NATIONAL MARINE CARBON DIOXIDE REMOVAL RESEARCH STRATEGY

A Report by the

FAST TRACK ACTION COMMITTEE on

MARINE CARBON DIOXIDE REMOVAL

of the

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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About the Fast Track Action Committee on Marine Carbon Dioxide Removal (mCDR FTAC)

The Fast Track Action Committee on Marine Carbon Dioxide Removal (mCDR FTAC) was established in September 2023 to provide overall guidance and direction regarding marine carbon dioxide removal science and policy to the NSTC through the SOST. The mCDR FTAC responds to a key recommendation of the Ocean Climate Action Plan (OCAP) to facilitate and accelerate relevant policy and research on marine carbon dioxide removal (mCDR).

About this Document

The mCDR FTAC was charged with developing this research plan to facilitate and accelerate relevant policy and research on mCDR. Any future federal activities will be considered in the broader context of Administration priorities and available resources.

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Abbreviations and Acronyms

BGC	Biogeochemical
CO_2	Carbon Dioxide
CDR	Carbon Dioxide Removal
CWA	Clean Water Act
CZMA	Coastal Zone Management Act
DOE	Department of Energy
DOI	Department of the Interior
EPA	Environmental Protection Agency
ESA	Endangered Species Act
GO-SHIP	Global Ocean Ship-Based Hydrographic Investigations Program
IK	Indigenous Knowledge
IWG-mCDR	Interagency Working Group on mCDR
LCA	Life Cycle Analysis
mCDR	Marine Carbon Dioxide Removal
mCDR FTAC	Fast Track Action Committee on Marine Carbon Dioxide Removal
MMRV	Measurement, Monitoring, Reporting, and Verification
MPRSA	Marine Protection, Research, and Sanctuaries Act
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NPDES	National Pollutant Discharge Elimination System
NSF	National Science Foundation
NSTC	National Science and Technology Council
OCAP	Ocean Climate Action Plan
OSTP	Office of Science and Technology Policy
SOST	Subcommittee on Ocean Science and Technology
TEA	Techno-Economic Assessment
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USFWS	U.S. Fish and Wildlife Service

Executive Summary

Since Day One, President Biden and Vice President Harris have delivered on the most ambitious climate agenda in history, including significant investments in clean energy, climate resilience and adaptation, nature-based solutions, and environmental justice. They set a goal to cut our greenhouse gas emissions in half by 2030 and achieve a net-zero emissions economy by 2050 to avoid the most catastrophic impacts to people and the planet.

The ocean spans 70 percent of the globe, from shallow bays to the depths and areas beyond any nation's jurisdiction. The White House recognizes that paving the path to a healthy and livable climate requires a healthy ocean, including the open ocean, coasts, estuaries, and the U.S. Arctic, Great Lakes, and territories. The ocean also has the potential to advance powerful climate solutions. That is why the Biden-Harris Administration released the first-ever Ocean Climate Action Plan (OCAP) in March 2023 as a whole-of-government roadmap to harness the power and capacity of the ocean to address the climate crisis.

The OCAP identifies marine carbon dioxide removal (mCDR) as an area that requires closer attention. mCDR refers to approaches that use ocean processes to increase the amount of atmospheric carbon dioxide taken up by the ocean, adding to the large, natural ocean carbon sink. Even without deliberate mCDR, the ocean will continue to absorb anthropogenic carbon dioxide but at a slower rate than greenhouse gases are building up in the atmosphere. If mCDR approaches could safely increase the ocean's uptake of carbon dioxide as a complement to deep emissions reductions, mCDR could become a valuable tool to help avoid the most devastating effects of climate change. However, more research is needed to determine if mCDR approaches are safe and effective.

Given the importance of the ocean, disruptions to its functioning have the potential to harm people and ecosystems and to undermine public trust. Additional information about both the benefits and risks of mCDR is needed, as are opportunities for public engagement in decision-making surrounding mCDR research. The OCAP established a target that, by 2030, the United States should develop sufficient knowledge about the different methods of mCDR to inform potential future decision-making. While valuable mCDR research is already being conducted across the federal government, academia, and the private sector, a comprehensive research strategy is needed to align disparate efforts across the government and the broader mCDR research community.

