Artificial Downwelling	0.1-1	Low Potential	High Potential	High Potential	High Potential	High Potential	High Potential	High Potential	High Potential	Low Potential	High Potential	High Potential	Low Potential	High Potential
Artificial Upwelling	0.1-1	Potential to exacerbate	High Potential	High Potential	High Potential	High Potential	High Potential	High Potential	High Potential	Low Potential	High Potential	High Potential	Low Potential	High Potential
Direct Ocean Carbon Capture and Storage (DOCCS)	1-10	Local, short-term	High Potential	High Potential	Unknown	High Potential	High Potential	High Potential	High Potential	Low Potential	Low Potential	Low Potential	Low Potential	Low (*shore-based*) High (*otherwise*)
Macroalgae Cultivation and Sinking	0.1-0.6	Local, short-term (*shallow*) Potential to exacerbate (*depth*)	High Potential	High Potential	High Potential	High Potential	High Potential	Low Potential	Low Potential	High Potential	High Potential	High Potential	Low Potential	High Potential
Ocean Alkalinity Enhancement (OAE): Electrochemical Methods	1-15+	Local, short-term	High Potential	High Potential	Unknown	High Potential	High Potential	High Potential	High Potential	High Potential	Low Potential	Low Potential	High Potential	Low (*shore-based*) High (*otherwise*)
Ocean Alkalinity Enhancement (OAE): Mineral Methods	1-15+	Local, short-term	Low Potential	High Potential	High Potential	High Potential	High Potential	Low Potential	High Potential	High Potential	Low Potential	Low Potential	High Potential	Low (*between deployment*) High (*during deployment*)
Ocean Nutrient Fertilization	0.1-1+	Local, short-term (*shallow*) Potential to exacerbate (*depth*)	Low Potential	High Potential	High Potential	High Potential	High Potential	Low Potential	High Potential	High Potential	Low Potential	High Potential	High Potential	Low (*between deployment*) High (*during deployment*)

The co-benefits and adverse impacts are displayed for various mCDR techniques (indicated in light grey on the left side of the rows) as predicted for projects at scale and for full life-cycle. For example, "potential climate mitigation" refers to the potential Gt of CO2 that is predicted to be removed by each technique. The "co-location potential" refers to the potential for techniques to be located alongside other mCDR techniques and/or marine uses. "Habitat alteration" is a term that refers to a wide number of processes, including shading from structures and/or biomass, ecosystem recovery, physical effects of mineral dispersion, etc. "Spatial competition with fisheries/aquaculture" refers to a broad number of ways that the technique could occupy space and/or establish permanent or semi-permanent obstacles that could compete with fisheries and aquaculture uses. The color shading of the boxes indicates the current research knowledge (less current knowledge in light blue and more current knowledge in dark blue). Orange "Unknown" boxes indicate that there is not enough knowledge to indicate "High Potential" (dark green text) or "Low Potential" (dark pink text). Information in the table is adapted from NASEM 2022 and Cross et al. 2023 and updated based on current state of knowledge.

activities is an option for some techniques and requires enabling conditions and planning, such as co-design with other industries (i.e. fisheries and aquaculture), adaptive management, and social license (See *Terminology and Phrases Box*), which are often regionally dependent (Hooper et al. 2021). Other techniques may only occupy areas of the ocean during select time periods for deployment (i.e. ship-based methods) and would hence be faced with different challenges. Some approaches are also likely to utilize the high seas beyond exclusive economic zones (EEZ), which will likely require following additional international treaties. Other general mCDR implementation challenges include operating emissions, infrastructure, energy demands as well as land-based support, resources, and personnel, thus intersecting with communities and other industries nearby and throughout the supply chain. These space- and resource-use considerations are heterogeneous across projects and would likely be evaluated during regulatory processes (details of which are beyond the scope of this paper and likely to be expanded upon in the ICES *Themed Set on mCDR and Fisheries*, 2025-2026), yet their consideration has previously been limited in other ocean-climate solution sectors such as offshore wind (Bonsu et al. 2024).

Potential fisheries and aquaculture responses to mCDR

By integrating fisheries and aquaculture considerations into mCDR planning in the early phases while small-scale field-trials are being designed and considered, projects (in particular, those that may have the potential to grow to climate-relevant scales) are more likely to consider potential risks and benefits of mCDR to the people and communities whose culture, economic stability and livelihoods depend on sustainable marine resources. Moreover, advanced consideration of potential interactions can help reduce tensions between the societal goals of climate mitigation via mCDR and the nutritional security and food sovereignty that are currently supported by fisheries and aquaculture (Fig. 1, Bozuwa and Mulvaney 2023). While emerging frameworks also highlight the interdisciplinary nature of the mCDR field (Cooley et al. 2023, Aspen Institute 2023, Doney et al. 2024), until recently (Roberts et al. 2024 in review; *ICES Themed Set on mCDR and Fisheries*, 2025-2026), there has been a lack of recognition in the overlaps and potential opportunities to collaborate with existing ocean-based industries, such as fisheries and aquaculture.

