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A sequential gated research framework for addressing potential impacts of marine carbon dioxide removal on fisheries, aquaculture, and Indigenous communities

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Abstract

Marine ecosystems are at risk due to the increasing pressures of climate change and other human activities. Fisheries and aquaculture, which employ 61.8 million people worldwide and supply ∼20% of human animal protein demand, are sectors that critically rely on healthy marine ecosystems. Marine carbon dioxide removal (mCDR) encompasses a portfolio of novel approaches that aim to mimic natural processes to increase the ocean's uptake and storage of atmospheric carbon dioxide through intentional human interventions in the marine environment. Alongside verifying the efficacy of mCDR techniques, their environmental and social impact must also be assessed to enable informed decisions about what, if any, research, development, and deployment of mCDR should move forward, accounting for the full spectrum of benefits, costs, and trade-offs and in comparison with other CDR interventions. Evaluating the footprint of mCDR requires identifying and understanding positive and negative impacts beyond carbon dioxide removal. Here, we provide a multi-stage research framework for mCDR project developers to assess these interdisciplinary impacts, specifically in relation to marine ecosystems, fisheries, and aquaculture. This framework considers how projects can implement these recommendations across five research phases, using a stage-gated approach that focuses on: Stage 0, Planning; Stage 1, Baseline Assessment and Experiments; Stage 2, Pilot Field Trial; Stage 3, Scaled-up Field Trial; and Stage 4, Operational Deployment and Long-term Monitoring. As an interdisciplinary team of

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academic and government scientists, non-governmental organizations, and fisheries and Indigenous community members, we offer this framework as a high-level user guide for projects to consider impacts through a fisheries and aquaculture lens. We point to current frameworks when possible and outline additional considerations that can be addressed as research scales.

Background and framing

Marine ecosystems and associated food production sectors are facing ever-increasing challenges from climate change, where a warming ocean, ocean acidification, and deoxygenation are shifting species distributions and altering productivity, ultimately affecting food provisioning and security (Cooley et al. 2023). Marine and freshwater fisheries and aquaculture globally provide important sources of food, supplying 20% of the protein needs of 3.2 billion people and livelihoods, employing 61.8 million people (FAO 2024), not to mention the strong, long standing socio-cultural ties that link coastal and Indigenous communities to fishing and marine life (Khakzad and Griffith 2016; Islam and Berkes 2016; McMillan and Prosper 2016). The productivity of fisheries relies on a healthy ocean; however, as anthropogenic carbon emissions continue to rise, climate change impacts threaten marine ecosystems. For each degree of atmospheric warming with climate change, there is an anticipated 4.2%–5% reduction in fish or macrofauna biomass within marine ecosystems (Lotze et al. 2019; Mariani et al. 2025), with projections of >30% declines for 48 countries and territories with warming of 3–4°C by 2100 (Blanchard and Novaglio 2024). Shifts in marine biomass will likely be spatially uneven, and their implications will likely disproportionately be borne by communities reliant on seafood as a source of protein and/or income (Bezner Kerr et al. 2022). Climate change models that project low-emissions scenarios and limit warming to below 2°C suggest marine ecosystem biomass losses could remain <10% (Blanchard and Novaglio 2024). However, achieving this target not only requires drastic reductions in greenhouse gas emissions to meet net-zero targets, but also the active removal of legacy carbon dioxide from the atmosphere (IPCC WG III AR6 2023).

The ocean is an important component of Earth's system that can help mitigate climate change. It already plays a vital role in the Earth's climate regulation, having naturally absorbed 90% of the excess heat and over 30% of the CO_2 emitted since the industrial revolution (IPCC 2019). In addition to its role as a large natural carbon sink that can store carbon for long periods, its expansive 71% global coverage makes the ocean a target for exploring ocean-based climate interventions, such as marine-based carbon removal, to critically assess whether they could play a role as a climate solution. Hence, marine carbon dioxide removal (mCDR) technologies (Box 1; NASEM 2022) are now being researched to assess their potential to help meet these climate targets. Marine CDR technologies are diverse, relying on physical (artificial downwelling), chemical [ocean alkalinity enhancement (OAE) and direct ocean carbon capture and storage (DOCCS), and biological (ocean nutrient fertilization (ONF), artificial upwelling, and macroalgae cultivation and sinking] processes to remove and store CO_2 away from the atmosphere (Box 1). Consequently, their associated CDR efficiency and durability, upscaling potential, energy use and costs, spatial requirements, technological readiness, and their potential environmental footprint are being examined and are likely to vary among and within approaches (Cross et al. 2023; NASEM 2022).

Whilst the primary goal of successful mCDR is to provide a crucial benefit to the safekeeping of Earth's health and ecosystem services by reducing the negative impacts of climate change, these operations involve a novel use of the ocean space that should be considered alongside existing activities and interests, such as fisheries and aquaculture. Importantly, mCDR techniques may have environmental, socioeconomic, and regulatory impacts, which can be both positive and negative, in addition to those derived from mitigating or alleviating climate change (Box 2) (Grabb et al. 2025; Roberts et al. 2026). In the marine realm, these impacts can layer onto others stemming from existing (e.g. fishing, shipping, oil and gas extraction) or emerging (e.g. renewable energy development, deep sea mining) uses of the sea, with footprints of pressures realistically overlapping in space and time (Borja et al. 2024; Halpern et al. 2025), much like the effects of climate change itself. This results in cumulative negative impacts, with local or downstream effects of different activities interacting in ways that may be additive, antagonistic, or synergistic. The development of an mCDR industry may cause a doubling of human-driven cumulative negative impacts on the marine environment by mid-century (Halpern et al. 2025), potentially alleviating climate change pressures while exacerbating or introducing other pressures. As potential positive and negative impacts of mCDR are being researched and characterized to enable decision making, a formidable challenge is thus to not only understand these potential impacts on the environment and people in isolation but in a cumulative sense to enable sound and informed management of ocean activities, meet sustainability goals, and ensure that impacts are not unfairly distributed (Bennett et al. 2025). Assessing both positive and negative impacts preemptively with communities that may bear the brunt of these impacts, such as local, fishery, and Indigenous communities, could help capitalize on opportunities for positive impacts, evaluate trade-offs to minimize risks, and/or or halt proposed projects with a net-negative effect (Grabb et al. 2025).

The positive and negative impacts of mCDR interventions remain poorly constrained, with some aspects receiving increasing attention in scientific studies and others purely hypothetical. For example, positive impacts of mCDR may include the creation of nursery habitats through macroalgae farming (Corliss et al. 2024; Fulton et al. 2020) or the hypothesized alleviation of ocean acidification and its impacts on marine organisms by OAE (Zhou et al. 2024; van de Mortel et al. 2025). Negative impacts of mCDR may include the release of toxic trace elements (e.g. from some minerals proposed for OAE), which could accumulate through marine food webs with implications for food safety (Flipkens et al. 2023). Biotic methods that enhance photosynthesis, such as ONF and macroalgae cultivation, could also result in nutrient robbing (Tagliabue et al. 2023) and deoxygenation (Oschlies et al. 2025), which can impact downstream environments, degrading ecosystems in regions outside of the mCDR perturbation, which could have implications for climate justice. In such cases, defining ecological thresholds and identifying vulnerable species and habitats could be key to mitigating risk by mapping the scale and loca-

Box 1 Brief summary of intended methodology for marine carbon dioxide removal technologies that are currently being researched (NASEM 2022; Cross et al. 2023)

Ocean process	mCDR method's objective
Chemical	Ocean alkalinity enhancement (OAE) aims to increase the ocean's capacity to take up and store carbon dioxide at the atmosphere–sea–air interface by either adding alkaline chemicals and/or minerals or using an alkaline solution produced electrochemically.
Chemical	Direct ocean carbon capture and storage (DOCCS) intends to remove carbon dioxide directly from seawater using electrochemical processes, with the resulting decarbonized seawater then returned to the ocean to allow for further carbon dioxide uptake from the atmosphere through air–sea carbon dioxide fluxes.
Biological	Ocean nutrient fertilization (ONF) involves adding iron, nitrogen, and/or phosphorus to the ocean, with the goal of stimulating phytoplankton production to increase the amount of CO_2 incorporated into biomass. The biomass then has to be exported to the deep ocean to sequester carbon for long periods, and the CO_2-diminished surface water has to equilibrate with the atmosphere to take up more atmospheric CO_2.
Biological	Macroalgae cultivation and sinking seeks to enhance photosynthetic processes within seaweeds, removing CO_2 from the surface waters by incorporating it into biomass. The seaweed then has to be removed from surface waters (i.e. exposure to the atmosphere). For example, this can be done by collecting and processing it for biochar or Bioenergy with Carbon Capture and Storage (BECCS) or sinking it to the deep sea, where it could remain sequestered for extended time periods. The CO_2-depleted surface water then equilibrates with the atmosphere, taking up more atmospheric CO_2.
Biological	Artificial upwelling proposes to stimulate biological primary production by delivering nutrient-rich deep-seawater to the surface, thereby incorporating CO_2 into biomass. The organic biomass must then be exported to the deep ocean for durable, long-term storage.
Physical	Artificial downwelling has the objective of exporting carbon from the surface to the deep ocean by pumping carbon-rich surface waters to depth, allowing the CO_2-diminished surface water to equilibrate with the atmosphere to take up more atmospheric CO_2.

Box 2 Definition of Terms. Working definitions of terms used within this paper, recognizing that some of these definitions may evolve with time.

- Impact (syn: effect): Wide-ranging changes or responses, relative to a baseline condition, exhibited as a consequence of a process, such as mCDR, on natural environments and human societies. Impacts implicitly deal with severity, intensity, duration, and directionality of an effect (i.e. positive or negative) (Gill et al. 2020). This paper focuses on impacts beyond the removal of atmospheric carbon. The positive, negative and neutral classification of each impact is likely to depend on one's perspective and it may differ with scale. Some impacts may be positive for some aspects yet negative for others and may be hypothesized or scientifically proven. While net costs/benefits are necessary to consider, they are outside the scope of this framework.
- Baseline (syn: reference): The baseline (or reference) is the state against which change is measured. It might be a "current baseline," in which case it represents observable, present-day conditions. It might also be a "future baseline," which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.
- Positive impacts: The beneficial effects that a measure aimed at one objective, such as removing carbon for mCDR techniques, might have on other objectives, thereby increasing the total net benefits for society or the environment relative to a baseline condition. Positive impacts are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Positive impacts are also referred to as co-benefits and ancillary benefits (IPCC AR6 Annex I 2023).
- Negative impacts: Adverse effects on natural and human systems relative to a baseline condition. They can also be referred to as negative consequences and/or outcomes. There can also be risk for adverse impacts when the outcome is uncertain (IPCC AR6 Annex I 2023).
- Neutral impact: When assessing potential effects, it is also possible that there is a no and/or null effect, resulting in no change in the circumstance being analyzed relative to a baseline.
- Stage-gate process: A management approach that divides an overarching project into a series of distinct stages and gates. Each stage is defined by a set of specific research activities that gather information to inform decision-making (e.g. the efficacy of mCDR methods, risks, benefits, and uncertainties). Gates are checkpoints where decisions are made based on pre-determined criteria (U.S. DOE 2007).
- Research-scale project: Recognizing that this definition is evolving, here we use a working definition to define a research-scale project as a project where the primary purpose is to ask research questions and improve scientific or process understanding. For mCDR, this includes projects that are focused on understanding the impacts of mCDR, regardless of how the research is funded, yet prior to sustained field trials for a commercial purpose. Suggested scales of research projects include removing zero to ∼Mega tons of CO_2 per year (Fawcett et al. 2025; de Baar et al. 2005).
- Fisheries community: A group whose members substantially depend on or engaged in the harvest or processing of fishery resources to meet social and economic needs and who reside in a specific location (Magnuson-Stevens Act 2007).

tion(s) where this particular mCDR activity could be safely and responsibly implemented. Although mCDR could play a role in reaching net zero emissions as part of the carbon removal portfolio (i.e. removing legacy emissions), weighing the potential trade-offs between its positive and negative impacts of mCDR is important to consider against the costs of climate change without the removal of carbon through mCDR pathways (i.e. only emissions reductions). An additional important difficulty in weighing trade-offs is that, even under optimal conditions, positive environmental impacts of mCDR, stemming from its contributions to climate change mitigation, would generally occur over long timescales (years to decades). In contrast, environmental impacts of activities may occur over the short to medium terms, particularly near the intervention site, complicating decision-making, particularly near the intervention site, as well as on the long-term if sustained mCDR deployment leads to sustained pressures on organisms or shifts in ecosystems and food webs, complicating decision- making. Much like emissions reduction, mCDR will raise the question of weighing short-term costs to particular people, ecosystems, ecosystem services, or geographies against long-term global benefits, and vice versa.

Meanwhile, other direct and indirect impacts will largely depend on the development and implementation pathways followed. For example, physical interactions between mCDR at scale and marine fisheries and aquaculture, both in the nearshore and offshore, can be anticipated (ICES WKmCDR 2025; Grabb et al. 2025; Gurney-Smith et al. In Review). Such interactions could establish new fishing exclusions or hazards, increase noise and contaminant pollution, and interfere with recruitment grounds (Lloret et al. 2023; Hengstmann et al. 2025; Hou et al. 2025; Bamber and Seaby 2004). Meaningful engagement with relevant fisheries and aquaculture communities would ideally mitigate potential conflicts to achieve more equitable outcomes (Grabb et al. 2025; Blythe et al. 2026).

While some mCDR techniques are beginning to demonstrate potential to remove atmospheric carbon, considerable uncertainty remains regarding their broader impacts on marine ecosystems (Roberts et al. 2026). This is especially true for fisheries and aquaculture-relevant species, for which a very limited number of studies have begun assessing their sensitivities and thresholds to each technique (Fig. 1; Grabb et al. 2026). Dedicated research, methodological frameworks, and interdisciplinary collaborations will be needed to advance risk-benefit assessments (U.S. White House 2024; Grabb et al. 2025). Provisions for cumulative impacts assessment are already integrated into some existing environmental policies (e.g. the United States National Environmental Policy Act), although operationalizing such assessment remains an active area of research with varying degrees of realized success (Lundquist et al. 2016; Stelzenmüller et al. 2020). The incorporation of social and economic factors, as well as environmental justice considerations, remains a particular area of development (Curren et al. 2022). Importantly, no coherent framework exists for addressing cumulative impacts at the international or global scale (Hamman 2025). However, the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction (i.e. BBNJ Agreement) may present a path forward. It is worth noting that the cumulative impacts of mCDR activities and development are not constrained to the marine environment, given the strong dependency of mCDR on energy and raw materials that need to be produced, processed, or transported from land to the coast through processes that have their own often well-documented social and environmental impacts.

Without dedicated research and a robust understanding of potential environmental and ecological impacts, social license and public trust would likely diminish. Even with proper recognition of Indigenous Peoples' rights, engagement, and inclusion of local, fisheries, and aquaculture communities throughout the project process (Grabb et al. 2025; Paul et al. In Review), social license and public support may not be granted and mCDR projects may not be supported. Entities interfacing with communities and rightsholders in the context of scoping and planning field research should consider a right of refusal, which may constitute an economic burden on these entities and necessitate flexible operations. Work is needed to develop tools and guidelines to include community members as decision-makers within the project and establish participatory processes to work toward recognitional, procedural, and distributional equity (Blythe et al. 2026). Robust multistage frameworks (i.e. stage-gated approaches like this framework) could be useful for steering the substantial research efforts that lie ahead, which will be key to informing larger-scale mCDR operations and aiding in holistic regulatory frameworks (Edwards et al. In Review) and the transparent and responsible implementation of any mCDR technology (Doney et al. 2025).