In addition to accelerating progress on mCDR research, the federal government should work to ensure that this research is carried out responsibly, ethically, and safely. Inclusive, effective, and meaningful participation and engagement is one of the foundational principles of government decision-making. Communities and diverse sectors of society should be engaged early and throughout the research process to increase their awareness and involvement in mCDR research. Recognizing the importance of building trust and understanding, the federal government should promote strong collaborations and connections across the many sectors interested in and affected by mCDR. This will build the capacity needed to help society decide whether to deploy mCDR as a climate solution in the future.

This National Marine Carbon Dioxide Removal Research Strategy (hereafter referred to as the Strategy) is intended to bring OCAP's target into reach. It outlines how the U.S. government can support and fill critical knowledge gaps relating to mCDR while identifying its positive effects and mitigating its negative environmental, social, and human health impacts. Further, the Strategy demonstrates pathways by which the communities where mCDR research may occur and interested public, nonprofit, and for-profit sectors may engage with mCDR research. The Strategy advances the following objectives to guide U.S. government efforts:

1. Promote responsible mCDR research that involves communities and minimizes environmental risk.
2. Strengthen interdisciplinary areas of research to answer key questions about mCDR safety and efficacy.
3. Advance reliable and accurate measurement, monitoring, reporting, and verification (MMRV) of mCDR and the sharing of research results.
4. Prioritize research toward mCDR approaches that show the greatest promise of achieving specific benchmarks for safety, efficacy, and other criteria.
5. Ensure mCDR research is efficiently and effectively permitted under applicable laws and regulations.
6. Promote coordination across diverse sectors and communities with interests in mCDR research.

The Strategy expands on these objectives by highlighting goals, principles, and recommendations that will responsibly produce sound science to guide future decision-making. The Strategy is guided by an overarching commitment to steward a healthy and sustainable ocean and planet. The Strategy prioritizes environmental justice and robust engagement with communities, Tribal Nations, and Indigenous Peoples, including Native Americans, Alaska Natives, Native Hawaiians, and Indigenous Peoples of the U.S. territories. The Strategy aims to integrate and coordinate actions across the federal government, including through the creation of an Interagency Working Group on mCDR (IWG-mCDR). It also outlines best practices for both publicly and privately funded mCDR research.

Introduction

The global climate crisis requires urgent and transformative action to avoid more catastrophic impacts on people and ecosystems. The planet is currently about 2°F (1.1°C) warmer on average than it was in the late 1800s, and the effects of human-caused climate change are already far-reaching and worsening across every region of the United States.[1] Climate change, resulting from emissions of carbon dioxide and other greenhouse gases, is harming the health and well-being of people and communities and exacerbating social inequality.[2] Impacts include sea level rise and the alteration of marine ecosystems in unprecedented ways, including increased ocean acidification and the degradation of important habitats, such as coral reefs and kelp forests; and changes in species' distribution and productivity, threatening food security and human health.[3] Even with rapid and deep reductions in global greenhouse gas emissions, marine ecosystems and the communities that depend on them will face significant continued and worsening effects from climate change, including marine heat waves, deoxygenation, sea level rise, and ocean acidification.[4,5]

While the ocean is experiencing the adverse effects of climate change, the ocean is also a resource to address the climate crisis.[6] Paving a path to a healthy and livable climate requires ocean-based climate solutions, and in turn, ocean climate action advances the well-being of people and ecosystems.[7] Technologies may be able to harness the potential of the ocean to accelerate natural carbon removal from the atmosphere while supporting economic development, sustaining the livelihoods of local communities, conserving natural resources and biodiversity, and potentially helping to address impacts like acidification. U.S.-led ocean-based research and innovation will also advance American economic competitiveness in a growing international field and support American national security.

Carbon dioxide removal[8] (CDR) encompasses technologies and practices that durably[9] remove carbon dioxide from the atmosphere. The Intergovernmental Panel on Climate Change analyses and reports include CDR in all pathways limiting warming to 1.5° C, which is necessary to avert the worsening human and ecosystem impacts of climate change.[10] Even with extensive emissions reductions, CDR will be required to achieve net negative greenhouse gas emissions and return atmospheric greenhouse gas concentrations to pre-industrial levels.[11] The U.S. government also considers gigaton scale CDR

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[1] U.S. Global Change Research Program. 2023. Fifth National Climate Assessment. https://nca2023.globalchange.gov/

[2] Ibid.

[3] Ibid.

[4] Ibid.

[5] Ocean Policy Committee (OPC). 2023. Ocean Climate Action Plan. https://www.whitehouse.gov/wpcontent/uploads/2023/03/Ocean-Climate-Action-Plan_Final.pdf

[6] Ibid.

[7] See footnote 1.