Given the large number of potential unintended or ancillary ecological impacts of mCDR (Table 1), there is an initial

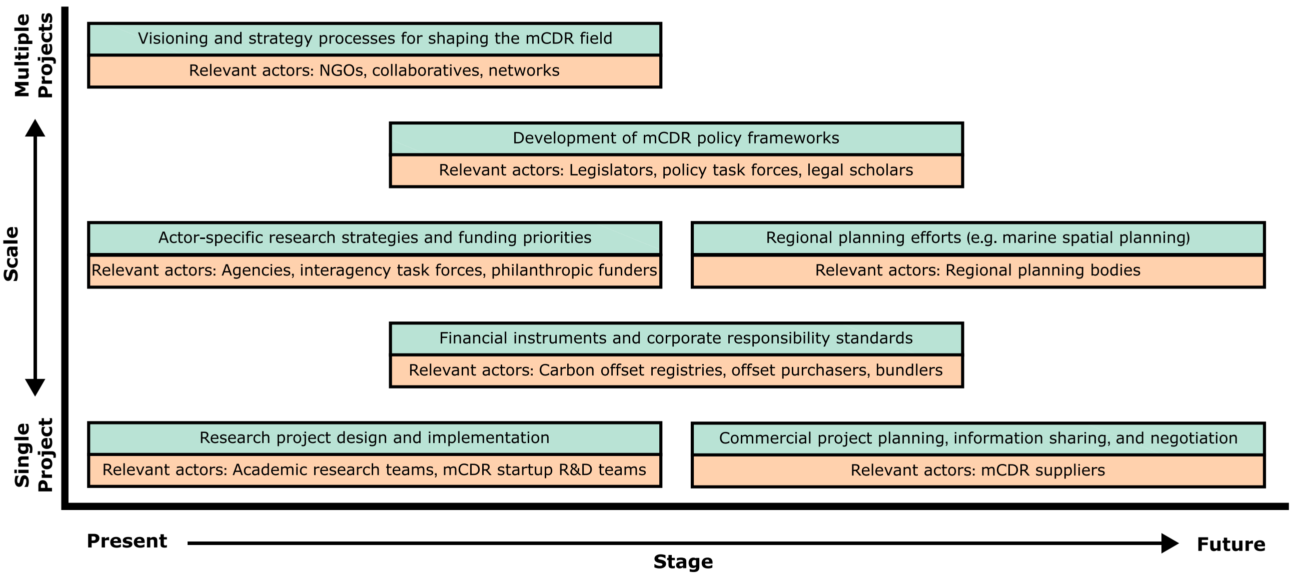

Figure 2. Engagement of members of the fisheries, aquaculture, and Indigenous communities in mCDR-related planning and decision making can take place in many different contexts, from private-sector to public sector, research-scale to commercial-scale, and the micro-scale (e.g. individual mCDR projects) to the macro-scale (e.g. development of mCDR policy frameworks; strategy processes for the mCDR field as a whole). At every stage (x axis) and scale (y axis), there is opportunity to improve outcomes by engaging the fishery and aquaculture communities. This figure presents a typology of opportunities (green upper bar) where engagement can help inform mCDR-related activities, along with relevant actors (orange lower bar) from the mCDR community associated with each engagement context. Members of the fisheries, aquaculture, and Indigenous communities are not shown in the figure because they can engage in any of these opportunities.

perception among some fishers and scientists that fisheries engagement with mCDR will largely focus on harm reduction, and that actual benefits to the fishery will be relatively rare. With this view, fisheries would mostly be playing defense and the best-case-scenario outcome for fisheries would often be “no impact.” Comprehensive risk-benefit analyses have not yet been completed so the reality of this view is unknown, but it is important to acknowledge this potential asymmetry in considering engagement of mCDR and fisheries communities.

As with other forms of CDR, the promotion and development of mCDR has the potential to create “mitigation deterrence" (See *Terminology and Phrases Box*), adversely affecting the willingness and incentive to reduce the burning of fossil fuels due to the risky and false assumption that CDR will mitigate all harm (Markusson et al. 2018, Cooley et al. 2023). The simultaneous deployment of large scale mCDR and continued high emissions of CO_2 would present a poor outcome for fisheries, which would likely incur potential negative effects of mCDR deployment compounded by the negative effects of increased climate change and ocean acidification. In considering large-scale mCDR deployments, mCDR project developers, fisheries, and aquaculture communities would benefit from evaluating risks and benefits in this grander context (Table 1).

Current status of engagement

In this section, we take stock of efforts to-date to involve the fisheries and aquaculture communities in informing mCDR projects and policies. As this overview suggests, there is substantial room to expand and improve the quality of engagement between the mCDR community and existing ocean users (Fig. 2).

One area where engagement can add value is in public sector priority-setting, planning, and policy making related to mCDR, which is especially important at this stage due to the field’s infancy (Fig. 2). For example, in 2024, the United States released a mCDR National Research Strategy that outlined key questions spanning topics from the efficacy of marine approaches to remove carbon (e.g. how long can the ocean hold removed carbon and how much carbon is emitted through operations), to the effects of mCDR on human and marine ecosystems, and the scalability of mCDR approaches (U.S. White House 2024). These questions were informed by input gathered through a structured public comment process with the motivation to understand the efficacy, scalability, and safety towards fisheries, aquaculture, and marine life of various mCDR approaches. The American Geophysical Union (AGU) also conducted extensive outreach and engagement across sectors and interested groups on climate intervention research to guide the development of an Ethical Framework for Climate Interventions (AGU 2024). However, given the nascent stage of the mCDR field, it is difficult to gauge the degree to which fishing and aquaculture community voices weighed into these public engagement processes. At least some fishing industry associations who were aware of the opportunity to comment on the U.S. mCDR National Research Strategy (e.g. Fishery Friendly Climate Action Campaign) did not submit input, due to their limited capacity at the time to understand and articulate key messages related to mCDR (personal communication with co-author S. Schumann).