Here, we propose a stage-gated framework (See Box 2) to support research-scale (See Box 2) mCDR assessment of impacts on fisheries and aquaculture across socio-economic, environmental, and regulatory aspects. While social license cannot be guaranteed, this framework aims to provide guidelines to increase the inclusivity of fishery and aquaculture community members and to support collective decision-making, helping guide projects toward more just and equitable outcomes (Blythe et al. 2026). This framework synthesizes existing guidelines (Table 1; Box 3) and, depending on the particular aims of a given project, points actors to the most relevant tools for mapping and evaluating potential positive impacts and negative impacts. This framework is designed to assist research-scale mCDR projects that intend to conduct field trials, but does not cover full commercial-scale operations, where additional risk assessments are likely to be required. This multistage framework was designed by an interdisciplinary group of experts, including representatives from academic and government science institutions, non-governmental organizations, and fisheries and Indigenous communities. This paper is a product of two workshops, routine online meetings, synthesis from published literature, and input drawing on our respective expertise and involvement in ongoing mCDR projects across science, policy, and community engagement. We present this framework to offer guidance for responsible mCDR research to mitigate risks and maximize potential community, environmental, and climatic benefits.

Introduction to this framework

Framework scope

The purpose of this framework is to provide a high-level fisheries- and aquaculture-focused, stage-gated approach that can be applied to specific projects and regions to help identify impacts resulting from carbon removal across disciplines relevant to

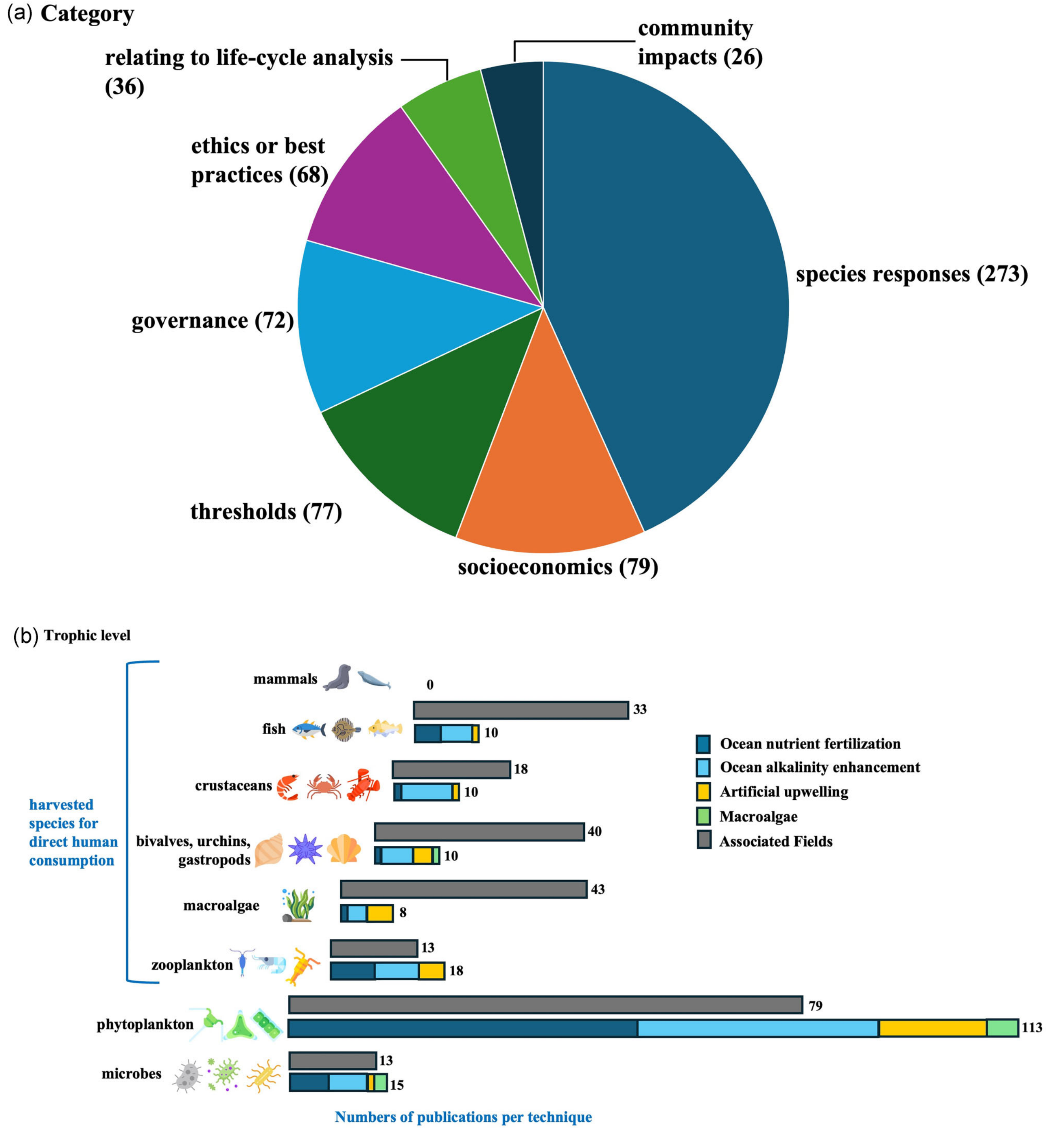

Figure 1 Summary of the number of papers within the mCDRxFisheries Literature Database (Grabb et al. 2026) for: a) relevant fields, and b) those that have assessed biological responses associated with different organisms from mCDR techniques. The bars represent the number of papers within the database that address biological responses to different organisms (as noted on the left), indicating those that are specific to mCDR techniques (colored bars) and those that are from associated fields (grey bars), such as ocean acidification.

fisheries and aquaculture. Here, we specifically address projects at the research stage (See Box 2), spanning from planning (Stage 0) to laboratory and mesocosm studies (Stage 1) to pilot and longer-term, sustained field trials (Stages 2–4). Whilst we focus here on research-scale studies, the questions suggested here could also apply to commercial operations undertaking research. This framework is designed to be easily accessible to a broad audience, including scientists, practitioners, decision-makers, verifiers, fishers, aquaculture farmers, and other interested community members. Contrary to traditional research approaches that academic researchers typically drive, the interdisciplinary approach here recognizes and suggests that project teams are likely to, and can benefit from, including diverse researchers across the public and private sectors, subject-matter experts, and community members throughout the project stages. Other regulators at the local, national, and international levels (e.g. implementers of the London

Table 1 Summary of existing relevant frameworks.

Framework	Author	Date	Summary	Relation to Fisheries and Aquaculture	Discusses potential positive and negative impacts	Socio-economic Topics	Regulatory Topics	Environmental Topics
This Stage-Gated Framework on mCDR Fisheries and Aquaculture Impacts	Grabb et al.	2026 (this study)	Stage-gated approach to assess potential positive and negative effects of mCDR related to fisheries and aquaculture	Focus	Focus	Focus	Focus	Focus
Principles for responsible and effective marine carbon dioxide removal development and governance—High Level Panel for a Sustainable Ocean Economy	Doney et al.	2025	High-level summary of technical and governance state of knowledge	Does not focus	Mentions Somewhat	Focus	Focus	Focus
Framework for ecotoxicological modeling of mCDR (FEMM)	Hourglass Climate	2025	Provides detailed background information about ecotoxicology with species examples	Mentions Somewhat	Mentions Somewhat	Does not Focus	Does not Focus	Focus
Engaging coastal communities on ocean alkalinity enhancement	Nawaz and Belotti	2025	A how-to best practice guide for conducting engagement on OAE projects	Mentions Somewhat	Mentions Somewhat	Focus	Mentions Somewhat	Mentions Somewhat
Environmental Impact Monitoring Framework for Ocean Alkalinity Enhancement (OAE)	PML Applications and Carbon to Sea	2025	Detailed guidance on conducting stage and gated approach to EIAs for OAE	Does not focus	Focus	Does not Focus	Mentions Somewhat	Focus

Table 1 Continued

Framework	Author	Date	Summary	Relation to Fisheries and Aquaculture	Discusses potential positive and negative impacts	Socio-economic Topics	Regulatory Topics	Environmental Topics
National Marine Carbon Dioxide Removal Research Strategy	U.S. Whitehouse, Fast Track Action Committee	2024	High-level road map for mCDR research focusing on interdisciplinary aspects	Does not focus	Mentions Somewhat	Focus	Mentions Somewhat	Focus
Ocean Carbon Dioxide Removal for Climate Mitigation: The Legal Framework	Webb et al.	2024	High-level synthesis on legal and governance frameworks related to mCDR	Does not focus	Does not focus	Does not focus	Focus	Does not focus
Ethical Framework Principles for Climate Intervention Research	American Geophysical Union	2024	High-level framework for ethical climate intervention across sectors	Does not focus	Mentions Somewhat	Focus	Focus	Mentions Somewhat
A Code of Conduct for Marine Carbon Dioxide Removal	Aspen Institute	2023	Guide to ensure equitable distribution of outcomes from mCDR research across interdisciplinary aspects.	Does not focus	Mentions Somewhat	Focus	Focus	Mentions Somewhat
Guide to Best Practices in Ocean Alkalinity Enhancement Research	Oschlies et al.	2023	Technical foundation and best practice guide for OAE including laboratory, mesocosm, and field trials	Does not focus	Mentions Somewhat	Mentions Somewhat	Mentions Somewhat	Focus
United Nations Declaration on the Rights of Indigenous Peoples	United Nations	2007	Legally non-binding instrument that delineates and defines individual and collective rights of Indigenous Peoples	Does not focus	Focus	Focus	Focus	Mentions Somewhat

This table identifies relevant frameworks, notes the title, author, and year published, and provides a summary. It notes whether the frameworks are focused primarily on ("Focus," blue), mentioned somewhat ("Mentions Somewhat," green), or do not focus on ("Does Not Focus," orange) topics relevant to fisheries and aquaculture or positive and negative impacts associated with socio-economic, environmental, and regulatory dimensions. For an additional summary of each framework's relevance to these categories, see Supplementary Table S1.

Box 3 mCDR Frameworks relevant to fisheries and aquaculture and/or effects

Given that frameworks, best practice guides, and codes of conduct related to responsible and ethical mCDR research are emerging (i.e. Aspen Institute Code of Conduct 2023; AGU Ethical Framework 2024; U.S. White House 2024; Oschlies et al. 2023; Hourglass Climate 2025; Fawcett et al. 2025; etc), this framework points to these previously published recommendations through a fisheries and aquaculture lens, which are briefly summarized in Table 1 (expanded in Supplementary Table S1). In this framework, we build on existing guides and incorporate recommendations from other sectors (e.g. offshore wind, deep-sea mining) to assess the potential impacts of mCDR research and identify both positive and negative impacts. This framework builds on international human rights standards, including the UN Declaration on the Rights of Indigenous Peoples (UNDRIP 2007). It provides actionable steps for projects to follow to recognize the governance, knowledge systems, and resource rights of Indigenous peoples in assessing potential impacts. While this framework offers a novel perspective through a fisheries and aquaculture lens and crosscutting interdisciplinary themes, it lacks the details and specific guidance to implement each recommendation, pointing users to other sources that focus on specific subjects and established practices (Table 1). While we recognize that mCDR approaches may have specific impacts that can call for dedicated focus and bespoke considerations, we offer this framework as a broad approach to consider all mCDR techniques and potential impacts related to fisheries and aquaculture (Grabb et al. 2025).

Convention and London Protocol and/or government agencies responsible for managing ecosystems and living marine resources) may find this guiding tool useful to advise and adapt for regional regulatory processes and/or assessments of projects that are seeking permits for field trials, especially as project scopes continue to scale up. Adapting and incorporating this framework into different governance regimes, regulatory processes, and/or funding mechanisms offers opportunities for oversight by third-party regulators and funders to assess project progress and enforce gated approaches, which could help ensure that projects comply with the framework's suggestions.

We recognize that operationalizing this framework will not be straightforward, especially given the complexity of each project, yet, given that few standards and/or readily implementable plans exist for assessing mCDR impacts, we provide this guide as a first attempt to outline interdisciplinary considerations for projects in an idealized situation, expecting that this guide will need to be iterated with shared learnings of applications across scale, geographies, and socio-ecological contexts. Research projects that utilize this framework are expected to be conceptualized with defined methodologies and goals that apply to researching specific mCDR approach(es) and strive to progress to scaled research field trials (Stage 3, see below). This framework is designed for use by one project at a time, but it can be extrapolated to apply to interdisciplinary projects, test beds with multiple projects (Cyronak et al. 2023), and/or basins and regions with multiple ongoing projects. When considering multiple projects taking place in the same local region, cumulative and/or compounding impacts must be evaluated using an adapted framework. As our understanding of mCDR techniques and their interactions with the environment improves the stages will likely need refinement.

Because a major potential benefit of mCDR activities for fisheries and aquaculture is their contribution to reducing long-term climate stressors (e.g. warming and ocean acidification), comprehensive assessments must also consider whether a proposed activity is likely to deliver net, durable atmospheric CO_2 removal at scale. Making this judgment is challenging during early-stage activities, which will not, in themselves, remove meaningful quantities of CO_2 but can set the stage for later deployment. It is expected that robust monitoring, reporting, and verification (MRV) will occur concurrently with the stages in this framework, noting that MRV methodology and considerations are not included, given the framework's focus on impacts related to fisheries and aquaculture.

Stage-gate approach

This framework relies on a stage-gate approach (Fig. 2: Overview Figure). Although this is the first application focused on mCDR and fisheries, this concept is not novel; it is emphasized in several mCDR-related guides, such as the OAE Best Practices Guide (Oschlies et al. 2023), the Code of Conduct for mCDR (Aspen Institute Code of Conduct 2023), and the OAE Environmental Impacts Monitoring Framework (EIMF) (Fawcett et al. 2025). The stages utilized here were inspired by stages within the EIMF (Fawcett et al. 2025):

- Stage 0: Planning (0 tons CO_2 removal per year)
- Stage 1: Baseline Assessment and Experiments (0 tons CO_2 removal per year)
- Stage 2: Pilot Field Trial (100 tons CO_2 removal per year)
- Stage 3: Scaled Field Trial (kilo- to mega- tons CO_2 removal per year)
- Stage 4: Long-Term Monitoring (Continuously removing mega-tons of CO_2 per year)

The suggested tons of CO_2 removal per year noted for each stage is based on the equivalent tons of CO_2 removal expected from research projects (Fawcett et al. 2025) and previous field trials (de Baar et al. 2005). At each stage, we recommend guidelines for the prescribed activities to inform decision-making. At the end of each stage, there is a "gate" that serves as a checkpoint for decision-making. The gate provides guidelines for projects to assess outcomes against a set of predetermined standards or indicators, review implications, and consider necessary improvements, ultimately deciding whether activities should move forward, be delayed, or require a project off-ramp. These gates also provide routine opportunities for stakeholders, rightsholders, and other community members to provide input, voice priorities, and/or express approval or disapproval of project aspects. If the project meets the desired standards and expectations and receives general approval from engaged publics, the project can proceed to the next stage, either in the original or a modified form, considering the results of activities from the relevant stage. The stage-gate approach is designed to be dynamic. This includes modular application to project aspects (i.e. project aspects can be as-