[8] CDR refers to technologies and practices that transfer carbon dioxide from the atmosphere to a reservoir away from the atmosphere.

[9] Durable CDR removes carbon dioxide from the atmosphere for a sufficiently long period of time to be climate relevant. This is typically considered to be decades to centuries.

[10] Intergovernmental Panel on Climate Change. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/

[11] Ibid.

necessary to achieve the goal of net-zero emissions economy-wide by no later than 2050.[12] Sustainable and climate-relevant[13] scales of CDR will involve a diversity of approaches, including emerging strategies and techniques.[14]

Potential CDR pathways include mCDR approaches that increase the amount of atmospheric carbon dioxide taken up by the ocean (see Box 1: mCDR Approaches). Such ocean processes are likely to have caused significant reductions of atmospheric carbon dioxide concentrations in the geologic past.[15] The ocean already naturally absorbs approximately one-third of human-made carbon dioxide emissions[16] and has the potential to hold 17 times more carbon than soils and land biota combined.[17] Enhancing the ocean's ability to take up carbon dioxide, therefore, could hold great potential for drawing down atmospheric carbon dioxide. Even without deliberately deploying mCDR, the ocean will continue to absorb increasing levels of anthropogenic carbon dioxide; however, this natural absorption is not sufficiently rapid to counteract anthropogenic carbon emissions. Furthermore, it is uncertain how climate change will affect the ocean's carbon dioxide absorption rate, which may vary over time.

Box 1: mCDR approaches

mCDR is any method that accelerates biological or non-biological processes to move carbon dioxide from the atmosphere into the ocean carbon sink. This document considers the following mCDR approaches (see also Figure 1).

<u>Artificial downwelling</u>: Using pumps or other methods to transport carbon dioxide-rich seawater from the surface ocean to the deep ocean.

<u>Artificial upwelling:</u> Using pumps or other methods to transport nutrient-rich seawater from the deep ocean to the surface ocean to increase photosynthesis in nutrient-limited surface waters, allowing the organic carbon created to eventually sink back down to the deep ocean.

<u>Macroalgae cultivation (aquaculture) and sinking</u>: Growing seaweed in the surface ocean or terrestrial crops to capture carbon dioxide and transporting that biomass to the deep ocean.

<u>Direct ocean capture</u>: Removing dissolved carbon dioxide from seawater by various engineered processes and returning carbon dioxide-depleted water to the surface of the ocean. Carbon dioxide

[12] U.S. Department of State and Executive Office of the President. 2021. The Long-Term Strategy of The United States. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-Strategy.pdf

[13] Climate-relevant refers to the timescales in which removed carbon would have a positive impact on mitigating climate change. This timescale will depend on the speed of transition to renewable energy and other reductions in greenhouse gas emissions.

[14] Deprez, A., et al. 2024. Sustainability limits needed for CO_2 removal. *Science*. https://www.science.org/doi/10.1126/science.adj6171

[15] National Academies of Sciences, Engineering, and Medicine. 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. https://doi.org/10.17226/26278

[16] Gruber, N., et al. 2019. The Oceanic Sink for Anthropogenic CO_2 from 1994 to 2007. https://doi.org/10.1126/science.aau5153

[17] Friedlingstein, P. et al. 2022. Global Carbon Budget 2022. https://doi.org/10.5194/essd-14-4811-2022

removed from seawater must then be stored through carbon sequestration in geologic formations or existing infrastructure.

Ocean alkalinity enhancement: Increasing the alkalinity of surface ocean waters to enhance the ocean carbon sink and allow for more carbon dioxide to be absorbed in the surface ocean. The approach involves modifying the natural air-sea gas exchange through the introduction of alkaline minerals, solutions, and/or electrochemical approaches.

Ocean fertilization: Adding micronutrients (e.g., iron) or macronutrients (e.g., phosphorus or nitrogen) to the surface ocean to increase photosynthesis and eventual organic carbon transport to the deep ocean.

Note: This list is non-exhaustive and derived from previous publications.[18,19] It does not imply endorsement. For the purposes of this document, mCDR approaches discussed do not include blue carbon activities or sub-seabed geologic carbon dioxide storage, but they can include actions that affect these ecosystems and/or processes. Given ongoing research and innovation, future mCDR efforts may include approaches not listed here.