Much of the engagement, dialogue, and field building around mCDR in recent years has taken place at conferences and gatherings hosted by professional societies like AGU, network-building organizations like Ocean Visions, and regional mCDR research nodes formed to support ongoing knowledge exchange at the international (Surface Ocean Lower Atmosphere Study (SOLAS): https://www.us-ocb.org/solas-mcdr-global-regional-nodes/) and subnational (Ocean Chemistry and Biogeochemistry (OCB): https://www.

us-ocb.org/problem-solving-in-mcdr/) levels. Convenings have overwhelmingly focused on understanding the efficacy of mCDR (e.g. measuring, monitoring, reporting, and verification; MMRV) while the convenings around ecosystem impacts, and in particular those affecting the fishing and aquaculture industries, are just now beginning. Levels of participation by members of the fishery and aquaculture communities in these convenings have been conspicuously low relative to the potential significance of future mCDR activities for these communities (Schumann 2025a). To initiate increased dialogue across mCDR and fisheries and aquaculture communities, in October 2024, an ICES workshop was held on *Assessing/Anticipating the Impact of Marine Carbon Dioxide Removal (mCDR) on Fisheries and Aquaculture Species and Management* with representatives from the mCDR communities, government agencies, and fisheries (ICES WKmCDR 2025a).

Project-level research design and planning represent another venue where deliberation that includes communities affected by mCDR can lead to mutually beneficial outcomes. Self-reported data indicates that between 2021 and 2024 the number of research projects executing mCDR field research has expanded from three to 30 per year, a tenfold increase (Ocean Visions 2025). Even with this increase in mCDR research funding, however, research focused on economically and culturally important species (e.g. shellfish and finfish) that are important to fishery and aquaculture communities is sparse. Moreover, social science research focusing on best practices for engaging the fishing and aquaculture communities has not kept pace with research into the technological effectiveness of mCDR. For instance, in a recent major federal mCDR funding opportunity in the U.S., only 0.4% of total funds were awarded to projects focusing on community engagement for the fishing and aquaculture communities (Schumann 2025a).

One of the first widespread engagement endeavors with the fisheries community at the mCDR project-level was conducted by Woods Hole Oceanographic Institution's LOC-NESS (Locking Ocean Carbon in the Northeast Shelf and Slope) project, which is one of the first initiatives to receive a U.S. federal research permit related to mCDR. While this project did not start engagement at the outset of the project (as suggested by Bozuwa and Mulvaney 2023), they did begin engaging with the fisheries community through existing networks and by hosting conversations and listening sessions throughout the permitting process (Schumann 2024, WHOI LOC-NESS Team 2025). These engagement events included 3 for Tribal communities, 10 for commercial fishing industry members, and 3 for commercial anglers between May 2024 and January 2025, as well as a web survey that was answered by 26 commercial fishers (WHOI LOC-NESS Team, 2025). These interactions helped the LOC-NESS team select a field trial site and incorporate new project elements aimed at capturing additional data on aspects important to fishers, such as impacts of alkalinity enhancement on early life stages of commercially important species (Schumann 2025b). A year into this engagement, a climate initiative led by commercial fishers concluded in its newsletter that "[t]he LOC-NESS project became a canvas on which the fishing industry sketched some initial contours detailing how it would like to be involved in planning and decision-making around OAE and other forms of mCDR" (Schumann 2025c).

While traditional resource access and cultural connectivity may also be altered by mCDR activities, engaging Indigenous communities, including fishers using traditional methods, in all aspects of mCDR activities can provide opportunities to align projects with communities' priorities and develop partnerships. Indigenous communities are legally mandated to be engaged (e.g. through Treaty rights and rights to consultation, UNDRIP 2007 UNDRIP 2007) and projects that recognize them as rights-holders, knowledge-holders, and potential co-managers of mCDR projects, design, and decision-making processes will benefit from established partnerships. Engagement specifically with Indigenous communities, including traditional fishers, is also in its infancy. For example, besides the three Tribal engagement events conducted by LOC-NESS (WHOI LOC-NESS Team, 2025), there are limited examples of other non-Indigenous-led mCDR projects conducting meaningful engagement with Indigenous communities to date. Emerging frameworks acknowledge the benefits and requirements to engage with Indigenous communities (Craik et al. 2024, Gardner et al. 2025, U.S. White House 2024) and Indigenous leaders are increasingly recognizing the benefits of engagement and expressing interest to lead and engage with mCDR, for example, in Atlantic Canadian First Nations (e.g. co-author K. Paul) and U.S. Pacific Northwest Tribes (Nawaz and Belotti 2025).

Not only is engaging Indigenous communities legally mandated, but collaborations and partnerships with Indigenous communities are also encouraged through social and ethical obligations (likely expanded upon in *ICES Themed Set on mCDR and Fisheries*, 2025-2026). Bringing Indigenous communities on board will increase the likelihood of access to, and use of, Indigenous and traditional knowledge, which can provide new approaches to problem solving and offer different values placed on environmental and fisheries resources (Strand et al. 2024). Co-production of knowledge and early and equitable engagement with Indigenous rights holders and their representatives can help co-design projects, build true partnerships, incorporate their priorities and perspectives, and enhance the success of mCDR research projects that will inform potential future large-scale implementation (Ford et al. 2016, Zurba et al. 2021, U.S. White House 2024, Craik et al. 2024, Gardner et al. 2025).