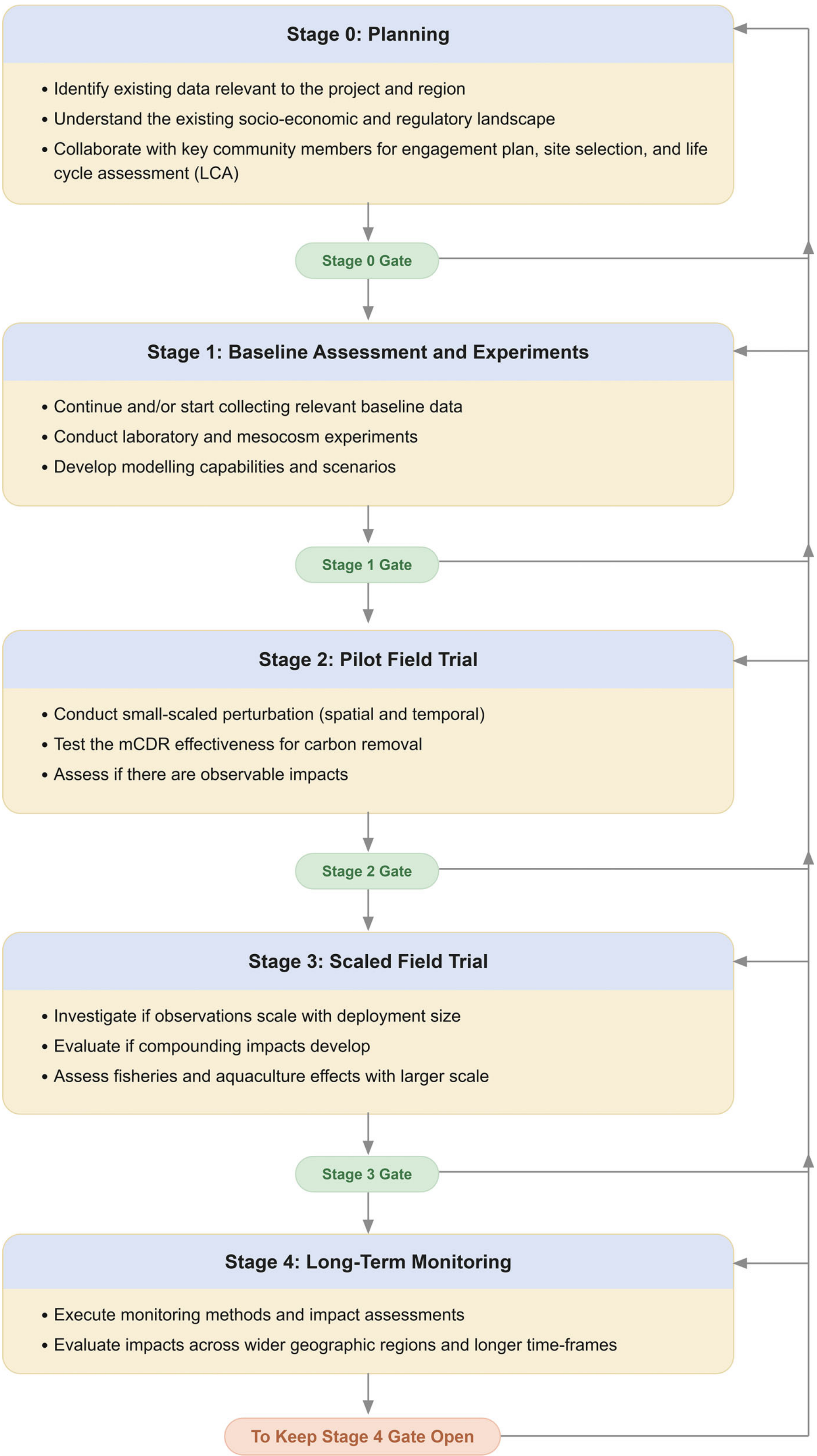

Figure 2 Overview of Stages: Figure displaying the stages (blue), what actions are suggested to be taken during the stage (yellow), the location of the gates (green) with arrows indicating the flow between stages and gates.

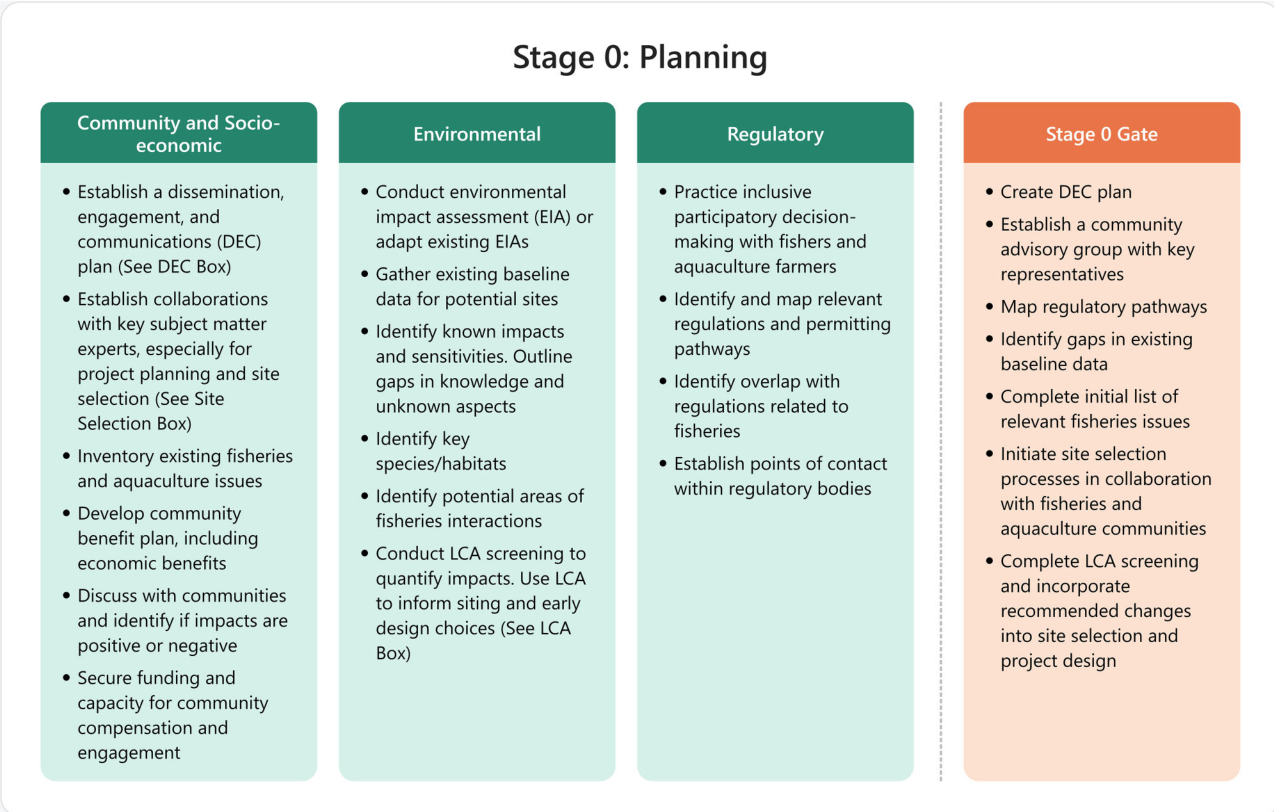

Figure 3 Stage 0: Figure describing the Stage 0 priorities (green) and gate (orange) for planning.

sessed independently and progress through stages and gates at different speeds); iteration (i.e. projects can repeat stages until all parameters are met at the gate); and two-way flow (e.g. a project aspect could progress to Stage 2, during which more is learned, which raises questions that need to be investigated back in Stage 1).

Framework recommendations

Stage 0: Planning (0 tons CO_2 removal per year)

Stage 0 (Fig. 3: Stage 0) includes considerations for planning, collating existing baseline measurements, and understanding the existing landscape, including sensitive habitats and fisheries operating in the project site. Early mCDR projects have demonstrated how critical it is to project success to conduct early and meaningful engagement with local and Indigenous communities (Schumann 2024; Grabb et al. 2025), and recommendations for such engagement already exist (UNDRIP 2007; Aspen Institute Code of Conduct 2023).

Stage 0: Community engagement and socio-economic impacts

Recognizing the power imbalance (between communities, individuals, and other organisms) and actively prioritizing inclusiveness of people with various knowledge and expertise can help work toward community decision-making, reciprocity, and trust. While community support cannot be guaranteed and lack of community support is not necessarily a failure, actively working toward community inclusivity, providing decision-making authority to community members, and recognizing Indigenous People's rights and self-determination are critical steps for projects to work toward gaining public support while also contributing to stronger project design and outcomes (Aspen Institute Code of Conduct 2023; UNDRIP 2007; Paul et al. In Review). During this initial planning stage, projects are recommended to establish a Dissemination, Engagement, and Communication (DEC) plan (see Box 4). While such plans may not currently be required by permitting authorities, early-stage mCDR research has demonstrated that engagement activities are critical (Nawaz and Belotti 2025), underscoring the need to develop a DEC regardless of regulatory requirements. This includes identifying key local subject matter experts within the fisheries and aquaculture industries, rightsholders (including Indigenous nations as political entities, not just as invested communities), and interested groups to provide genuine participation, shared decision making, and collaboration on project components, such as project design, siting, and monitoring (Nawaz and Belotti 2025). For example, fisheries, aquaculture, and Indigenous community members can be included as equal partners on the project team, with decision-making power to help design and influence project activities (Paul et al. In Review). These engagement practices can also be guided by established consultation processes, such as those developed by government agencies (i.e. the Environmental Protection Agency, EPA, in the USA), and should also be grounded in rights-based approaches, especially when potential impacts are likely to influence Indigenous commu-

Box 4 Establishing a dissemination, engagement, and communication (DEC) plan

At the beginning of the project, it is highly recommended to consider a DEC plan, such as through methods presented by the European Commission (European Commission 2025). To ensure this goes beyond a cursory exercise, best practice is to co-produce a dissemination, engagement, and communication (DEC) plan with the community advisory group and third-party oversight (e.g. regulatory authorities and/or external ethics committees) that outlines the DEC strategy throughout the project and serves as a living document that is amended as the project progresses. Including input and feedback for the DEC plan from the community and third-party members through equitable engagement processes can help reduce biases by project developers and openly communicate both potential positive and negative impacts throughout the project stages. In doing so, the project can generate meaningful engagement with tangible outcomes by including community members, providing participatory processes that align with community interests, and working toward building trust, which takes time and is not guaranteed (Aspen Institute 2023; UNDRIP 2007). It is expected that developing a DEC plan will require dedicated capacity by experts with knowledge of this process and should be implemented as a funded aspect of the project. DEC plans may be strengthened by incorporating into local and regional engagement processes, such as those recommended by regulatory authorities and permitting processes, including recognition of rights, inherent sovereignty, and self-determination of Indigenous Peoples (UNDRIP, 2007; Paul et al. In Review).

- ***Definitions:***
- Dissemination is about one-way communication: ensuring that research results and knowledge are shared, publicly available, and accessible to those who can use them. Dissemination generally takes the form of publishing research papers, technical reports, or presenting at conferences and fishery council meetings.
- Engagement is an ongoing two-way process of building relationships with stakeholders and rights holders to gain their input and facilitate the use of findings. Engagement can range from soliciting feedback on public communication to holding discussion groups and workshops to fully integrating stakeholders and rights holders into the project planning and design (full co-design).
- Communication is the process of raising awareness and generating interest about the project among a broad audience. It often takes the form of media coverage, public events, social media, and/or a project website.

What should a DEC plan include:

A DEC plan should start with background information, including a project overview, objectives, key issues, relevant stakeholders and rights holders, and local context. It should detail, for each DEC aspect, the logistics for undertaking the activities (e.g. meeting formats, timelines, budgets, roles, and resource requirements) and the target audience. Finally, the DEC plan should include details of how community members will evaluate the DEC activities and how community-based feedback will be incorporated into the project. Evaluation can be conducted by developing indicators to assess the effectiveness of DEC activities and by including qualitative and quantitative metrics (e.g. participation rates, knowledge uptake). There should be iterative feedback mechanisms that allow this evaluation, as well as stakeholders themselves, to influence the DEC plan over time.

Additional considerations (Aspen Institute 2023; UNDRIP 2007):

1. Inclusivity and accessibility: Ensure materials and engagement formats are accessible to diverse audiences, including non-English speakers, people with disabilities, and those with limited internet access. Use plain language and visual aids to explain complex concepts, such as mCDR and its potential impacts.
2. Cultural sensitivity and ethical considerations: Incorporate cultural protocols and traditional knowledge systems when engaging with Indigenous and local communities. Include ethical review processes for communication and engagement activities, especially when working with vulnerable groups.
3. Risk communication: Develop clear messaging that addresses both ecological and socio-economic risks and uncertainties.
4. Adaptive communication: Use adaptive strategies to respond to emerging concerns or changes in stakeholder priorities.
5. Capacity building: Include training sessions or informational workshops to build stakeholder capacity to engage with mCDR research—support community-led monitoring or citizen science initiatives where appropriate.
6. Integration with policy and governance: Align dissemination, analysis, and engagement efforts with local, regional, and national policy frameworks. Identify opportunities to inform marine spatial planning, fisheries management, and climate adaptation strategies.
7. Transparency and accountability: Make project decisions, funding sources, and data openly available where possible. This includes information provided to regulatory bodies for the purposes of permit application or subsequent requests for information. Provide regular updates and maintain open channels for questions and concerns.

nities such as Indigenous fishers (Paul et al. In Review). Identifying the most relevant participants and existing forums for interaction across interested groups can help leverage established relationships and decrease engagement fatigue (Grabb et al. 2025). Creating a compensated, decision-making power, which consists of key fisheries, aquaculture, and Indigenous representatives from diverse communities that the project may impact, is an important mechanism to ensure that community voices are represented in the project and project outcomes (Paul et al. In Review). The community advisory group can work with project leads to establish and guide decision-making processes for the project, ensuring a wide array of perspectives are incorporated. Deciding on the composition of this group can be guided by community members, and compensation for participation is expected.

To understand the existing landscape within which a project is being conducted, it is also important to work directly with the fishing and aquaculture communities to understand their needs and to inventory general spatial (at sea and in port) overlaps and operational interactions (Nawaz and Belotti 2025). This can also help identify cultural sensitivities toward existing and previous practices, potential compounding impacts stemming from existing human-caused environmental impacts and sensitivities that project activities may exacerbate or be synergistic with, and inform project decisions, such as siting. Through these community collaborations, it is also important to discuss and explicitly identify whether potential impacts are positive or negative. It should also be recognized that many community members may be hearing about mCDR for the first time, so projects, especially those conducted by commercial entities, should be sensitive to the growing knowledge base concerning moral hazard in carbon removal and ensure that operations and external communications do not increase the risk of moral hazard (Markusson et al. 2024; Lawford-Smith and Currie 2017). Projects should also be prepared to communicate about the global-scale needs to reduce carbon emissions in addition to exploring carbon removal techniques, while placing mCDR in a broader context within potential climate interventions (Lawford-Smith and Currie 2017). Note that best practices recommend setting aside funding to compensate community members for their participation in project activities, which requires budgetary consideration in the project planning stage. Engaging with communities and stakeholders would also require dedicated capacity on a project team.

A socioeconomic impact analysis should be conducted at this stage to assist in deconflicting site selection issues (or identifying areas that should not be used for research) and to understand better the overall impact the project may have on fisheries and aquaculture. Any displacement of fishing effort could have a negative economic impact on an individual fishery unless compensatory actions are successful. Any benefits from mCDR for Earth's climate system require a long perspective (e.g. timescales on the order of tens of thousands of years); however, effects from mCDR projects will be felt by affected communities on a much shorter timescale. Describing these effects at Stage 0 increases transparency with affected communities. A cumulative impact analysis will enhance understanding of the impact on fishing communities, as it includes other factors (such as fishery management measures, offshore renewable energy development, and dredging) that also affect fishing. It is also recommended to identify the economic drivers within a fishing and aquaculture community to outline shared goals and to develop a community economic impact plan that includes economic benefits and risks, while considering the fishery's baseline economics. To inform the economic impacts plan, it is useful to gather economic data related to the mCDR technique and assess the ability to leverage existing opportunities, including activities in other sectors.