Interest in mCDR is growing across academia, industry, and philanthropy, and ongoing research is advancing the scientific understanding of this field. However, mCDR research spans a wide range of approaches, each with different levels of scientific and technical maturity, knowledge gaps, environmental, social, and environmental justice concerns, and regulatory needs prior to deployment.[20,21] Additional research is needed before any mCDR technique is deployed at climate-relevant scales to ensure it is safe, scalable, affordable, and effective. Therefore, an integrated and interdisciplinary mCDR research portfolio is needed to holistically assess the potential benefits, risks, and sustainability tradeoffs of mCDR approaches.

[18] See footnote 15.

[19] Cross, J. N., et al. 2023. Strategy for NOAA Carbon Dioxide Removal Research. https://sciencecouncil.noaa.gov/wp-content/uploads/2023/06/mCDR-glossy-final.pdf

[20] See footnote 5.

[21] See footnote 15.

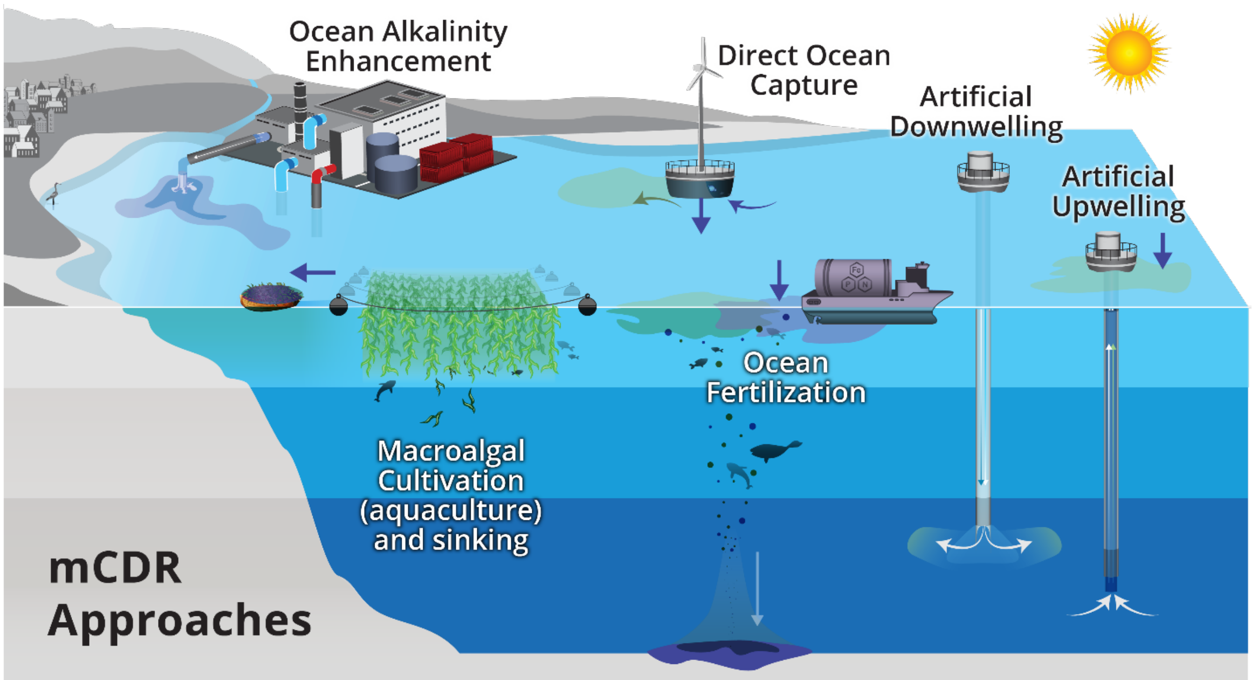

Figure 1: Schematic illustrating marine CDR approaches discussed in this Strategy. Figure by Sarah Battle, National Oceanic and Atmospheric Administration (NOAA).

All mCDR approaches elicit environmental changes at various spatial and temporal scales, which could consist of both positive and negative effects on ecosystems and people. Deploying mCDR may risk disrupting the natural carbon sink and may carry potential unintended consequences for ecosystems, human health, and other ocean uses.[22] However, the potential risks of deploying mCDR need to be weighed against the consequences of ongoing climate change without the use of mCDR. Research is needed to help inform understanding of these risks.

Goals of the National mCDR Research Strategy

This Strategy is guided by the objective established in the OCAP to build sufficient knowledge about the efficacy, safety, and tradeoffs of different methods of mCDR by 2030 to further guide decisions about potential deployment.[23] This Strategy focuses on defining and guiding the interdisciplinary research[24] needed to determine whether deployment of any mCDR approaches should be pursued, and if so, how the Federal government should prioritize those approaches. Efforts will need to include foundational research into the safety and efficacy of mCDR approaches, social science to understand the societal impacts of mCDR, and the technological development and MMRV of mCDR approaches.