Contending with uncertain and complex impacts of mCDR in the context of engagement

Not only can research on impacts (both positive and negative) assess the degree and type of potential impacts, but it is recommended for future studies to also capture the scale (in space and time) of the processes involved, which may be interjurisdictional, adding a further layer of complexity that needs to be understood. Fisheries regulations also apply at multiple scales, and mCDR impacts within one EEZ may affect fisheries productivity in another governmental jurisdiction. This highlights the need for coordinated mCDR considerations that interact with existing international governance frameworks such as processes and instruments created for other sectors such as fishing management, shipping regulations, and sustainable use of biological diversity (UN Convention on the Law of the Sea, UNCLOS; International Maritime Organization, IMO; Biodiversity Beyond National Jurisdiction; BBNJ). Additionally, a potential mismatch of scale exists for costs and benefits: the potential climate benefits of mCDR are global and likely to

Lessons learned box 1: understanding state of knowledge within new blue industries

A recent analysis indicates that inequities, particularly for fisheries, may be exacerbated by blue economy growth initiatives that inadvertently promote displacement and ocean grabbing (defined as actions, policies or initiatives that deprive fishers of resources, dispossess vulnerable populations of coastal lands, and/or undermine historical access to areas of the sea; Bennett et al. 2015). In turn, this can push out fishing communities (Das 2023). Other more established blue economy growth sectors, such as ocean energy, highlight that the fishing communities are the main group that have negative and mixed reactions to ocean-climate solutions; these perceptions begin during implementation and have been heightened when at operational scale (Cisneros-Montemayor et al. 2022, Cox et al. 2024). Such findings in other blue industries highlight the need for emerging sectors, such as mCDR, to understand the current state of knowledge related to fisheries and aquaculture and to identify avenues for early, meaningful, and equitable engagement of those communities.

occur on decadal time scales, but any negative impacts and ecological co-benefits may disproportionately affect particular regions, communities and industries (e.g. where deployment occurs)—for better or worse—and may increase food security risks and regional vulnerabilities on a shorter time scale (Lezaun 2021). Given that current mCDR management systems are often geared towards situations where costs and benefits are confined to a single project, societal value, or activity in a specific location, it can be challenging to consider benefits and adverse impacts at these different geographic and temporal scales, especially across international communities and sectors (Cash and Moser 2000, Abhinav et al. 2020, Haugen et al. 2024). The potential impacts of new activities like mCDR are often considered in isolation and on shorter time horizons compared to other activities happening in the region, including prior history of fisheries activities (Bonar et al. 2015, Abhinav et al. 2020). If mCDR is considered alongside other marine uses and co-designed with existing marine-based sectors, it can help diminish potential adverse impacts such as compounding pressures alongside the recent expansion of marine energy generation (e.g. with offshore wind development, see *Lessons Learned Box 2 and 6* below, Pol and Ford 2020).

Fisheries, aquaculture, and Indigenous engagement: high-level recommendations based on lessons learned

There is a wealth of experience from related sectors that could provide lessons on how mCDR research and development should be conducted in order to maximize coordination and engagement. Here we provide some recommendations based on learnings from the ocean renewable energy (ORE) sector (i.e. offshore wind), oil and gas industry, and ocean acidification (OA) research. These recommendations are not aimed to be fully comprehensive across all topics but instead highlight select examples that are most relevant to fisheries, aquaculture, and Indigenous community engagement with mCDR. While this manuscript provides high-level recommendations, additional manuscripts are contained in the *ICES Themed Set on mCDR and Fisheries (2025-2026)* that dive deeper into specific topics and provide additional best practices and frameworks related to the intersection of mCDR and fisheries and aquaculture. Note that increased coordination and engagement does not guarantee a specific outcome; communities express the desire to be continuously engaged and reserve the right for their opinions and participation to evolve (Nawaz and Belotti 2025). However, without responsible and meaningful engagement, mCDR development is likely to forego the benefits that can be gained through enhanced interactions with the fisheries and aquaculture communities (Fig. 1).

Recommendation 1: synthesize and expand current state of knowledge of mCDR related to fisheries, aquaculture, and Indigenous communities

The emerging mCDR sector can benefit by understanding the current state of knowledge related to fisheries, aquaculture, and Indigenous groups and by identifying the main concerns of those communities. Increasing resources that support engagement with the fishing and aquaculture practitioners will help uncover unique concerns of the global, national, and regional communities that depend on the ocean for their livelihoods. This information can better inform research experiments on fisheries and aquaculture responses to mCDR by tailoring species of concern to the region where a project may move forward. The most impactful research will balance cost-effectiveness, feasibility, and usefulness of the results. The latter point is often a point of conjecture unless effective engagement has focused on the potentially impacted communities.

Recommendation 2: conduct early and meaningful engagement with transparent collaboration

Engagement of fisheries- and aquaculture-dependent industries, coastal communities, and regulators by mCDR developers, researchers, and permitters can be most useful for informing the field's scalability now, when mCDR is in the early stages. Community engagement workshops highlight the importance of actively including community actors in dialogues early about the diverse and complex nuances of the mCDR sector to provide them with opportunities to reconsider their viewpoints and provide input to projects that are not yet preconceived (Nawaz and Belotti 2025). While it is beneficial for all actors within the mCDR community to participate, establishing independent bodies that can remain unbiased and removed from financial interest in mCDR deployments and potential carbon credits (i.e. boundary organizations, academic groups, non-profits, government agencies, etc.) to lead this engagement is key to generate trust, collaboration, and help address concerns about potential techniques (Markusson et al. 2018, Nawaz et al. 2024b, Smythe 2024). The engagement framework produced by the International Association for Public Participation highlights five steps that are necessary to increase the public participation in the design of a project, which include: inform the public through outreach and education, consult the public for feedback, involve the public throughout the process, collaborate through partnerships with all decisions, and empower partners through shared leadership (IAP2 2024). It is important for any proposed cli-