Stage 0: Environmental impacts

Existing environmental data can be collated to inform project decisions, establish a baseline, and indicate where additional research is needed to address gaps in the baseline data (Cyronak et al. 2023; Oschlies et al. 2023). Best practices include conducting an Environmental Impact Assessment (EIA) or adapting existing EIAs for each project to assess environmental impacts relevant to the specific technique and region. Reviewing the literature on the ecological effects of the chosen mCDR technique can also inform about potential impacts and overlaps with fisheries and aquaculture activities. It is also important to identify existing models for the region and, if available, assess potential future climate change impacts in the absence of climate mitigation techniques to help estimate potential future impacts of mCDR and project a future environment in which mCDR activity will likely take place. Within the region of interest, identification of key species and/or habitats, and assessment of known sensitivities based on the literature, should occur during this initial planning stage. It is also recommended to identify potential areas of fisheries interactions, including sensitive locations, species, and/or times of year. Identifying gaps in existing knowledge that are necessary to inform the specific project is recommended to guide the collection of additional baseline data during Stage 1.

While these activities focus on characterizing local biophysical conditions and direct interactions with fisheries and aquaculture, they do not capture the full set of upstream and downstream environmental burdens associated with mCDR deployment (Chlela et al. 2025; Foteinis et al. 2022). Complementary, system-scale assessment tools are therefore needed at Stage 0 to evaluate how material sourcing, logistics, energy use, and end-of-life management may shift pressures across impact categories relevant to marine ecosystems (Arvidsson et al. 2018; Pelletier et al. 2007). In this context, life cycle assessment (LCA) provides a structured, quantitative framework to identify environmental impacts and hotspots (the life-cycle stages, processes, or inputs that dominate an impact category) along the mCDR supply chain, thereby informing technology design and site selection before field trials commence (ISO 14044: 2006, Bruijn et al. 2002; Chlela et al. 2025; Huijbregts et al. 2017). Box 5 outlines how a Stage 0 screening LCA can be integrated into the sequential gated framework to support environmentally robust decisions for mCDR projects interacting with fisheries and aquaculture.

Stage 0: Regulatory considerations

Understanding the regulatory landscape and the permitting pathways for specific mCDR techniques is vital to prepare for future stages of mCDR projects (Webb et al. 2024). Throughout the project and permitting process, it is important to practice inclusive participatory decision-making with fishers and aquaculture farmers, especially when considering potential site selection for field trials (See Box 6). At the start of the project, it is recommended to identify relevant regulations and permitting pathways for the project approach. In the event of negative environmental impacts, remediation plans should be developed before the experiment begins. Developing monitoring, reporting, and verification (MRV) plans is an important component of the regulatory process at this stage. It can be helpful to review analogous projects and processes and to map potential permitting pathways within the region of interest to assess their applicability. During this process, overlaps with regulations related to fisheries and aquaculture can be identified. Establishing points of contact within regulatory bodies may be critical to liaising with them throughout these processes.

Box 5 Life cycle assessment

Early incorporation of LCA results into project design can allow for reformulation of an mCDR project with environmental sustainability in mind, leading to greater reductions in impacts arising from its implementation (Bergerson et al. 2020; Thoneman et al. 2020; Myridinas et al. 2026). For example, early LCA results can inform decisions on location, logistics, vessel type, energy sourcing, material selection, monitoring priorities, and end–of–life treatments to maximize carbon removal and minimize environmental impacts due to mCDR activity. Indeed, experts recommend including LCA as an obligatory component at an early stage for R&D projects of emerging technologies (Bergerson et al. 2020; Myridinas et al. 2026). Early integration of LCA helps avoid locking in designs and supply chains that later prove environmentally unsustainable or very difficult to change (Moni et al. 2019; Wender et al. 2014).

Best practice suggests implementing a screening Environmental LCA in Stage 0 (Bruijn et al. 2002; Chela et al. 2025). LCA is a quantitative method that documents all inputs and outputs of a product/service/project's lifecycle from the extraction of materials and production to use and end-of-life treatment and quantifies its environmental impacts (Bruijn et al. 2002). It is designed to fairly compare the environmental performance of options that fulfill the same need, identifying environmental trade-offs, environmental hotspots, and areas for improvement in a product's/project's life cycle (Bruijn et al. 2002). Having people on the team with knowledge of mining, energy, and water demands will expedite this step. In the case of mCDR projects, a screening LCA would be fundamental for identifying environmental impacts, and likely "hotspots" before site selection, the design freeze (the point at which the technical design is fixed and major changes become costly or impractical), and field trials (Fuss et al. 2018; Chlela et al. 2025; Myridinas et al. 2026).

How can a Stage 0 LCA inform mCDR-relevant decisions?

A robust "Stage 0" life cycle assessment goes beyond carbon accounting. It evaluates a range of environmental impact categories, ensuring that positive and negative impacts are quantified and identified. Standard LCA methodologies already include multiple impact categories, some of them relevant to marine environments (Langlois et al. 2014). Below, we align some impact categories that can be quantified by LCA and applied to marine ecosystems in the context of mCDR implementation projects. In the following table, we refer to characterization factors (CFs), i.e. numerical factors derived from fate–exposure–effect or productivity models used in life cycle impact assessment to convert a unit of emission or resource use (e.g. 1 kg CO_2, 1 kg N, 1 m^2 of seafloor disturbed) into a quantified contribution to a specific impact category (e.g. potential species loss or loss of primary production).

Impact category	What LCA quantifies	Why is it important for marine ecosystems relevant to fisheries and aquaculture
Ocean acidification (biodiversity loss in marine ecosystems)	New characterization factors (CFs) link atmospheric emissions of CO_2 (and the CO_2 formed by oxidation of CH, CO) to ocean pH change and species loss, developed from taxon– and climate–zone–specific species sensitivity distributions (Scherer et al. 2022). Anderson et al. (2025) extend this to a fully operational spatially explicit OA characterization model across marine ecoregions (coastal) and FAO major fishing areas (open ocean) (Anderson et al. 2025).	LCA gives a defensible, quantitative measure (PDF/species·yr per unit emission) for upstream/downstream emissions along an mCDR supply chain that affect shellfish, coral–reef–associated fisheries, and other pH–sensitive species. By applying spatially explicit CFs, the impact of ocean acidification can be distinguished across marine regions/fishery areas, thereby increasing its relevance to the fishery/aquaculture context.∗
Marine eutrophication (hypoxia and loss of marine animal richness)	LC–IMPACT provides endpoint CFs for hypoxia–driven reductions in marine animal species richness caused by dissolved inorganic nitrogen (DIN) reaching coastal/marine waters; factors are spatially differentiated (Cosme and Hauschild 2017). LCI—Marine Ecotoxicity (Cosme et al. 2015)	The assessment can capture risks of dead–zone formation from nutrient additions (e.g. fertilization concepts), NO_x/NH_3 deposition from shipping, and coastal effluents, yielding a direct biodiversity proxy for nursery function and stock resilience.
Marine ecotoxicity (toxic stress on fish and shellfish)	ReCiPe's toxicity modeling (with USEtox data) provides marine ecotoxicity CFs for thousands of chemicals, including dissociating organics, with explicit fate/exposure modeling (Rosenbaum et al. 2008).	Links material choices and discharges to toxic pressure, e.g. trace metals accompanying alkaline minerals, antifouling biocides, or electrolytic by–products, so that pilots can set discharge limits and sourcing criteria ex ante (Dong et al. 2018).
Microplastics (physical impacts on biota), entanglement/ingestion impacts.	The MarILCA method supplies CFs for physical impacts on biota from microplastics emitted to aquatic systems, combining polymer/size/shape–specific fate factors with an updated exposure–effect factor of 1067.5 PAF·m^3/kg; inventories can include losses from fishing devices and marine coatings (Corella-Puertas et al. 2023; Lavoie et al. 2022). Complementary LCIA methods characterize additional impacts (ingestion/entanglement) but remain less harmonized (Woods et al. 2021) (Marhoon et al. 2026; Hoiberg et al. 2025). Newly developed methods also include Schwarz et al. (2024).	Could be used to quantify, i.e. harm from gear, ropes, nets, lines, and coatings used in seaweed farms and test rigs that may shed microfibres/fragments affecting fish, invertebrates, and their prey (Hoiberg et al. 2025). Early LCA screening can identify hotspots driven by rope, abrasion rate, and coating type, serving as a potential procurement guideline and operational design before pilot implementation.
Sea–use (occupation and transformation), life–support functions (LSF) of marine ecosystems	A dedicated sea–use category expresses how shading, biomass removal, seafloor destruction, and artificial habitat creation change the free net primary production ($fNPP_eq$) available to the food web. Reported CFs span 0.1 kgC_eq/kg (seaweed removal) to 111.1 kgC_eq/kg (tunas/billfishes) and 0.164–0.342 kgC_eq/m^2 for seafloor destruction, by ecosystem type (Langlois et al. 2015).	This quantifies how macroalgae farms (shading/structure), anchors/pipelines (benthic disturbance), or biomass extraction alter the bottom–up energy supporting local fish populations.

∗Current OA CFs are emissions–driven; they do not directly credit local buffering alkalinity-based mCDR (e.g. OAE), nor do they capture local-scale risks from deliberately altering carbonate chemistry (e.g. transient over-alkalinization, mineral precipitation, changes in trace metal speciation, and biological responses). These local impacts must be evaluated through dedicated monitoring, process-based modeling, and, where relevant, other LCA impact categories (e.g. ecotoxicity, sea-use), rather than relying solely on OA CFs(de Castro et al. 2025). These OA characterization factors capture the pH-driven pathway by which atmospheric CO_2 emissions affect marine biodiversity and are therefore complementary to climate-change impact categories in LCA, which represent temperature-driven impacts of greenhouse gases on marine and terrestrial ecosystems.

Another essential aspect to consider in Stage 0 is indirect value-chain emissions, often referred to as scope 3 emissions in greenhouse-gas accounting frameworks. These include upstream and downstream emissions outside the project's direct operations (e.g. extraction and processing of alkaline materials, manufacture of equipment and vessels, and transport logistics) and are critical for determining the net carbon removal following mCDR implementation. In LCA, the same processes are represented through inventory flows (e.g. CO_2, NO_x, dissolved inorganic nitrogen, metals, plastics) that are translated into impact categories such as climate change, ocean acidification, marine eutrophication, marine ecotoxicity, microplastic impacts, and sea-use. For example, if an OAE project requires mining large quantities of rock, the associated fuel use in mining and transportation may become a significant source of CO_2 (Foteinis et al. 2023). In contrast, the management of mining waste and tailings can have additional impacts, such as freshwater and marine ecotoxicity (Foteinis et al. 2023; Rosenbaum et al. 2018; Myridinas et al. 2026). By quantifying these contributions, a Stage 0 LCA informs developers which components dominate overall climate and environmental impacts, highlighting where, for example, cleaner fuels, alternative materials, or different sourcing strategies are needed (Foteinis et al. 2022; Myridinas et al. 2026, Katish et al. 2026). In this way, early-life-cycle assessment guides projects to mitigate indirect emissions and impacts at a stage when changes to project design and supply chains are still most feasible.

Because LCA is an inherently iterative process, this initial Stage 0 screening should be revisited and progressively refined as mCDR projects move through subsequent stages and more site-and technology-specific data become available. This allows uncertainties to be reduced, impact estimates to be updated, and design choices to be adjusted accordingly (Nurdiawati et al. 2025).

Stage 0 Gate—Evaluate prior to moving to Stage 1

Prior to passing through the Stage 0 Gate and proceeding to Stage 1 (Fig. 3: Stage 0 Figure), considerations discussed above should be addressed and the following check-points are recommended to be met: (1) Establish a community advisory group of key representatives from diverse groups across fisheries, aquaculture, and Indigenous communities to help work with project leads and regulators to guide project decision-making processes; (2) Establish a DEC plan with oversight from the community advisory committee and third-party key actors (See Box 5); (3) map potential regulatory pathways and incorporate regulatory requirements into the project plan, including permits for field trial; (4) identify gaps in existing baseline data; (5) complete an initial list of relevant fisheries and aquaculture issues; and (6) initiate site selection process in collaboration with fisheries and aquaculture communities as well as regional spatial planning agencies; (7) conduct LCA to assess potential impacts throughout life cycle and show how results are incorporated into site selection and project design (See Box 6). If any of these steps have not yet been completed, it is recommended to remain in Stage 0.

Stage 1: Baseline assessment and experiments (0 tons CO_2 removal per year)

After the initial planning in Stage 0, Stage 1 recommends collecting new baseline data and conducting experiments to address the identified gaps and inform field-trial planning (Fig. 4: Stage 1 Figure). Baseline assessments are expected to occur before the project commences and should collect data on the project location, design, operation, and mitigation measures relevant to communities, socio-economic considerations, and environmental and ecological aspects (EXIM 2025). It is best for these assessments to also consider current and proposed development activities within the project area that are not directly connected to the project. To contribute to baseline data collection, laboratory experiments and mesocosm studies should be conducted on key species and/or habitats relevant to the project area. Modeling studies, including those focused on socio-economic analysis and environmental aspects, can also inform project design and future experiments. Informed by experiments and models, this stage includes planning field trials, applying for permits, and identifying off-ramps for small-scale trials.

Stage 1: Community engagement and socio-economic impacts

During Stage 1, understanding the baseline conditions for socio-economic aspects is important. Baseline data on people, communities, and societal issues should be prioritized during this stage to inform the project's progression. Meaningful engagement with interested groups, including members of the fishery and aquaculture community, can yield information, guidance, and feedback that benefits project plans (Nawaz and Belloti 2025). The best mechanisms for engagement (e.g. workshops, town hall meetings, asynchronous opportunities) will be determined by the community to align with their preferred and/or ongoing activities (Nawaz and Belotti 2025). Through this engagement, it is important to build on the relationships established during Stage 0 with fisheries and aquaculture communities to ensure that priorities align with project planning, such as choosing key species for experiments, prioritizing research on the most concerning impacts, and/or assessing potential agreed-upon sites. Discussing potential off-ramps and societal, environmental, and ecological thresholds that trigger them with community members can help agree on predetermined off-ramps before field trials commence. This engagement is central to implementing the DEC plan created in Stage 0, such as by practicing inclusive participation for fisheries and aquaculture communities and/or through monitoring, sample collection, collaborations, advisors, and/or partnerships. At this stage, the project can also consider and work with community members to design direct economic benefits and opportunities, such as co-ownership or co-PI status, hiring fishers for ship time, and/or contracting consultants for experiments and aquaculture rearing. Engagement of fishers and farmers throughout these processes is expected to be compensated for their time, and the capacity to guide these engagement processes is included in the project design and funding.

Box 6 Recommendations for site selection

Site selection is a critical aspect to consider during Stage 0, the project conception. It requires close collaboration with fisheries and aquaculture communities and crosscuts socio-economic, regulatory, and environmental elements. Starting the site selection process by including communities and considering the priorities and concerns of other ocean users, such as fishers and aquaculture farmers, is important in addition to evaluating environmental parameters (Guo et al. 2025). This should happen before submitting the permitting application and undergoing official consultations with other interested groups, regardless of permitting requirements. Permit applications require an understanding of essential fish habitats, fisheries survey methods, protection acts, and/or affected species that the field trial will interact with or overlap. Starting the site selection process during the project's planning stages will also inform baseline measurements, environmental parameters, and key species of interest to evaluate through experiments, mesocosms, and modelling studies in Stage 1. Reaching out and establishing open communication with potential permitting agencies can also ensure that regulatory considerations are being integrated alongside other spatial planning activities, such as conservation targets and renewable energy planning, and therefore ensuring compliance with expected permitting requirements.