[22] See footnote 15.

[23] See footnote 5.

[24] "Research" refers to scientific inquiry into mCDR approaches that the federal government has an interest in supporting or executing. This includes foundational research into the safety and efficacy of mCDR methods, social science to understand the societal impacts of mCDR, and the technological development and accounting of mCDR approaches.

This Strategy will guide the U.S. government's efforts to fill critical knowledge gaps on the efficacy, safety, tradeoffs, benefits, and drawbacks of emerging mCDR approaches. It will also inform how to maximize co-benefits while mitigating the potential negative environmental, societal, and human health impacts and safety risks. The Strategy provides guidelines for how those who are conducting mCDR research in any capacity should engage and involve communities. The Strategy will guide the research and community engagement needed to assess the viability of mCDR approaches at scale as a climate solution. The Strategy will inform priority-setting for federal funding of mCDR research and for non-federal engagement in mCDR research, and it summarizes the permitting and regulatory programs that may be applicable to mCDR research.

This Strategy was developed by the Marine Carbon Dioxide Removal Fast Track Action (mCDR FTAC) of the Subcommittee on Ocean Science and Technology (SOST) of the National Science and Technology Council (NSTC), composed of subject matter experts across the federal government. The mCDR FTAC received input from the public, including academia, philanthropic organizations, community members, and the private sector. The mCDR FTAC solicited public input through a Request for Information published in a Federal Register Notice[25] as well as three public listening sessions. The mCDR FTAC also solicited input from Tribal Nations through four Tribal engagement sessions.

The Strategy is informed by previous work synthesizing the mCDR research landscape, such as the 2022 Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration[26] published by the U.S. National Academies of Science, Engineering, and Medicine and the 2023 Strategy for NOAA Carbon Dioxide Removal Research.[27] The Strategy also builds upon existing federal research efforts[28,29] and ongoing efforts by Federal agencies to develop informational resources describing the applicable permitting process for mCDR field research activities.

The Strategy provides recommendations for work that the federal government can undertake in collaboration with Tribal Nations, Indigenous Peoples, states, U.S. territories, communities, the private sector, and civil society. This Strategy emphasizes transparency and intergovernmental coordination, including through the creation of an IWG-mCDR (see Objective 6). Furthermore, each recommendation should be advanced across the federal agencies, as resources allow. The mCDR FTAC has suggested key agencies that have roles and responsibilities related to the execution of the recommendations.

[25] NSF. 2024. Federal Register Notice: Marine Carbon Dioxide Removal Research Plan. https://www.federalregister.gov/documents/2024/02/23/2024-03758/marine-carbon-dioxide-removal-research-plan

[26] See footnote 15.

[27] See footnote 19.

[28] DOE. 2023. DOE Announces $36 Million to Advance Marine Carbon Dioxide Removal Techniques and Slash Harmful Greenhouse Gas Pollution. https://www.energy.gov/articles/doe-announces-36-million-advance-marine-carbon-dioxide-removal-techniques-and-slash#:~:text=WASHINGTON%2C%20D.C.%20%E2%80%94%20The%20U.S.%20Department,mCDR)%20capture%20and%20storage%20technologies.

[29] NOAA Ocean Acidification Program. 2023. Announcing $24.3M investment advancing marine carbon dioxide removal research. https://oceanacidification.noaa.gov/fy23-nopp-mcdr-awards/

Objective 1: Promote responsible mCDR research that involves communities and minimizes environmental risk.

Best Practices for mCDR Research

The federal government should work with interested communities to establish best practices, or a 'code of conduct', to help researchers build and maintain public trust around successful and safe mCDR research projects and approaches. A code of conduct should lay out factors that all involved parties should consider when conducting mCDR research, including assessing when, where, and how mCDR research should be conducted, as well as how to incorporate and address social, ethical, public safety, and environmental considerations. This code of conduct should be separate and distinct from, yet consistent with, the existing laws and regulations outlined in Objective 5.