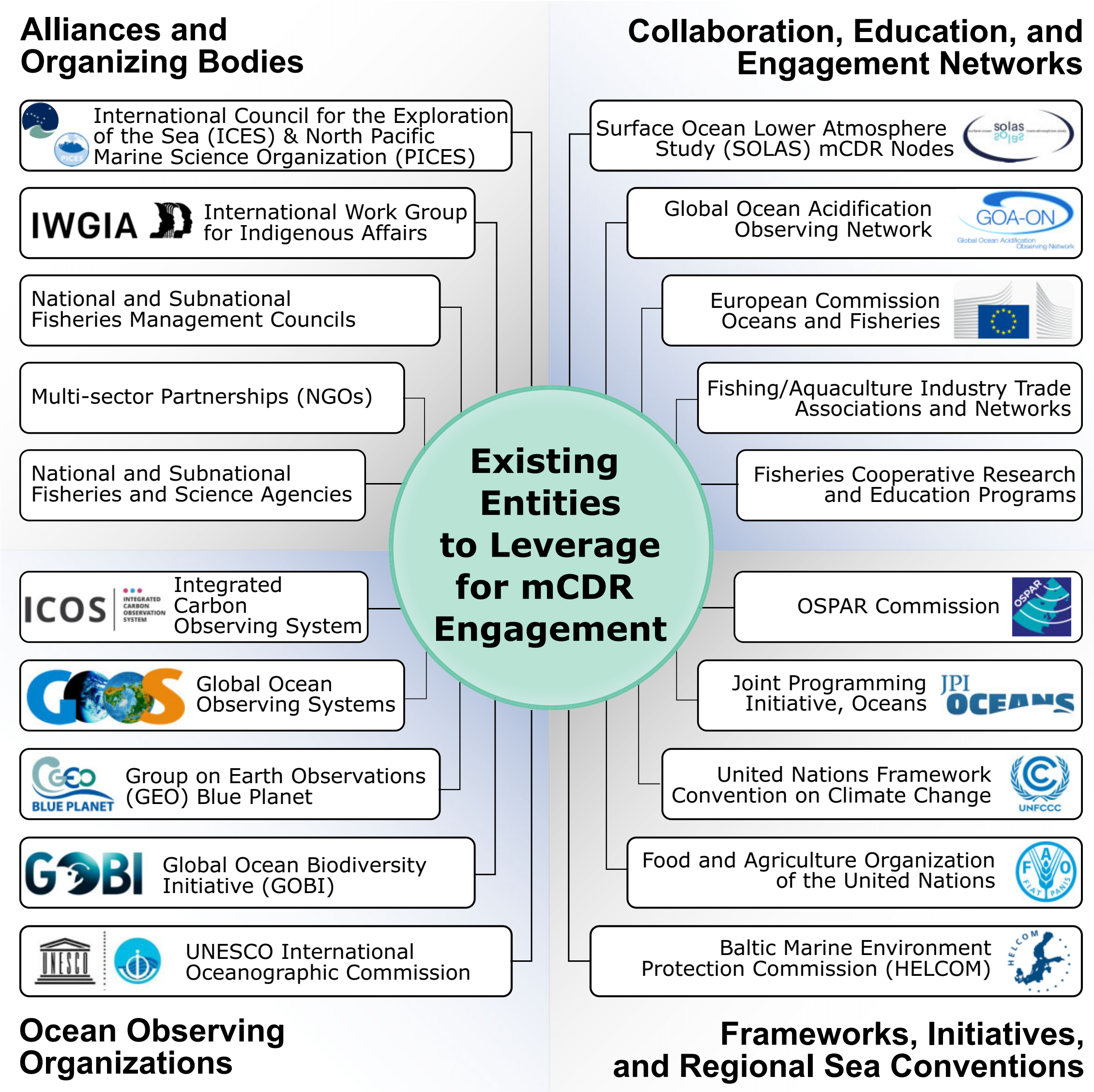

Figure 3. Examples of existing entities that can be leveraged for mCDR engagement. Entities are loosely characterized by Alliances and Organizing Bodies, Collaboration and Engagement Networks, Ocean Observing Organizations, and Other Programs and Initiatives, recognizing that these entities may fall within several of these categories. These entities are not an exhaustive list of existing entities that can be leveraged for mCDR engagement, but offer select examples.

mate change mitigation measure, like mCDR technologies, to plan effectively, coordinate, and provide the trained workforce to conduct engagement to reduce the risk of community burnout, maladaptation, and/or greenwashing.

Improving technological understanding related to mCDR and avenues of communication can both inform the fisheries- and aquaculture-dependent industries and coastal communities about potential mCDR activities as well as strengthen mCDR techniques by allowing rapid feedback and local knowledge to refine the implementation of mCDR activities. Given that mCDR is a technically complex process, creating communication and education tools for various audiences (i.e. technically-inclined audiences as well as the broad public) can help rapidly spread this information in meaningful ways. Early engagement and co-design can be improved through communication, purposeful planning, and science-based evidence on socio-economic and ecological impacts to nearby fisheries as well as accessible financial resources to support adaptations (Bonsu et al. 2024). Through coordinated active engagement and collaboration networks, mCDR technology development can also advance more quickly as lessons learned are incorporated from various ongoing activities and un/favorable approaches and/or geographic regions are highlighted from both the scientific and fisheries perspectives.

Recommendation 3: leverage existing networks

Identifying existing pathways for information sharing instead of trying to create new ones can help streamline complimentary outreach and collaboration efforts to help preserve limited resources and bandwidth required to establish new engagements (Lomonico et al. 2021, FAO 2024, Fig. 3). Examples of existing fisheries engagement avenues include established multi-sectoral councils for fisheries, which incorporate representatives from the fishing industry, scientists, govern-