Other ocean-based sectors have developed site-selection processes that can inform the mCDR community. For example, reflections on offshore wind site selection processes, including previous mistakes, offer insights for tools and practices that can enhance the opportunity for inclusive site selection for mCDR projects that balance environmental, techno-economic, and social considerations (Spyridonidou and Vagiona 2020; Abdel-Bassett et al. 2021; Diaz et al. 2022). Processes that help narrow down potential sites can include phases that first identify exclusion areas based on ocean-use and community input, then assess potential suitable areas against agreed-upon criteria, and finally optimize to maximize beneficial attributes and minimize risks (Spyridonidou and Vagiona 2020). Throughout the planning process, spatial planning tools, such as GIS, can be powerful to precisely integrate interdisciplinary considerations that contribute to site selection and marine spatial planning, including existing marine protected areas, environmental factors, fishing grounds, and other ocean uses (Spyridonidou and Vagiona, 2020).

To enhance participatory practices, a number of methods have been tested and assessed in offshore wind processes, which can be selected based on their suitability for the project at hand and/or used in combination. Some of these techniques include Analytic Hierarchy Process, Multiple Attribute Decision Analysis, multi-criteria decision-making, Evidential Reasoning, and Preference Ranking Organization Method for Enrichment Evaluations (Abdel-Bassett et al. 2021; Diaz et al. 2022). These techniques can be preceded by a comprehensive index system of evaluation criteria specific to the proposed region and aligning with community priorities (Abdel-Bassett et al. 2021). For example, in the US, spatial modeling was done by NOAA at the request of the Bureau of Ocean Energy Management (BOEM) to narrow down wind energy sites according to other uses, including fish species presence and fishing activity; benthic characterization, national security uses, etc. (O'Brien et al. 2025). By considering spatial planning techniques and practices recommended by other sectors, ocean users, and interdisciplinary experts, the mCDR community can promote site-selection processes that are inclusive and optimized to maximize co-benefits and minimize adverse impacts across environmental, socio-economic, and regulatory aspects.

Stage 1: Environmental impacts

Based on the gaps in the existing data identified during Stage 0, including community- and locally relevant concerns, Stage 1 recommends conducting additional experiments and collecting baseline data under natural environmental conditions to inform project decisions (Oschilles et al. 2023; Cyronak et al. 2023). To ensure these assessments are unbiased and trustworthy, analyses could be conducted or reviewed by independent, third-party actors (non-project-specific, including reviewers from public and/or private entities) to evaluate the mCDR methodologies and potential impacts, with results published openly and transparently and/or reviewed by regulatory agencies. With paid guidance from fisheries and aquaculture farmers, experiments can be tailored to address community priorities to yield open-source data to assist local decision-making.

Laboratory and mesocosm experiments that emulate perturbations expected from mCDR techniques can be designed to complement each other and investigate potential environmental and ecological impacts on key species. (Dupont and Metian 2023; Iglesias-Rodriguez et al. 2023; Riebesell et al. 2023). Experiments should be conducted following best practices, such as those established in related fields, such as ocean acidification (Findlay et al. 2025), recognizing that methodologies may need to be modified to more effectively simulate mCDR perturbations (Hooper et al. 2025). These experiments can help collect data on species' sensitivity to proposed mCDR conditions, which can also be used to produce curves for modeling. There is value in assessing a range of conditions and concentrations to implement response curves into models and evaluate impacts at different locations and scales. This can help consider the impacts of potential accidents that may generate conditions outside of normal planned operations.

More specifically, for models, at this stage it is important to develop and verify regional-scale biogeochemical models for the sites of interest so they can be used before, during, and after field trials for MRV and EIA (Fennel et al. 2025). Assessing potential nutrient dynamics (i.e. nitrogen and phosphorus processes) and cascading biogeochemical changes, in addition to the carbon cycle, is important to feed into ecosystem-based models and extrapolate potential impacts to multiple species and across higher and lower trophic levels. Assessing biogeochemical and ecosystem changes can also be a critical component of carbon accounting, since nu-

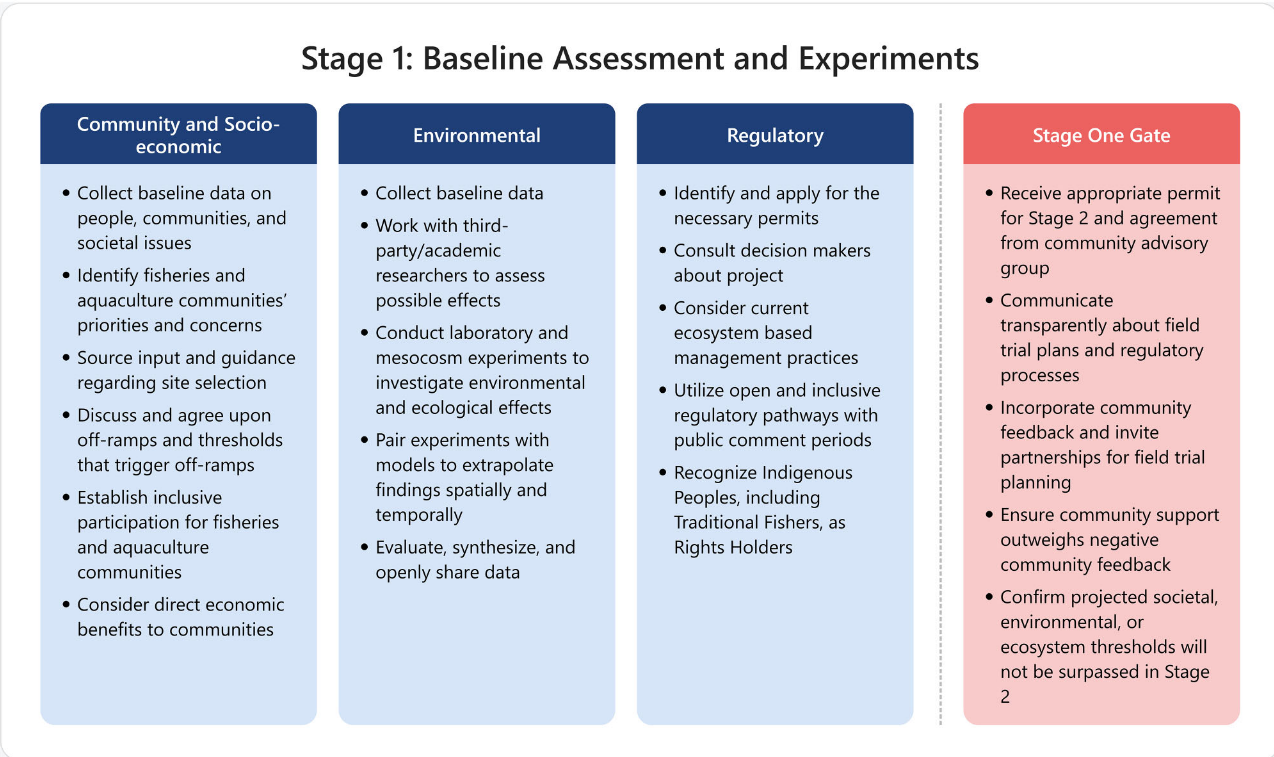

Figure 4 Stage 1: Figure describing the Stage 1 priorities (blue) and gate (red) for baseline assessment and experiments.

trient cycles can have feedbacks on greenhouse gas emissions beyond carbon dioxide (e.g. nitrous oxide, which is 300 times more potent than carbon dioxide). Models can also help provide a reference for future baselines without mCDR techniques, accounting for potential climate impacts that may occur without climate intervention. Enhancing existing ecosystem and fisheries models to incorporate mCDR efforts is a possibility; the suitability of these models for mCDR work can be evaluated in Stage 0. Collaboration between experimentalists and modelers can inform experimental parameters and modeling variables, ensuring experimental findings and baseline data can be incorporated into model scenarios. While comparing models and developing standards remains an active research area (Fennel et al. 2025; Ward et al. 2025), model scenarios can be co-developed with fishers and aquaculture farmers to investigate specific questions aligned with their priorities, such as key species, areas of interest, and potential co-benefits. Collaboration with local researchers and research centers across public and private entities may help expedite model development by leveraging regional knowledge and capacity to develop targeted, robust models for mCDR purposes.

As projects collect laboratory, mesocosm, and modeling results throughout this stage, it is expected that the data will be evaluated and synthesized to inform field trial planning. Providing results to the broader community can be done not only through academic publishing pathways but also by reaching relevant communities through public communications and presentations. These practices should follow modern data-management practices, including opportunities for the community to provide feedback and input (FAIR Data, U.S. White House 2024; AGU Ethical Framework 2024). Considering input from fisheries and aquaculture practitioners alongside experimental results can help identify biological and ecological thresholds that inform the field trials' stop points. To support field trial plans, these stop-points are essential for predetermined off-ramps. Best practices suggest that stop-points be co-developed with community members and decided upon before commencing field trials (Ocean Visions 2025). Input from experts across sectors can also inform the experimental and modeling tools used in this stage to develop long-term monitoring plans and strategies, including methodologies, metrics, and/or indicators that can be deployed and/or innovated upon to enhance MRV and EIA during field trials.

Stage 1: Regulatory considerations

At this stage, alignment with regulatory processes relevant to the project type and jurisdiction is important to inform initial experiments and baseline measurements. Given that this framework is designed for projects aiming to progress to field trials, this stage should focus on obtaining and applying for the necessary permits for the field trial site and conducting the required preliminary experiments that assess potential impacts, inform risk, and address community priorities. It is important for projects to consider current ecosystem-based management practices and regional spatial planning to determine how the project may complement and integrate with existing ocean-based activities. At this stage, the project should include consultations with decision-makers (e.g. regulatory and rights holders) regarding the project and proposed research, to ensure the project is prepared to comply with current and future permitting requirements. Throughout these processes, it is essential to recognize the rights of Indigenous Peoples, including Traditional Fishers, and include Indigenous representatives as decision-makers, not just as invested communities.

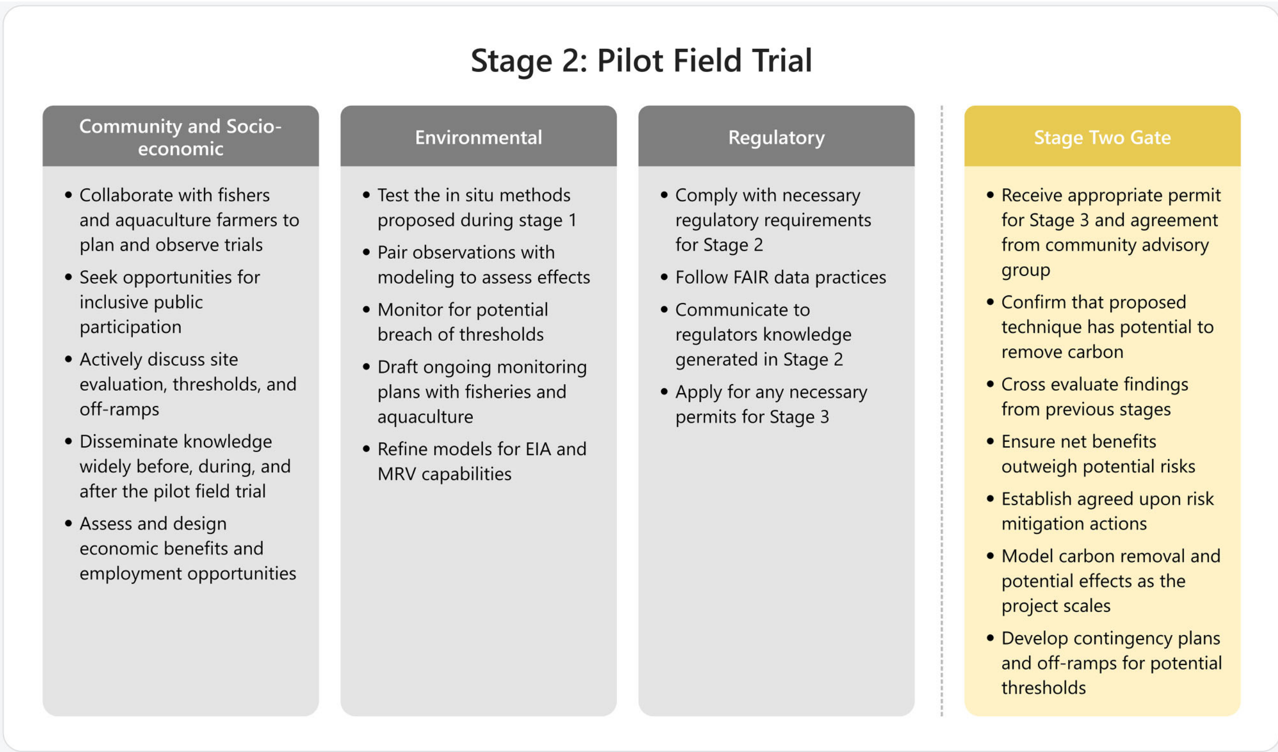

Figure 5 Stage 2: Figure describing the Stage 2 priorities (gray) and gate (yellow) for pilot field trials.

Stage 1 gate—Evaluate prior to moving to Stage 2

Prior to passing through the Stage 1 Gate and proceeding to Stage 2, all projects are expected to adhere to the considerations outlined above and obtain the appropriate permit to conduct small-scale field trials (Fig. 4: Stage 1). Additionally, the project should comply with the following check-points: (1) Obtain the appropriate permits for Stage 2 and support for community advisory group; (2) share results with fisheries, aquaculture, and interested communities from laboratory, mesocosm, and modeling experiments, alongside plans for potential field trials, noting that this stage should consider the time required to conduct experiments. This should include transparent data presentations and honest reporting of uncertainties. By applying the precautionary principle, an absence of knowledge does not necessarily preclude projects to proceed (AGU Ethical Framework 2024); (3) inform communities about the regulatory process to encourage participation and gain feedback to incorporate into in future processes, including open access to information and communication with co-design features; (4) incorporate findings from Stage 1 into ecosystems-based models to ensure projected impacts during Stage 2 are net positive; (5) invite partnerships with communities/fishers/aquaculture for projects, including planning for participation in field trials; and (6) present and discuss any thresholds observed during laboratory, mesocosm, and modeling experiments with community members to collectively agree on limits and off-ramps that can be applied to future field trials.

If the following conditions are encountered, the project is recommended to remain in Stage 1 until they have been resolved or consider alternative project plans (1) Community support outweighs negative community feedback (i.e. through engagement and/or public comments), especially from major fisheries associations within the region and/or community engagement suggest additional research is needed to address community concerns or incorporate mitigating protocols in the design; (2) regulatory pathways restrict the progression of the project to field trials; (3) if societal, environmental, and ecosystem thresholds determined through this stage, especially those associated with key species, are projected to be surpassed in Stage 2, the project developer should consider project alterations, such as modifying plans to reduce or eliminate the risk and/or scaling down the research and sharing results of the decision to ramp down.

Stage 2: Pilot field trial (100s tons CO_2 removal per year)

After passing through the Stage 1 Gate, Stage 2 suggests small-scale pilot field trials. While the MRV of carbon removal is not addressed in this framework, projects progressing through Stage 2 and subsequent stages are assumed to have tested and verified the effectiveness of carbon removal at each field-trial stage. Here, we assess whether there are any effects beyond carbon removal (Fig. 5: Stage 2). While the mCDR community does not have consensus on what constitutes a small-scale field trial, leaning on the suggested addition of 10s of tons of alkalinity during OAE within the EIMF (Fawcett et al. 2025), and recommends that this stage supports projects that assess their initial field research, which includes a small perturbation, while considering temporal and spatial scales. While this framework does not focus on monitoring, reporting, and verification (MRV) of carbon removal, moving beyond Stage 2 will depend on additional research confirming that the mCDR technique can viably and durably remove and store carbon at scale (Fennel et al. 2025). It is, however, worth noting that numerical tools used for carbon removal MRV can also provide insights into non-carbon responses, given their reliance on biogeochemical models. Although a primary goal of many initial mCDR field trials may be to assess effectiveness in carbon dioxide removal, we also recommend maximizing data collection on socio-economic, environmental, and regulatory impacts as they relate to fisheries and aquaculture, which can provide critical information needed before a project can scale up.