Specifically, the federal government should identify a common set of norms and best practices to advance responsible, collaborative, and ethical mCDR research, whether conducted by public or private entities. These practices should span the life cycle of an mCDR project, engage the public, build public trust, inform research design, develop awareness of social and environmental impacts, and enforce scientific integrity and ethical stewardship of materials and data. In that vein, guidance in line with environmental justice principles can minimize the potential risks of mCDR research to the public, the marine environment, and other uses of the ocean while advancing research and development of potential mCDR approaches. A societal framework for environmentally just decision-making is imperative to ensure that the benefits and impacts of potential mCDR activities are understood and addressed throughout the lifecycle of a project.

The federal government and other interested parties should consider the following principles when identifying best practices and developing a code of conduct for mCDR research.

- **Environmental Justice**: Environmental justice is the just treatment and meaningful involvement of all people, regardless of income, race, color, national origin, Tribal affiliation, or disability, in agency decision-making and other federal activities that affect human health and the environment so that people: (i) are fully protected from disproportionate and adverse health and environmental effects (including risks) and hazards, including those related to climate change, the cumulative impacts of environmental and other burdens, and the legacy of racism or other structural or systemic barriers; and (ii) have equitable access to a healthy, sustainable, and resilient environment in which to live, play, work, learn, grow, worship, and engage in cultural and subsistence practices.[30] All people should be able to engage with decisions that impact their lives, including through actively engaging those who have been excluded from past environmental decision-making. Researchers should consider justice and equity throughout the full life cycle of a project, from design to project siting to the timing of the project to resource acquisition and waste disposal to the sunsetting of the project.[31]

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[30] E.O. 14096. Revitalizing Our Nation's Commitment to Environmental Justice for All. 2023. https://www.federalregister.gov/documents/2023/04/26/2023-08955/revitalizing-our-nations-commitment-to-environmental-justice-for-all

[31] Environmental Justice Subcommittee. 2024. Environmental Justice Science, Data, and Research Plan. https://www.whitehouse.gov/wp-content/uploads/2024/07/NSTC-EJ-Research-Plan-July-2024.pdf

People, especially those who have historically been burdened and underserved, should have access to information and the capacity, tools, and resources necessary to engage in federal, state, and local ocean decision-making processes.[32,33,34] mCDR research and potential deployment should not perpetuate or excuse pollution.

- **Local Community Engagement:** Early, frequent, and meaningful engagement with interested parties and local communities where projects may be deployed or where impacts may occur should be an element of any mCDR project, beginning with project conceptualization. It is critical that project developers establish long-term relationships with people who rely on ocean resources that may be impacted by mCDR activities. Engagement should continue throughout the project, as relationship and trust building are time-intensive processes and require sustained and sincere action from project developers.
- **Consideration of impacts on people and ecosystems:** Direct, indirect, and cumulative[35] effects of mCDR on people, ecosystems, the ocean economy, and other uses of the ocean should be considered throughout a project's life cycle. For example, accounting for the cumulative effects of mCDR may include assessing impacts on communities that rely on the ocean for subsistence or face challenges such as local pollution and economic distress. Project developers are encouraged to develop evaluation, safety and response, and continuity plans in coordination with community representatives.
- **Collaborative stewardship with Indigenous Peoples:** Project developers should seek opportunities to partner with Tribal Nations and other Indigenous Peoples to plan, design, carry out, and evaluate the results of mCDR projects where possible.[36]
- **Informed and iterative research:** Research that takes place in the ocean should build on, be preceded by, and be continuously informed by other mCDR research conducted outside the marine environment (e.g., in the lab or through modeling) to safeguard human health and ecosystem well-being.
- **Data sharing and transparency:** Research projects should prioritize data sharing and follow best practices for public data accessibility and transparency to ensure scientific integrity, accelerate mCDR research, alert others engaged in oceanographic research and observations to the existence of mCDR activities, and bridge the gap between field observations and subsequent decision-making based on these data.

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[32] OPC. 2023. Ocean Justice Strategy. https://www.whitehouse.gov/wp-content/uploads/2023/12/OceanJustice-Strategy.pdf

[33] See footnote 30.

[34] The White House. Justice40. https://www.whitehouse.gov/environmentaljustice/justice40/.