Lessons learned box 2: early engagement of fisheries with offshore wind sector

The offshore renewable energy (ORE) sector, and in particular offshore wind projects, have learned that early and meaningful engagement is critical to create pathways for community input, build trust among interested parties, and work collectively to minimize impacts on the fisheries and aquaculture communities (Haggett et al. 2020, ICES WKSEIOWFC 2021, Brunbauer et al. 2023). For example, in New England, U.S., offshore wind projects have faced pushback and lawsuits from the fishing communities and other stakeholders, in part due to unspoken assumptions about common goals, poor timing of engagement on key decision points, and lack of transparency and adequate framing of discussions by those conducting the outreach (Pol and Ford 2020). Assumptions that outreach and conversations would result in favorable outcomes and positive engagement from the fisheries communities to support offshore wind were also presumptuous (Pol and Ford 2020). Marine spatial planning processes and siting could have been co-designed better from the beginning to consider the potential co-existence of offshore wind projects with certain fisheries (i.e. passive gear fisheries, aquaculture, and recreational fisheries) (Stelzenmueller et al. 2016, Pol and Ford 2020). These tactics for early engagement are important for marine spatial planning approaches across mCDR projects, especially provided that climate-relevant scale mCDR projects will offer unique challenges and opportunities for each mCDR technique that will likely be region-specific (i.e. potential to co-locate and/or deployment only during certain times of the year or specific geographic regions; NASEM 2022, Cross et al. 2023).

In identifying the need to include fisheries liaisons earlier and in more meaningful ways during planning and decision-making processes, offshore wind developers conducted cumulative studies to better understand the effects on fisheries through collaborative approaches (Haggett et al. 2020). Even with the engagement that has ensued, there continue to be challenges incorporating fishing activities in planning processes (Pol and Ford 2020, Methratta et al. 2020). Based on experiences with offshore wind development such as these, recommendations for improved engagement include building trust through co-creating priorities, co-designing methods and approaches, and identifying conflict resolution strategies (Pol and Ford 2020, Methratta et al. 2020).

Lessons learned box 3: leveraging networks within ocean acidification research community

Ocean acidification (OA) scientists and practitioners have developed collaborative networks with fishery and aquaculture representatives, such as through the Coastal Acidification Networks (CANs) within the U.S. (NOAA OAP 2025b). The CANs support other independent bodies to coordinate engagement and bring together interested groups across industries (e.g. fisheries and aquaculture), sciences, communities, and governments to address common challenges related to OA and develop locally relevant adaptive strategies (McLaughlin et al. 2015, Cross et al. 2019, Gassett et al. 2021). CANs have built strong relationships and disseminated OA information by establishing communication networks across their websites, email list serves, webinar series, and working groups (Cross et al. 2019). The working groups have proved to be an effective tool to establish collaborative conduits to communicate and co-design OA research, management practices, and risks across scientists, stakeholders, industry members (including aquaculture and fishery industries), and community members (Cross et al. 2019).

CANs are also intertwined with the Global Ocean Acidification Observing Network (GOA-ON), which connects 1000 + scientists, decision makers, and communities across 100 + countries to coordinate, advance, and support OA science that can inform adaptation and mitigation (Newton et al. 2015). GOA-ON has already begun to integrate the mCDR community into their network through the mCDR Working Group, which works to consolidate findings and recommendations learned through OA research and engagement that can inform mCDR activities (Findlay et al. 2025) and has produced early career recommendations for equitable growth of the mCDR sector (Kitch et al. 2025). GOA-ON also has a biological working group, which has coordinated research methods and monitoring techniques on the effects of changes in pH on marine organisms (Widdicombe et al. 2023) and could offer insights on assessing potential biological impacts of mCDR on organisms.

ment representatives and NGOs all working together to digest the scientific assessments of specific fish populations and ecosystem trends to determine acceptable harvest levels, appropriate allocations of harvests among sectors, practical regulatory frameworks, and methods for enforcing compliance. Engaging with the established fisheries management councils (FMCs) in the U.S. is one of many ways to enable two-way flow of information about emerging uses of the ocean, such as mCDR. Engagement with the FMCs proved to be beneficial for the LOC-NESS project (described in *Current status of engagement* section) by effectively increasing dialogues between mCDR researchers and fishers, which led to additional experiments that addressed fishers' concerns about species of interest. As another example, NOAA's Cooperative Research Program plays a vital role in engaging the fishing industry, fishermen, scientists, invested communities, and rights holders to improve evaluation of stock status and management of fisheries resources. Fishermen are additionally compensated for participating in cooperative surveys. This effort aims to build trust, incorporate fishermen's knowledge into the process and lead to better survey outcomes which are more broadly accepted. By incorporating fisheries' priorities and perspectives at the outset of new mCDR research and projects (Bozuwa and Mulvaney 2023), perceived risk can be minimized while beneficial environmental responses are maximized and opportunities to work towards social license are developed (as defined in Kelly et al. 2017).

Recommendation 4: establish strong interdisciplinary collaboration with communication conduits

Targeted decision support tools, formal (i.e. school curriculum, certification programs, courses) and informal (i.e. experiential learning, community-based science, public engagement) educational products for designed for fisheries, aquaculture, and Indigenous communities can increase mCDR literacy, build a foundational knowledge base, and provide an avenue for continued discussion (Kelly et al. 2022, Schmidt and Kelter 2017, Dublickas and Ilich 2017). The movement to increase ocean literacy since the early 2000s and through the

Lessons learned box 4: interdisciplinary collaborations within oil and gas sector

To increase the likelihood that collaborations are beneficial to all partners' interests, Norway has successfully built partnerships and communication conduits between oil and gas and fishery industries by consulting fisheries before building platforms, having fishermen co-own oil and gas infrastructure, transferring technology across industries, and creating job opportunities for fishery communities (Arbo and Thuy 2016). In Australia, the government coordinated and outlined commitments for effective communication and engagement by the oil and gas with fisheries. Through this coordination, they developed a co-existence framework (Australian Government Guidance Framework) and protocols (i.e. National Energy Resources Australia Commercial Fishing Industry Adjustment Protocol, Collaborative Seismic Environment Plan, etc. NERA 2022, Molyneux et al. 2023) to further guide coordination. Through coordination and communications, many studies have found that oil and gas structures have the potential to provide habitats for hundreds of marine species, thus creating fishing hot spots (Lyons 2013). Efforts such as Rigs-To-Reef coordinate with fishery communities and representatives to convert decommissioned structures, when viable, to reefs rather than removing them (Jagerroos and Krause 2016). Both aquaculture and offshore wind industries are also exploring opportunities to use these repurposed existing structures for their industries (Pal and Kuo, 2021, Kaiser et al. 2011).