Stage 2: Community engagement and socio-economic impacts

Engagement should continue during Stage 2 by providing opportunities for interested groups (especially fishers, aquaculture farmers, and resource managers) to participate in ongoing work and prepare for future stages. Projects are encouraged to continue expanding partnerships and collaborations with fishers and aquaculture farmers as relevant. By seeking opportunities for community-based science and inclusive public participation, fisheries and aquaculture communities can be involved in the projects, such as by collecting data for monitoring and/or accessing ship time during the pilot field trials. Fisheries and aquaculture observers can be invited to observe the field trials and encouraged to report back to their communities. Including observers in planning for future field trials, discussions, and reassessments about critical aspects as new information is generated provides fishers an opportunity to participate and learn first-hand about the project, enabling them to form their own opinions (Schumann 2025). Essential topics to actively discuss include site evaluation, societal, environmental, and ecological thresholds, and potential off-ramps. By assessing these aspects after they were agreed upon in Stage 1 and tested during the field trial in Stage 2, they can be re-evaluated with the new information to agree upon decisions for Stage 3. To continue increasing the number of actors engaged in these conversations and mCDR literacy, projects are encouraged to disseminate knowledge widely before, during, and after the pilot field trials, including through publications and fora commonly used by fishers and farmers. To continue evaluating economic impacts for fishers and aquaculture farmers, projects are encouraged to assess the potential financial implications at larger field trials and climate-relevant scales. For example, assessments could investigate potential economic effects on the commercial fishing industry, such as spatial competition between shoreside and ocean (e.g. displacements, limited port space for all vessels, support businesses forced to leave a port), environmental impacts, and seafood quality (Hogan et al. 2023). Through robust and meaningful engagement pathways, fishers and aquaculture farmers can actively influence opportunities to benefit economically as the projects progress and create employment opportunities that align with their interests.

Stage 2: Environmental impacts

Evaluation of potential environmental impacts is an important component of conducting small-scale field trials (Riebesell et al. 2023). However, since Stage 2 is limited to small-scale trials, small perturbations may make it difficult to measure or observe environmental changes, so it is useful to pair observations with modeling efforts. This Stage provides an opportunity to test the *in situ* methods proposed in Stage 1 and to align measurements of environmental and biological metrics/indicators between the field and laboratory/mesocosms. Then mCDR trials can be designed as ecological perturbation experiments using before-after-control-impact (BACI), before-after-gradient (BAG), or other methodologies using captive organisms deployed in the zone of mCDR activity or by measuring aspects of the native ecosystem (Jankowska et al. 2025; Methratta 2020). Designing these experiments requires careful collaboration with biogeochemical and oceanographic modelers who can estimate exposure patterns around mCDR test deployments (Dupont and Metian 2023). Depending on the scale of the mCDR test, ecosystem-based models, designed to examine food-web interactions, may be informative. However, most pilot-scale tests of abiotic methods (OAE and DOCCS) are likely to be of such limited spatial or temporal extent that ecosystem or fisheries models may not be very sensitive in estimating project impact. Biotic mCDR methods (i.e. ONF, macroalgae, upwelling) involve explicit ecosystem manipulation, and therefore ecosystem-based or fisheries models may generate useful projections that can be evaluated at the pilot study scale. It is also recommended that environmental conditions are monitored for potential breach of the agreed thresholds (McElhany et al. 2026). Informed by these learnings, an environmental monitoring plan can be drafted with fisheries and aquaculture farmers to prepare for larger field trials.

Stage 2: Regulatory considerations

Complying with regulatory processes and associated permits is a priority in this stage. A key part of this is to follow best practices for FAIR data (i.e. Aspen Institute Code of Conduct 2023; AGU Ethical Framework 2024; U.S. White House 2024) to promote data transparency, including compliance with academic and government requirements for open access and unbiased data. Further work can also be done at this stage to communicate with regulators about the knowledge generated from trials to inform future permitting applications or regulatory processes for larger-scale field trials (Webb et al. 2024). To prepare for Stage 3, it is also important to apply for any additional permits required to move from a small-scale to a larger-scale field trial.

Stage 2 gate—Evaluate prior larger-scale field trial

Before passing through the Stage 2 Gate and proceeding to larger field trials in Stage 3, the considerations mentioned above should be implemented. The project should show (Fig. 5: Stage 2) that there is evidence (MRV assessments, not discussed in this framework) that confirms that the technology being investigated has the potential to remove carbon at scale and/or any other potential benefits at scale (i.e. a project may provide local ocean acidification mitigation or provide habitats even if it is not effective for global carbon reduction). It is also beneficial to cross-evaluate all conclusions from Stage 1 and Stage 2, based on laboratory, mesocosm, modeling, and small-scale field trial data, to ensure that predictions for scaling up the project to Stage 3 demonstrate that the expected benefits outweigh the projected risks. Before proceeding to Stage 3, the project is recommended to have any appropriate permits and agreement from the community advisory group.

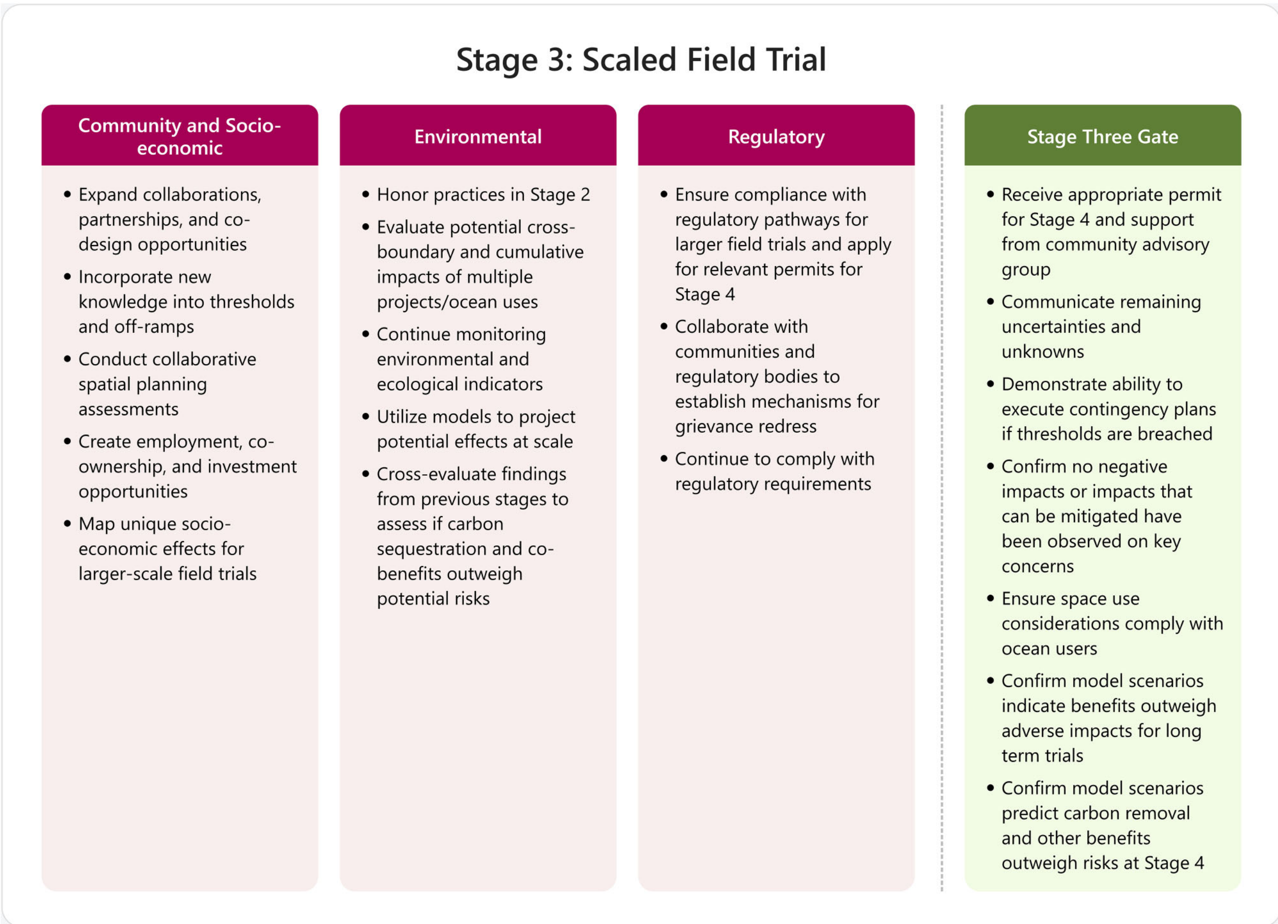

Figure 6 Stage 3: Figure describing the Stage 3 priorities (pink) and gate (green) for scaled field trials.

The following check-points are also recommended before proceeding to Stage 3: (1) continued overall positive support from critical communities, open communication with communities and decision-makers, and transparent sharing of information and data; (2) ensure that future field trial plans (developed in collaboration with communities and regulatory bodies) are compliant with permitting regulations and community priorities, especially relating to site selection; (3) establish agreed upon risk mitigation actions (i.e. monitor for passing thresholds; only discharge certain concentrations; only conduct technique in certain locations), based on results from Stages 1 and 2, to minimize risk of adverse impacts; (4) model the carbon removal and potential impacts as the project scales to inform a risk assessment that establishes risk mitigation actions; and (5) develop contingency plans that allow for halt in operations if a threshold is reached for larger field trials in Stage 3.

Stage 3: Scaled up field trial (kilo- to mega-tons CO_2 removal per year)

Stage 3 recommends similar actions and assessments to those in Stage 2, except that it includes larger-scale field trials (Fig. 6: Stage 3). The goal of this stage is to investigate whether observations from Stage 2 scale with deployment size and to assess whether compounding impacts become present at these larger scales. This stage also allows fisheries and aquaculture communities to determine whether larger deployments interfere with and/or benefit their communities in disproportionate ways as mCDR scales up.

Stage 3: Socio-economic impacts

Projects in Stage 3 are recommended to continue focusing on many of the Stage 2 priorities. For example, projects are recommended to continue meaningful engagement with identified key groups and communicate findings to explore additional avenues for collaboration, partnership, and co-design. This stage should also continue to incorporate new knowledge into key discussions around assessing and adjusting societal, environmental, and ecological thresholds that inform potential off-ramps and/or decisions to modify or cease operations. Collaborative assessments with fishers and aquaculture farmers, community members, and decision-makers should also continue to coordinate spatial planning assessments and to consider ethical choices for site selection (See Box 6) as information is learned throughout the project. As the project scales, potential economic opportunities for fisheries and aquaculture communities should also continue to be created through employment, co-ownership, and future investments. Mapping socio-economic risks and opportunities and identifying aspects unique to larger-scale field trials and/or more sustained operations are also critical considerations before proceeding to the next stage.

Stage 3: Environmental impacts

To assess potential adverse impacts and co-benefits at larger scales, Stage 3 is recommended to honor Stage 2 practices, such as monitoring ecological and environmental metrics/indicators before, during, and after the trial to detect changes relative to the background state. Projects are also encouraged to continue using models to project potential effects at scale and consider potential cross-boundary and cumulative impacts of multiple mCDR operations that could co-exist in each area as well as those stemming from other human ocean uses and associated pressures on the local or regional marine environment and ecosystems (e.g. other industrial uses of the ocean or cumulative impacts stemming from land-ocean interactions). By cross-evaluating findings from Stages 0–3, projects at this stage should assess the impacts and uncertainties to determine if observed carbon removal and co-benefits outweigh potential adverse impacts.

Stage 3: Regulatory considerations

With larger field trials in Stage 3, it is important to remain transparent, make ethical choices, and partner with independent third parties for unbiased evaluation of the potential impacts of mCDR techniques. Projects are expected to continue to conduct environmental and species-related impact monitoring to comply with regulatory requirements. Projects in Stage 3 should establish regulatory compliance requirements for larger field trials and apply for any additional permits required to continue for sustained periods of time during Stage 4. At this Stage, project leads should also work with regulatory bodies to assess the implications of spatial-temporal overlap between CDR projects and other ocean uses. The project should continue collaborating with communities and regulatory bodies to establish mechanisms for grievance redress, including formal reporting, third-party review, and integration into permitting infrastructure (UNDRIP).

Stage 3 gate—Evaluate prior to pre-commercialization

Prior to passing through the Stage 3 Gate and proceeding to Stage 4, it is recommended to obtain support from the community advisory group (Fig. 6: Stage 3). Remaining uncertainties should be communicated to acknowledge the unknowns, including, but not limited to, the magnitude of carbon removal. In addition to this, before proceeding to long-term field trials, the following checkpoints must be met: (1) obtain any relevant permits for Stage 4; (2) demonstrate ability to execute contingency plans if agreed upon thresholds are reached; (3) confirm no negative impacts or impacts which cannot be mitigated have been observed on key concerns identified during previous engagement; (4) ensure space use considerations still comply with fishers, aquaculture farmers, and other ocean users' priorities; (5) confirm model scenarios of mCDR technique extrapolated temporally and spatially to the next scale, indicate that carbon removal and other benefits still outweigh any adverse impacts in Stage 4 across societal, economic, environmental, and ecological impacts.

Stage 4: Long-term monitoring (continuously removing mega-tons of CO_2 per year)

Long-term monitoring

At the pre-commercialization stage, projects are expected to deploy for near-continuous periods on the same scale as Stage 3 (Fig. 7: Stage 4). At this scale, projects will implement methods and impact assessments aligned with practices in previous stages but will cover wider geographic regions and longer timeframes. Given the extended timeframe, it is expected that projects continue to engage fisheries and aquaculture communities actively, routinely share findings, and reassess priorities periodically. Co-developed socio-economic, regulatory, and environmental thresholds established with fisheries, aquaculture, and other invested communities can be compared to baseline values to determine if impacts are adverse or beneficial. Most recommendations from Stage 2 and Stage 3 apply here, with specific recommendations to: (1) continue to collect data and use data in models to extrapolate potential impacts spatially and temporally; (2) communicate routinely with fisheries and aquaculture communities, including by sharing all data and making it available to community members, and iterate on project design to incorporate feedback and increase involvement in project; (3) train additional fishers and aquaculture farmers on monitoring techniques and other relevant skills to enhance opportunities for co-ownership/partnership and community monitoring for long-term deployments and future opportunities, (4) provide recommendations to regulatory pathways for fisheries and aquaculture participation based on learnings; and (5) empower fishers and aquaculture farmers to explore additional opportunities in related mCDR projects.

To keep the gate open for Stage 4

To keep the gate open and continue conducting a pre-commercial stage field trial, it is essential that the community advisory group continues to support the project. The following considerations are also recommended (Fig. 7: Stage 4): (1) continuously conduct long term monitoring and assess chronic and cumulative adverse impacts and co-benefits; and (2) have established clear off-ramps and stop research deployment if: (a) agreed thresholds are exceeded, (b) iterative reassessment within the Stages shows that adverse impacts outweigh the benefits (both carbon removal and additional co-benefits), (c) regulatory pathways suggest the research is not compliant, and/or (d) communities are impacted negatively more than they are benefited.