[35] For definitions, see Council on Environmental Quality (CEQ). 2024. National Environmental Policy Act Implementing Regulations Revisions Phase 2. https://www.federalregister.gov/documents/2024/05/01/2024-08792/national-environmental-policy-act-implementing-regulations-revisions-phase-2

[36] For more information, see Joint Secretarial Order No. 3403. 2022. Joint Secretarial Order on Fulfilling the Trust Responsibility to Indian Tribes in the Stewardship of Federal Lands and Waters. https://www.bia.gov/sites/default/files/dup/inline-files/joint-so-3403-a1_0.pdf

- **Scientific integrity:** Research should adhere to professional practices, ethical behavior, and the principles of honesty, objectivity, and transparency when conducting, managing, using the results of, and communicating about mCDR science and scientific activities.[37]

The federal government should develop the code of conduct in strong collaboration with the broader mCDR community and other interested parties. Once developed, the mCDR code of conduct would be most effective if adopted by the entire mCDR community, including researchers inside and outside of government. Federal agencies should consider how to incorporate the code of conduct into research and funding opportunities, such as requiring grant recipients to adhere to the code's best practices.

Similar efforts have been conducted by the broader CDR research community, such as the Department of Energy (DOE) Responsible Carbon Management Initiative,[38] and frameworks have been published by non-federal partners[39,40,41] and developed in other research fields (e.g., biosecurity[42] and nuclear science[43]). Implementation should consider relevant recommendations from federal guidance and strategy documents, such as the Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts,[44] the Ocean Justice Strategy,[45] the Guidance for Federal Departments and Agencies on Indigenous Knowledge,[46] and the Environmental Justice Science, Data, and Research Plan.[47]

Recommendations:

- **Develop a detailed 'code of conduct' for mCDR research,** building upon the list above, with robust input from mCDR researchers, communities, Tribal Nations, Indigenous Peoples, states, U.S. territories, the private sector, and civil society. Key agencies: IWG-mCDR.
- **Encourage adoption of the code of conduct** throughout the mCDR research community and its application to relevant federally funded and permitted mCDR research efforts, when appropriate. Key agencies: IWG-mCDR.

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[37] OSTP. 2023. Scientific Integrity Policy. https://www.whitehouse.gov/wp-content/uploads/2023/06/OSTP-SCIENTIFIC-INTEGRITY-POLICY.pdf

[38] Office of Fossil Energy and Carbon Management. Responsible Carbon Management Initiative. https://www.energy.gov/fecm/responsible-carbon-management-initiative

[39] Aspen Institute. 2023. A Code of Conduct for Marine Carbon Dioxide Removal Research. https://www.aspeninstitute.org/wp-content/uploads/2023/11/110223_Code-of-Conduct_FINAL2.pdf

[40] American Geophysical Union. 2022. AGU Climate Intervention Engagement: Leading the Development of an Ethical Framework. https://www.agu.org/learn-about-agu/about-agu/ethics/-/media/a8f267f3216d4bd7af49607ddc7940d4.ashx

[41] American Geophysical Union. 2024. Ethical Framework Principles for Climate Intervention Research. https://doi.org/10.22541/essoar.172917365.53105072/v1

[42] The Tianjin Biosecurity Guidelines for Codes of Conduct for Scientists. 2021. https://centerforhealthsecurity.org/sites/default/files/2023-01/20210707-iap-tianjinguidelines.pdf

[43] American Nuclear Society. 2022. Code of Ethics. https://www.ans.org/about/coe/

[44] DOE. 2023. Pathways to Commercial Liftoff: Overview of Societal Considerations & Impacts. https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Overview-of-Societal-Considerations-Impact.pdf

[45] See footnote 32.

[46] OSTP and CEQ. 2022. Guidance for Federal Departments and Agencies on Indigenous Knowledge. https://www.whitehouse.gov/wp-content/uploads/2022/12/OSTPCEQ-IK-Guidance.pdf.

[47] See footnote 31.

- **Advance scientific understanding of the ethical and social dynamics of mCDR and other climate intervention technologies**, harnessing inter-disciplinary engagement across natural, social, and behavioral sciences. Key agencies: National Science Foundation (NSF), IWG-mCDR.

Community Engagement

A key reason to conduct mCDR research is to understand the potential risks and benefits that potential deployment of these approaches pose to the environment and communities that rely on the ocean. However, mCDR research has the potential to both positively and negatively impact coastal communities. mCDR project developers and researchers should consider and address these potential impacts, from the implications for human health and safety to local economic considerations. Care should be taken to ensure that communities that rely on the marine environment for their well-being are not negatively impacted by mCDR research. Researchers should acknowledge that mCDR pilot projects[48] and field trials[49] may impact environmental, social, cultural, and economic practices and that there is a risk of inequitable distribution of these impacts. Research activities should be designed to identify risks and eliminate or minimize them, maximizing benefits for local communities by giving them a voice in the design and execution of this research.[50] By recognizing varying levels of risk that communities may face, research activities should tailor approaches to address community-specific needs and vulnerabilities. Social science research methodologies are important tools that should be used in identifying and evaluating potential community impacts and understanding what is important to communities. While the reach of individual mCDR research projects is limited, a focus on community engagement and benefit-sharing across the mCDR research landscape will identify community impacts, advance public trust, maximize positive societal outcomes, and improve communication pathways.