Lessons learned box 5: co-design of ocean acidification research and mitigation

OA is threatening marine resources, such as shellfish, that local and Indigenous communities rely on for food security, livelihoods, and cultural practices and traditions. To strengthen the ability for local communities and Indigenous communities to guide region-specific OA research and mitigation, local and Indigenous community representatives have collaborated with OA practitioners to co-design and co-develop OA regional vulnerability assessments, OA action and mitigation plans, and capacity-building networks to serve their priorities (Newton et al. 2025, Grabb et al. 2025). For example, the Olympic Coast in the Pacific Northwest, U.S. is already experiencing the effects of OA and local priorities for social, cultural, and ecological health guide the collaborative regional vulnerability assessment that is underway and co-designed with tribal co-investigators and regional resources managers (Washington Sea Grant 2025). The Makah tribe in the Pacific Northwest, U.S., also developed an OA Action Plan to combine their Indigenous perspectives and priorities with scientific research and outline actions to mitigate OA that are specific to their region (Hutchins 2025). Regional GOA-ON networks have also been co-designed from the ground up by local community members to prioritize, identify, and help build OA research and mitigation capacity that is aligned with their local and regional needs (Newton et al. 2015, Grabb et al. 2025). To invite full participation from all groups, the OA initiatives were backed by funding to compensate contributors for their time and expertise.

Additional recommendations for co-design processes are currently being co-developed in emerging studies by the mCDR, fisheries, aquaculture, and Indigenous communities (See *ICES Themed Set on mCDR and Fisheries*, 2025-2026).

UN Ocean Decade can offer avenues, techniques, and existing networks that the mCDR community can utilize to increase connections between the public and mCDR (Schoedinger et al. 2010, Fauville et al. 2019). Throughout the U.S. the Marine Resource Education Program run by the Gulf of Maine Research Institute develops regional workshops and materials about fisheries science and management that are designed and presented by fishermen, for fishermen (Marine Resource Education Program, 2025). Creating exchanges and partnerships where traditional and local knowledge (i.e. knowledge of key fisheries recruitment areas, areas of Indigenous significance for traditional food harvests, etc.) can be shared with the mCDR community to help align mCDR activities with communities' priorities and increase common understanding (Brossard et al. 2005). Sharing knowledge and collaborations can increase the likelihood that mCDR efforts will honor interested parties' priorities due to awareness and established relationships. Such collaborative efforts can also encourage the development of products that translate science to public audiences, which can also serve to make science accessible by policymakers and relevant to constituents' priorities (Costa and Caldeira 2018, Cvitanovic et al. 2015, Fernandez Otero et al. 2019).

Recommendation 5: co-design projects with local and Indigenous fisheries

Prioritizing adequate funding and resources to enable Indigenous and traditional-led ocean planning and research would enable Indigenous Peoples (including Traditional fishers) and traditional communities to develop and implement their own projects and support their contributions to the ocean research field (Strand et al. 2024). For example, the Advancing Indigenous Partnerships in Ocean Science for Sustainability (AIPOSS) UN Ocean Decade Endorsed Project in Canada has increased equitable, sustainable, and inclusive involvement of Indigenous peoples as equals in ocean governance and science, while also producing resources for community-based engagement roadmaps and meaningful Indigenous participation (Caldeira et al. 2025). By co-designing and co-developing mCDR activities with diverse partners, including Indigenous partners, from the beginning, natural conduits will be more likely to develop and ensure that the techniques are tailored to the nuances and priorities of the region while also allowing the Indigenous and local communities to directly benefit from any potential economic or business opportunities (e.g. job opportunities, co-ownership, carbon credits, environmental co-benefits, etc) (Strand et al. 2024, Caldeira et al. 2025). This engagement can also involve governance at municipality and national scales, as well as the broader local communities, to ensure that discussions of possible benefits and adverse impacts provide scenarios that are more effective for all. For example, the ICES workshop to assess and anticipate the impact of mCDR on fisheries and aquaculture species and management (ICES WKmCDR 2025a) and the *ICES Themed Set on mCDR and Fisheries* (2025-2026) included Indigenous co-leadership (e.g. co-author K. Paul) to co-design these efforts, include Indigenous perspectives from the onset, and expand engagement and participation from additional Indigenous communities. Additional perspectives and guidance from these efforts will be presented within the emerging literature associated with the *ICES Themed Set on mCDR and Fisheries* (2025-2026).

Lessons learned box 6: frameworks and best practice guides for offshore wind

Frameworks and best practice guides can be valuable tools to set out principles for engagement, such as those developed based on case studies with offshore wind and tidal energy projects in Scottish waters (Withouck et al. 2023). In the Northeast U.S., the creation of regional non-governmental (NGO) entities such as the Responsible Offshore Science Alliance (ROSA; Responsible Offshore Science Alliance 2025) enables cross-sectoral conversations, identification of research priorities and collaborative funding of research. ROSA has developed offshore wind monitoring frameworks and guidelines (ROSA 2021) to address responsible engagement and best practices that are developed as a living document by their inter-sectoral working groups, including representatives from offshore wind energy developers, state and federal scientists, other NGOs, and the fishing industry. On an international level, several offshore wind energy working groups have been established with fishing industry members under the auspices of ICES (e.g. ICES Working Group on Offshore Wind Development and Fisheries, WGOWDF. ICES WKWIND 2025b). Similar mechanisms could be developed for mCDR and/or mCDR could be added to the subject matter portfolios of existing organizations, networks, and frameworks, and other entities currently engaging fisheries practitioners (Fig. 3).