Recommendations to improve impact assessment capacity

This framework outlines a holistic approach to scaling mCDR projects, including assessing socio-economic, regulatory, and environmental co-benefits and adverse impacts through a fisheries and aquaculture lens. However, the authors recognize gaps in foundational knowledge needed to conduct this research at scale, which may complicate the framework's implementation. Therefore, some recommendations to enhance the effective research on impact include:

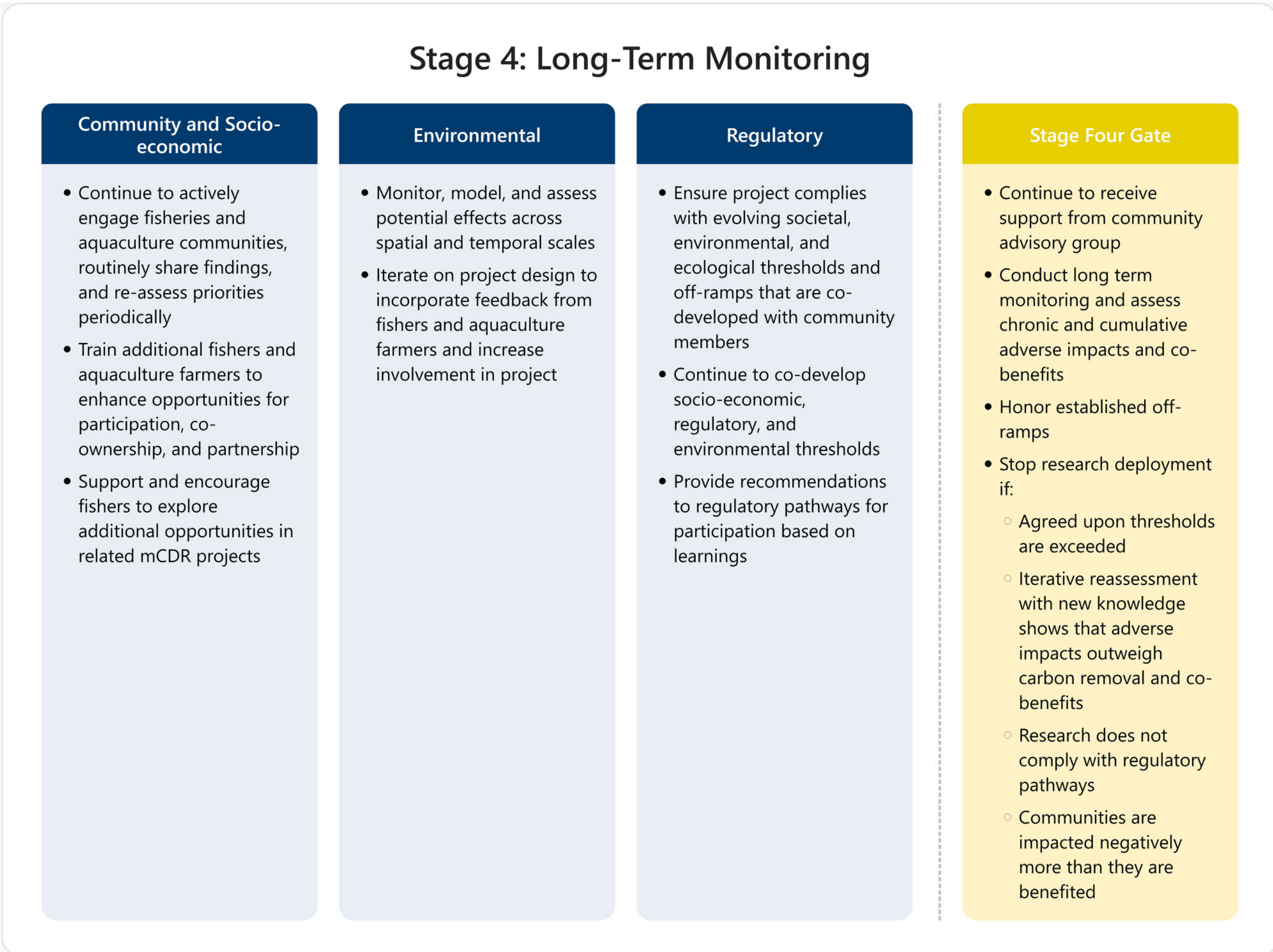

Figure 7 Stage 4: Figure describing the Stage 4 priorities (blue) and gate (yellow) for long-term monitoring.

- Create interdisciplinary test-bed sites to assess potential impacts in collaboration with fishers and aquaculture farmers to encourage partnerships across natural and social science, enable community engagement, and assist with navigating regulatory pathways;
- Consider selecting sites for projects where sufficient baseline ecological/environmental information exists to constrain natural variability, thereby facilitating evaluation of departures from the natural state;
- Assess potential economic impacts associated with co-benefits and adverse impacts to incorporate into carbon markets and economic analysis of mCDR pathways;
- Continue to improve methodologies and technologies to monitor and observe environmental perturbations associated with mCDR and develop methodologies that fisheries and aquaculture farmers can conduct.
- Critically test models' capability to reliably forecast environmental conditions temporally and spatially to understand environmental and ecological perturbations associated with mCDR techniques and co-design model scenarios with fishers and aquaculture farmers' input;
- Increase support for fisheries and aquaculture farmers' engagement from boundary organizations and other unbiased third-party organizations to assess and communicate widely community priorities related to impacts;
- Co-develop, with fisheries and aquaculture representatives, research on regulatory pathways to encourage environmental and ecological impact assessments associated with mCDR projects;
- Develop pathways to enable information sharing on application of this framework to field settings between activities mCDR entities to enable iterative improvement, which would enable more effective and streamlined research on this topic;
- Bring capacity to bear to data transparency and data management issues that could enable broader dissemination of knowledge gained through mCDR activities and application of this framework;
- Support capacity building on the topic of mCDR to enable more informed engagement and participation in activities and decision-making processes.

Holistic approaches that consider the co-benefits and risks across sectors will require collaboration, with private and public research funds dedicated to conducting experiments to determine whether each mCDR technique has positive or negative impacts on commercially and recreationally important fish and shellfish species. With emerging frameworks on environmental impacts (i.e. Fawcett et al. 2025; funded Fugro EIA) and social and ethical best practices (i.e. Aspen Institute Code of Conduct 2023), groups pursuing mCDR projects are beginning to recognize the need to improve our understanding of the impacts of mCDR. Here, we present the first framework to assess the potential socio-economic, regulatory, and environmental impacts on fisheries and aquaculture communities. We envision this framework remaining a living document in association with the official ICES Working Group on Marine carbon dioxide removal (mCDR) and interactions with ecosystems, fisheries and aquaculture (WGmCDRFISH), so that it can evolve to address fishers and aquaculture farmers' priorities as the sector develops and as information is learned, and mCDR projects continue to develop. By presenting this framework, we encourage all mCDR projects to consider the benefits of enhancing collaboration and interactions with the fisheries and aquaculture communities.

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Author contributions

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Supplementary material

Supplementary material is available at *ICES Journal of Marine Science* online.

Conflict of interest

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Data availability

The data underlying this article are available in the article and in its online Supplementary material.

References

Abdel-Basset M, Gamal A, Chakrabortty RK *et al.* A new hybrid multi-criteria decision-making approach for location selection of sustainable offshore wind energy stations: a case study. *J Cleaner Prod* 2021;**280**:124462. https://doi.org/10.1016/j.jclepro.2020.124462

American Geophysical Union. Ethical framework principles for climate intervention research. *ESS Open Archive* 2024;**1**:1–28.

Anderson SR, Stadler K, Verones F. From global emissions to local impacts: spatially explicit modeling of ocean acidification in life cycle assessment. *Environ Sci Technol* 2025;**59**:22508–17. https://doi.org/10.1021/acs.est.5c02069

Arvidsson R, Tillman A-M, Sandén BA *et al.* Environmental assessment of emerging technologies: recommendations for prospective LCA. *J Ind Ecol* 2018;**22**:1286–94. https://doi.org/10.1111/jiec.12690

Aspen Institute Staff and Energy and Environment Program. A code of conduct for marine carbon dioxide removal. *Science* 2023;**354**:182–3. https://doi.org/10.1126/science.aah4567

Bamber RN, Seaby RMH. The effects of power station entrainment passage on three species of marine planktonic crustacean, Acartia tonsa (Copepoda), Crangon crangon (Decapoda) and Homarus gammarus (Decapoda). *Mar Environ Res* 2004;**57**:281–94. https://doi.org/10.1016/j.marenvres.2003.08.002

Bennett NJ, Relano V, Roumbedakis K *et al.* Ocean equity: from assessment to action to improve social equity in ocean governance. *Front Mar Sci* 2025;**12**:1473382. https://doi.org/10.3389/fmars.2025.1473382

Bergerson JA, Brandt A, Cresko J *et al.* Life cycle assessment of emerging technologies: evaluation techniques at different stages of market and technical maturity. *J Ind Ecol* 2020;**24**:11–25. https://doi.org/10.1111/jiec.12954

Bezner Kerr R, Naess LO, Allen-O'Neil B *et al.* Interplays between changing biophysical and social dynamics under climate change: implications for limits to sustainable adaptation in food systems. *Global Change Biol* 2022;**28**:3580–604. https://doi.org/10.1111/gcb.16124

Blanchard JL, Novaglio Ce. Climate change risks to marine ecosystems and fisheries—Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project.Technical Paper, No. 707. FAO, Rome, 2024.

Blythe JL, Claudet J, Gill D *et al.* The ocean equity index. *Nature* 2026;**650**:123–8. https://doi.org/10.1038/s41586-025-09976-y

Borja A, Elliott M, Teixeira H *et al.* Addressing the cumulative impacts of multiple human pressures in marine systems, for the sustainable use of the seas. *Front Ocean Sustain*, 2024;**1**:1308125. https://doi.org/10.3389/focsu.2023.1308125

Bruijn H, Van Duin R, Huijbregts MA *et al.*. (Eds.) 2002 *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards, Eco-Efficiency in Industry and Science*. Dordrecht: Springer Netherlands. https://doi.org/10.1007/0-306-48055-7

Chlela S, Selosse S. Life cycle assessment and system integration of carbon dioxide removal: addressing challenges in environmental evaluation and model representation. *Current Sustain Renew Energy Rep* 2025;**12**:21. https://doi.org/10.1007/s40518-025-00271-y

Cooley SR, Klinsky S, Morrow DR *et al.* Sociotechnical considerations about ocean carbon dioxide removal. *Annu Rev Mar Sci* 2023;**15**:41. https://doi.org/10.1146/annurev-marine-032122-113850

Corella-Puertas E, Hajjar C, Lavoie J *et al.* MarILCA characterization factors for microplastic impacts in life cycle assessment: physical effects on biota from emissions to aquatic environments. *J Cleaner Prod* 2023;**418**:138197. https://doi.org/10.1016/j.jclepro.2023.138197

Corliss K, von Biela V, Coletti H *et al.* Relative importance of Macroalgae and Phytoplankton to nearshore consumers and growth across climatic conditions in the Northern Gulf of Alaska. *Estuaries Coasts* 2024;**47**:1579–97. https://doi.org/10.1007/s12237-024-01371-6

Cosme N, Hauschild MZ. Characterization of waterborne nitrogen emissions for marine eutrophication modelling in life cycle impact assessment at the damage level and global scale. *Int J Life Cycle Assess* 2017;**22**:1558–70. https://doi.org/10.1007/s11367-017-1271-5

Cosme N, Koski M, Hauschild MZ. Exposure factors for marine eutrophication impacts assessment based on a mechanistic biological model. *Ecol Modell* 2015;**317**:50–63. https://doi.org/10.1016/j.ecolmodel.2015.09.005

Cross JN, Sweeney C, Jewett EB *et al. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio*. (NOAA Special Report). Washington DC: NOAA. 2023.

Curren G, Fanning L, Lawton P *et al.* Challenges to incorporating social and economic factors into cumulative effects assessments in Canada's marine conservation areas. *Ecol Soc*, 2022;**27**:35. https://doi.org/10.5751/ES-13342-270235

Cyronak T, Albright R, Bach LT. Field experiments in ocean alkalinity enhancement research. *State of the Planet* 2023:2–oae2023, https://doi.org/10.5194/sp-2-oae2023-7-2023

de Baar HJW, Boyd PW, Coale KH *et al.* Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment. *J Geophys Res: Oceans* 2005;**110**:C09S16. https://doi.org/10.1029/2004JC002601

de Castro I, Ribeiro SC, Louvado A *et al.* Ocean liming effect on a North Atlantic microbial community: changes in composition and rates. *Front Mar Sci* 2025;**12**:1–11. https://doi.org/10.3389/fmars.2025.1602158

Díaz H, Loughney S, Wang J *et al.* Comparison of multicriteria analysis techniques for decision making on floating offshore wind farms site selection. *Ocean Eng* 2022;**248**:110751. https://doi.org/10.1016/j.oceaneng.2022.110751

Doney S, Lebling K, Ashford OS *et al.*. *Principles for responsible and effective marine carbon dioxide removal development and* *governance*. Washington, DC: World Resources Institute, 2025. https://doi.org/10.69902/84b3a9a8

Dong Y, Rosenbaum RK, Hauschild MZ. Metal toxicity characterization factors for marine ecosystems—considering the importance of the estuary for freshwater emissions. *The International Journal of Life Cycle Assessment* 2018;**23**:1641–53. https://doi.org/10.1007/s11367-017-1376-x

Dupont S, Metian M. General considerations for experimental research on ocean alkalinity enhancement. *State of the Planet 2-oae2023*. 2023;**4**. https://doi.org/10.5194/sp-2-oae2023-4-2023

Edwards PET, Haugan PM, Schumann S *et al.* Harmonising fisheries and aquaculture with marine carbon dioxide removal governance: challenges and opportunities. *ICES J Mar Sci*. In Review.

European Commission, European Research Executive Agency (EREA). Dissemination and exploitation. 2025. Available at: https://rea.ec.europa.eu/dissemination-and-exploitation_en#:~:text=Download-,The%20complementary%20role%20of%20communication,16%20June%202023 (8 December 2025, date last accessed).

Export Import Bank of United States (EXIM) "Environmental Impact Assessment Reports." Environmental Impact Assessment Reports | EXIM.GOV. https://www.exim.gov/policies/exim-bank-and-environment/environmental-impact-assessment-reports#:~:text=Baseline%20data:%20assesses%20the%20dimensions,and%20cumulative%20impacts%20as%20appropriate (10 November 2025, date last accessed).

FAO. The State of World Fisheries and Aquaculture 2024–Blue Transformation in action. 2024. https://doi.org/10.4060/cd0683en

Fawcett S, Kitidis V, Findlay H *et al. Ocean Alkalinity Enhancement (OAE) Environmental Impact Monitoring Framework*. Plymouth, United Kingdom: PML Applications, 2025.