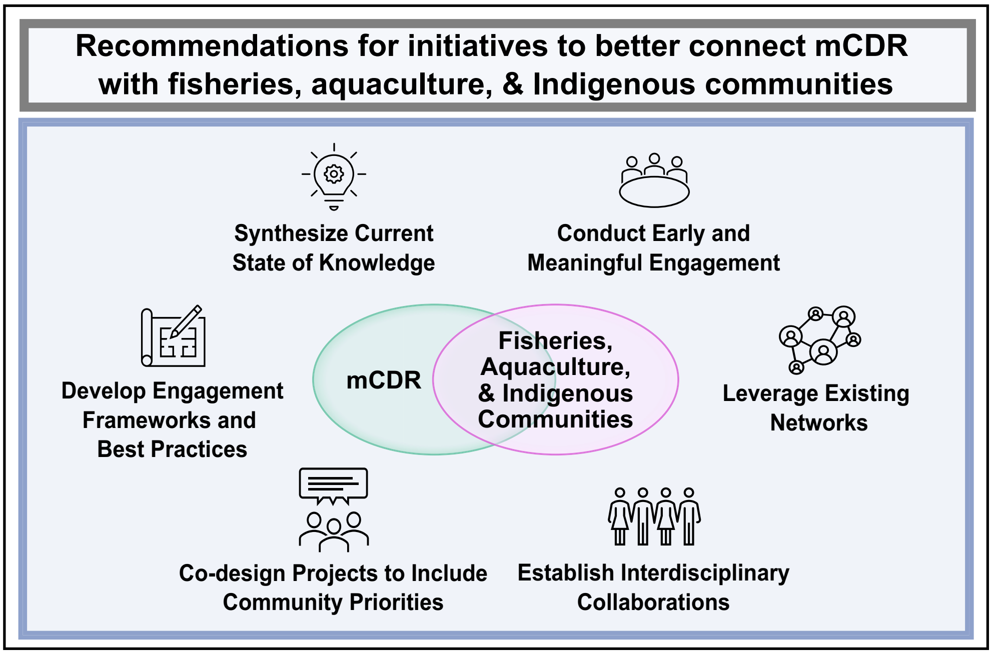

Figure 4. Select recommendations for initiatives across mCDR and fishery- and aquaculture-dependent industries, communities, and rights holders, including Indigenous communities, that can increase engagement, collaborations, co-development, and co-production of knowledge.

Recommendation 6: develop targeted engagement frameworks and best practice guides

Achieving a high level of communication, collaboration, engagement, and outreach can be enhanced by wide scale coordination and agreed upon mutual practices and priorities, which is often communicated through frameworks and best practice guides. Frameworks and best practice guides for mCDR research have been emerging, with some focused on specific techniques (i.e. OAE; Oschlies et al. 2023) and others that address multiple techniques across the mCDR sector and offer regulatory frameworks (Webb et al. 2023) and responsible research practices that align with social priorities, governance, and decision-making (Aspen Institute 2023, Lebling et al. 2022, Ocean Conservancy et al. 2023, Satterfield et al. 2023). These guides touch on aspects that relate to fisheries and aquaculture, yet were not designed specifically to address inter-sectoral collaboration needs. National and international fisheries have separately developed some best practice guides across coordinated networks to increase adaptation and resilience practices to emerging threats, such as climate change (Bahri et al. 2021). Specific frameworks co-developed with mCDR communities and fisheries and aquaculture representatives can provide common grounds for these communities to enhance engagement and cross-communication.

Summary of future actions and recommendations

Awareness of the value of increasing partnerships, communication conduits, literacy, and best practices for engagement between the mCDR community and fishery- and aquaculture-dependent industries, communities, and rights holders is growing. Where feasible and appropriate, this increased engagement can leverage existing networks, organizations, and collaborations by incorporating mCDR as a complimentary topic to ongoing work to streamline resources and capitalize on established relationships (Fig. 3). In October 2024, a group of science, fisheries, Indigenous, and governance representatives convened an ICES workshop to assess and anticipate the impact of mCDR on fisheries and aquaculture species and management (ICES WKmCDR 2025a). This was one of the first of many proposed activities to continue this discussion across mCDR practitioners and fisheries- and aquaculture-dependent representatives. There is a large opportunity to undertake a variety of initiatives across the mCDR and fisheries and aquaculture communities to further this goal, including, but not limited to the following actions (Fig. 4):

- **Recommendation 1:** Synthesize and expand upon the current state of knowledge of mCDR in relation to potential influences on and interactions with fisheries and aquaculture;
- **Recommendation 2:** Conduct early and meaningful community engagement with transparent and unbiased communication to help increase mCDR literacy, build trust with affected communities, and encourage collaborations;
- **Recommendation 3:** Leverage existing networks to incorporate mCDR priorities into global, national and local coordination and engagement;
- **Recommendation 4:** Establish strong communication conduits and interdisciplinary collaborations between the mCDR community and those working across the science-policy interface to inform decision-makers and regulators;
- **Recommendation 5:** Co-design mCDR projects with local and Indigenous fisheries and aquaculture communities to integrate priorities into projects, especially related to spatial planning and siting; and
- **Recommendation 6:** Develop mCDR-focused engagement frameworks and best practice guides to increase widespread adoption of responsible engagement with the fisheries, aquaculture, and Indigenous communities.

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Data availability

The data underlying this article are available in the article.

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