Fennel K, The Verification Challenge of Marine Carbon Dioxide Removal. *Annu Rev Mar Sci* 2025c;141–64. https://doi.org/10.1146/annurev-marine-032123-025717

Findlay HS, Feely RA, Grabb K *et al.* Perspectives on marine carbon dioxide removal from the global ocean acidification observing network. *Oceanograph* 2025;**38**:24–39, https://doi.org/10.5670/oceanog.2025.e308

Flipkens G, Horoba K, Bostyn K *et al.* Acute bioaccumulation and chronic toxicity of olivine in the marine amphipod *Gammarus locusta*. *Aquat Toxicol* 2023;**262**:106662. https://doi.org/10.1016/j.aquatox.2023.106662

Foteinis S, Andresen J, Campo F *et al.* Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. *J Cleaner Prod* 2022;**370**:133309. https://doi.org/10.1016/j.jclepro.2022.133309

Foteinis S, Campbell JS, Renforth P. Life cycle assessment of coastal enhanced weathering for carbon dioxide removal from air. *Environ Sci Technol* 2023;**57**:6169–78. https://doi.org/10.1021/acs.est.2c08633

Fulton CJ, Berkström C, Wilson SK *et al.* Macroalgal meadow habitats support fish and fisheries in diverse tropical seascapes. *Fish Fisher* 2020;**21**:700–17. https://doi.org/10.1111/faf.12455

Fuss S, Lamb WF, Callaghan MW *et al.* Negative emissions—Part 2: costs, potentials and side effects. *Environ Res Lett* 2018;**13**:063002. https://doi.org/10.1088/1748-9326/aabf9f

Gill AB, Degraer S, Lipsky A *et al.* Setting the context for offshore wind development effects on fish and fisheries. *Oceanography* 2020;**33**:118–27. https://doi.org/10.5670/oceanog.2020.411

Grabb K, Wood M, McElhany P. An annotated literature database to support research on marine carbon dioxide removal (mCDR) and fisheries impacts. 2026. Preprint, CDRXIV. https://cdrxiv.org/preprint/519?version=1

Grabb KC, Clevenger S, Findlay HS *et al.* The importance of engagement with fisheries, aquaculture, and Indigenous communities in the planning and implementation of marine carbon dioxide removal (mCDR). *ICES J Mar Sci* 2025;**82**:fsaf198. https://doi.org/10.1093/icesjms/fsaf198

Guo Y, Chen K, Subhas AV *et al.* Site selection for ocean alkalinity enhancement informed by passive tracer simulations. *Commun Earth Environ* 2025;**6**:535. https://doi.org/10.1038/s43247-025-02480-1

Gurney-Smith H, Grabb K, Findlay H *et al.* State of the knowledge on the interactions between mCDR and fisheries. In Review.

Halpern BS, Frazier M, O'Hara CC *et al.* Cumulative impacts to global marine ecosystems projected to more than double by mid-century. *Science* 2025;**389**:1216–1219. https://doi.org/10.1126/science.adv2906

Hamman E. Cumulative effects assessment under the World Heritage and Ramsar regimes. *Environ Manag* 2025;**75**:2886–900. https://doi.org/10.1007/s00267-025-02236-9

Hengstmann E, Corella PZ, Alter K *et al.* Chemical emissions from offshore wind farms: from identification to challenges in impact assessment and regulation. *Mar Pollut Bull* 2025;**215**:117915. https://doi.org/10.1016/j.marpolbul.2025.117915

Hogan F, Hooker B, Jensen B *et al. Fisheries and offshore wind interactions: synthesis of science*. Woods Hole, MA, USA: National Oceanic and Atmospheric Administration (NOAA), 2023.

Høiberg MA, Borgelt J, Mostert PS *et al.* Marine debris impacts on Hawaiian green sea turtles (Chelonia mydas): high prevalence of hook-and-line fishing gear in strandings. *Mar Pollut Bull* 2025;**215**:117869.

Hooper G, Findlay HS, Bell TG *et al.* Removal of dissolved inorganic carbon from seawater for climate mitigation: potential marine ecosystem impacts. *Front Clim* 2025;**7**:1–15. https://doi.org/10.3389/fclim.2025.1528951

Hou L, Lu Y, Xu N *et al.* Unveiling the impacts of noise pollution on marine fish community dynamics. *Ecol Modell* 2025;**505**:111117. https://doi.org/10.1016/j.ecolmodel.2025.111117

Hourglass Climate. Framework for Ecotoxicological Modeling of mCDR (FEMM). 2025.

Huijbregts MAJ, Steinmann ZJN, Elshout PMF *et al.* ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 2017;**22**:138–47. https://doi.org/10.1007/s11367-016-1246-y

Iglesias-Rodríguez MD, Rickaby REM, Singh A *et al.* Laboratory experiments in ocean alkalinity enhancement research. *State of the Planet 2-oae2023*. 2023;**5**. https://doi.org/10.5194/sp-2-oae2023-5-2023

Intergovernmental Panel on Climate Change (IPCC), ed. *Climate Change 2022–Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, 2023.

Intergovernmental Panel on Climate Change (IPCC). Sixth Assessment Report (AR6) Annex I Glossary, 2023. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_Annex-I.pdf

Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. 2019;3–35 pp.

ICES WKmCDR. Workshop on marine Carbon Dioxide Removal (WKmCDR; outputs from 2024 Meeting). *ICES Sci Rep* 2025;**7**:16. https://doi.org/10.17895/ices.pub.28246358

Islam D, Berkes F. Indigenous peoples' fisheries and food security: a case from northern northern Canada. *Food Security* 2016;**8**:815–26. https://doi.org/10.1007/s12571-016-0594-6

ISO 14044:2006 [WWW Document], n.d. ISO. URL https://www.iso.org/standard/38498.html (30 November 2025, date last accessed).

Jankowska E, Matthew S, Bonnie XC *et al.* Limited impact on oysters in first-of-its-kind field trial of marine carbon dioxide removal (mCDR) strategy. *Preprint CDRXIV* 2025;**1**.https://cdrxiv.org/preprint/326

Katish M, Millar R, Foteinis S *et al.*. Life cycle assessment of ocean alkalinity enhancement using hydrated carbonate minerals. *Environ Technol Innovatio* 2026;104849. https://doi.org/10.1016/j.eti.2026.104849

Khakzad S, Griffith D. The role of fishing material culture in communities' sense of place as an added-value in management of coastal areas. *J Mar Isl Cult* 2016;**52**:95–117. https://doi.org/10.1016/j.imic.2016.09.002

Langlois J, Fréon P, Steyer J-P *et al.* Sea-use impact category in life cycle assessment: state of the art and perspectives. *Int J Life Cycle Assess* 2014;**19**:994–1006. https://doi.org/10.1007/s11367-014-0700-y

Langlois J, Freon P, Steyer J-P *et al.* Sea use impact category in life cycle assessment: characterization factors for life support functions. *Int J Life Cycle Assess* 2015;**20**:970–81. https://doi.org/10.1007/s11367-015-0886-7

Lavoie J, Boulay A-M, Bulle C. Aquatic micro- and nano-plastics in life cycle assessment: development of an effect factor for the quantification of their physical impact on biota. *J Ind Ecol* 2022;**26**:2123–35. https://doi.org/10.1111/jiec.13140

Lawford-Smith H, Currie A. Accelerating the carbon cycle: the ethics of enhanced weathering. *Biol Lett* 2017;**13**:20160859. https://doi.org/10.1098/rsbl.2016.0859

Lloret J, Wawrzynkowski P, Dominguez-Carrió C *et al.* Floating offshore wind farms in Mediterranean marine protected areas: a cautionary tale. *ICES J Mar Sci* 2023;**82**:1–14.

Lotze HK, Tittensor DP, Bryndum-Buchholz A *et al.* Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc Natl Acad Sci* 2019;**116**:12907–12. https://doi.org/10.1073/pnas.1900194116

Lundquist CJ, Fisher KT, Le Heron R *et al.* Science and societal partnerships to address cumulative impacts. *Front Mar Sci* 2016;**3**. https://doi.org/10.3389/fmars.2016.00002

Magnuson-Stevens Fishery Conservation and Management Act. National Oceanic and Atmospheric Administration, U.S. Department of Commerce. 2007. https://www.fisheries.noaa.gov/s3//dam-migration/msa-amended-2007.pdf (7 September 2025, date last accessed).

Marhoon A, Murphy EL, Høiberg MA *et al.* An effect factor for macro- and microplastic ingestion impacts on marine ecosystems for use in life cycle assessment. *Mar Pollut Bull* 2026;**223**:118968. https://doi.org/10.1016/j.marpolbul.2025.118968

Mariani G, Guiet J, Bianchi D *et al.*. The combined impact of fisheries and climate change on future carbon sequestration by oceanic macrofauna. *Nat Commun* 2025;**16**:8845, 1–15 .

Markusson N, Buck HJ, Carton W *et al.* Carbon removal and the empirics of climate delay. *Environ Sci Policy* 2024;**161**:103884. https://doi.org/10.1016/j.envsci.2024.103884

McElhany P, Cape M, Faucher G *et al.* Biological thresholds for mCDR changes to seawater carbonate chemistry. *EGU Sphere* 2026. Preprint. https://doi.org/10.5194/egusphere-2026-1597

McMillan LJ, Prosper K. Remobilizing netukulimk: indigenous cultural and spiritual connections with resource stewardship and fisheries management in Atlantic Canada. *Rev Fish Biol Fisher* 2016;**26**:629–47. https://doi.org/10.1007/s11160-016-9433-2

Methratta ET. Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. *ICES J Mar Sci* 2020;**77**:890–900. https://doi.org/10.1093/icesjms/fsaa026

Moni SM, Mahmud R, High K *et al.* Life cycle assessment of emerging technologies: A review. *J Ind Ecol* 2019;**24**:52–63. https://doi.org/10.1111/jiec.12965

Myridinas M, Fennel K, Laurent A *et al.* Prospective site-specific life cycle assessment of ocean alkalinity enhancement. *Environ Res Lett* 2026;084010. https://doi.org/10.1088/1748-9326/ae5a4e

NASEM. *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. Washington, D.C: National Academies Press, 2022. https://doi.org/10.17226/26278

Nawaz S, Belotti G. *Engaging coastal communities on ocean alkalinity enhancement*. Washington, DC: Institute for Responsible Carbon Removal, American University, 2025.

Nurdiawati A, Mir BA, SG A-G. Recent advancements in prospective life cycle assessment: current practices, trends, and implications for future research. *Res Environ Sustain* 2025;**20**:100203. https://doi.org/10.1016/j.resenv.2025.100203

O'Brien B, Jennifer A, Rich W *et al.* Mapping the Way Forward: Spatial Data Inventory and Insights for Marine Planning in the Central Atlantic Region. *NOAA NOS NCCOS Tech Memo 359*, 2025;**74**. https://doi.org/10.25923/5dyp-nv24

Ocean Visions. Ocean Visions mCDR Field Trial Map. 18 July 2025. https://oceanvisions.org/mcdr-field-trial-map/ (20 October 2025, date last accessed).

Oschlies A, Slomp CP, Altieri AH *et al.* Potential impacts of marine carbon dioxide removal on ocean oxygen. *Environ Res Lett* 2025;**20**:073002.https://doi.org/10.1088/1748-9326/ade0d4

Oschlies A, Stevenson A, Bach LT *et al.*. *Guide to Best Practices in Ocean Alkalinity Enhancement Research*. Göttingen, Germany: Copernicus Publications, 2023;1–242. https://doi.org/10.5194/sp-2-oae2023

Paul K, McCarty M, Grabb KC *et al.* An Indigenous Approach to Marine Carbon Dioxide Removal (mCDR): the importance of recognizing Indigenous Peoples and traditional fisher harvester rights to inclusive engagement, partnership, and co-ownership. *ICES JMS*. In Review.

Pelletier NL, Ayer NW, Tyedmers PH *et al.* Impact categories for life cycle assessment research of seafood production systems: review and prospectus. *Int J Life Cycle Assess* 2007;**12**:414–21. https://doi.org/10.1065/lca2006.09.275

Riebesell U, Basso D, Geilert S *et al.* Mesocosm experiments in ocean alkalinity enhancement research. *State of the Planet 2-*

oae2023 2023;**6**. https://doi.org/10.5194/sp-2-oae2023-6-2023

Roberts KE, Rohr T, Raven MR *et al.* Potential impacts of climate interventions on marine ecosystems. *Rev Geophys* 2026;**64**:e2024RG000876. https://doi.org/10.1029/2024RG000876

Rosenbaum RK, Bachmann TM, Gold LS *et al.* USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int J Life Cycle Assess* 2008;**13**:532–46. https://doi.org/10.1007/s11367-008-0038-4

Rosenbaum RK, Hauschild MZ, . Boulay A-M *et al. Life Cycle Assessment* 2018;167–270. https://doi.org/10.1007/978-3-319-56475-3_10

Scherer L, Gürdal İ, van Bodegom PM. Characterization factors for ocean acidification impacts on marine biodiversity. *J Ind Ecol* 2022;**26**:2069–79. https://doi.org/10.1111/jiec.13274

Schumann S. Fishermen Voice Concerns about Ocean Alkalinity Experiments National Fisherman, 2024. Available at: www.nationalfisherman.com/fishermen-voice-concerns-about-ocean-alkalinity-experiments”⟩/fishermen-voice-concerns-about-ocean-alkalinity-experiments (7 September 2025, date last accessed).

Schumann S. A fisherman’s report to the fleet on an ocean alkalinity enhancement field trial. 2025. Available at: https://mailchi.mp/876f13f4539b/a-fishermans-report-to-the-fleet-on-an-ocean-alkalinity-enhancement-field-trial (7 September 2025, date last accessed).

Schwarz AE, Herlaar S, Cohen QM *et al.* Microplastic aquatic impacts included in life cycle assessment. *Resour Conserv Recycl* 2024;**209**:107787. https://doi.org/10.1016/j.resconrec.2024.107787

Spyridonidou S, Vagiona DG. Systematic review of site-selection processes in onshore and offshore wind energy research. *Energies* 2020;**13**:5906. https://doi.org/10.3390/en13225906

Stelzenmüller V, Coll M, Cormier R *et al.* Operationalizing risk-based cumulative effect assessments in the marine environment. *Sci Total Environ* 2020;**724**:138118. https://doi.org/10.1016/j.scitotenv.2020.138118

Tagliabue A, Twining BS, Barrier N *et al.* Ocean iron fertilization may amplify climate change pressures on marine animal biomass for limited climate benefit. *Global Change Biol* 2023;**29**:5250–60. https://doi.org/10.1111/gcb.16854

Thonemann N, Schulte A, Maga D. How to conduct prospective life cycle assessment for emerging technologies? a systematic review and methodological guidance. *Sustainability* 2020;**12**:1192. https://doi.org/10.3390/su12031192

U.S. White House. *National Marine Carbon Dioxide Removal Research Strategy.* . Washington DC: Executive Office of the President of the United States, 2024.

United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) : resolution /adopted by the General Assembly. Refworld. 2007. Available at: https://www.refworld.org/legal/resolution/unga/2007/en/49353 (6 September 2025, date last accessed).

Ward ND, Hinson KE, Pagès R *et al.* Regional ocean biogeochemical modeling challenges for predicting the effectiveness of marine carbon dioxide removal. *Front Clim* 2025;**7**:1640617. https://doi.org/10.3389/fclim.2025.1640617

Webb RM. International governance of ocean-based carbon dioxide removal: recent developments and future directions. *Sabin Center for Climate Change Law, Columbia Law School*, 2024;**1**:1–26. https://scholarship.law.columbia.edu/sabin_climate_change/216

Wender BA, Foley RW, Prado-Lopez V *et al.* Illustrating Anticipatory Life Cycle Assessment for Emerging Photovoltaic Technologies. *Environ Sci Technol* 2014;**48**:10531–8. https://doi.org/10.1021/es5016923

Woods JS, Verones F, Jolliet O *et al.* A framework for the assessment of marine litter impacts in life cycle impact assessment. *Ecol Indic* 2021;**129**:107918. https://doi.org/10.1016/j.ecolind.2021.107918

van de Mortel H, Bednaršek N, Pelletier G *et al.* Substantial limitations of ocean alkalinity enhancement in mitigating the negative impacts of ocean acidification on marine calcifiers. *Environ Sci Technol* 2025;**60**:622–41. https://doi.org/10.1021/acs.est.5c09298

Zhou J-H, Guo Y-Z, Zhao X *et al.* Impacts of shellfish and macroalgae mariculture on the seawater carbonate system and air-sea CO2 flux in Haizhou Bay, China. *Mar Environ Res* 2024;**202**:106774. https://doi.org/10.1016/j.marenvres.2024.106774

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