Recommendations:

- **Develop a roadmap to raise awareness and engage communities in mCDR research** through workshops with participants representing the diversity of the mCDR community, including industry, philanthropy, the public, government, etc. Key agencies: NOAA, DOE, Environmental Protection Agency (EPA), Department of the Interior (DOI).
- **Prioritize community benefits of mCDR research for** disadvantaged communities that are marginalized by underinvestment and overburdened by pollution, as consistent with the goals of the Justice40 Initiative.[51,52] Key agencies: IWG-mCDR.
- **Assess and communicate potential direct, indirect, and cumulative impacts from mCDR research** to the communities that rely on ocean and coastal resources. Coastal communities and

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[48] A pilot project is an initial scale-up of an mCDR technology beyond the laboratory- or bench-scale that is used to prove the viability of this technology at a larger-scale under real-world, non-ideal marine operating conditions.

[49] A field trial is an mCDR experiment in the environment that is of sufficient scale to produce results, in terms of removal and environmental impact, that are representative of the results of a commercial-scale removal.

[50] See footnote 31.

[51] E.O. 14008. Tackling the Climate Crisis at Home and Abroad. 2021. https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

[52] The White House. Justice40. https://www.whitehouse.gov/environmentaljustice/justice40/. See also Climate and Economic Justice Screening Tool. https://screeningtool.geoplatform.gov/en/#3/33.47/-97.5

those who rely on the ocean resources of a particular project location should be involved in identifying culturally and economically important species and sites. Researchers should communicate potential impacts and benefits with local communities and interested parties in a timely manner, so that communities can stay informed, involved, and able to make educated decisions about regional mCDR projects. Key agencies: NOAA, DOE, U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), EPA, DOI.

- **Enhance public education about ocean science, climate change, and ocean climate solutions** by fostering an exchange of knowledge and insights between researchers and community members. mCDR presents a valuable opportunity to improve ocean and climate literacy in coastal communities. Communication materials should be accessible to a broad audience and incorporate information presented in various formats and languages. Key agencies: NOAA, IWG-mCDR.
- **Support capacity building for mCDR research and technology development** through training opportunities, as appropriate. Emerging ocean uses such as mCDR can support a diverse and inclusive future ocean workforce that can provide insights on and capacity for the needs of the local ecosystem and community where mCDR activities occur. Key agency: NSF.
- **Provide funding to support mCDR research led by communities and Tribal Nations**, where possible. Federal agencies should build upon existing efforts[53] to compensate or provide funding to communities and Tribal Nations to increase their capacity to engage in the research permitting process and promote mCDR workforce development. Key agency: NOAA.

An Informed and Iterative Approach to mCDR Research

Research in the ocean will ultimately be necessary to answer key questions regarding mCDR, but it should be conducted in a way that minimizes risk to people and ecosystems. An informed and iterative approach to mCDR research, in which pilot projects and field trials are preceded and continuously informed by other research methods, will advance sound science, ecosystem health, and public trust. Projects should progress from hypothesis to modeling, laboratory, mesocosm,[54] and social science studies in an iterative manner as new results inform further areas of study. Pilot projects and field trials should only be undertaken when prior studies demonstrate a clear need to conduct research in the ocean (Figure 2).

Factors such as community engagement, regulatory requirements, and ecological monitoring are critical during early planning of pilot projects or field trials. In general, mCDR pilot projects and field trials conducted in the ocean, including those funded by the federal government, require environmental review and permitting before they can be conducted. While smaller-scale pilot projects may present a different risk profile than larger-scale field trials for specific mCDR techniques, pilot projects and field trials may present environmental and societal risks. Therefore, promising mCDR techniques should employ modeling, laboratory, mesocosm, and environmental response research

[53] NOAA. 2024. NOAA to make $1.5 million available to tribes for Regional Ocean Partnerships. https://www.noaa.gov/news-release/noaa-to-make-15-million-available-to-tribes-for-regional-ocean-partnerships

[54] A mesocosm is an experimental system that interrogates a research question in a natural or semi-natural environment under controlled conditions.

before pilot projects and field trials to demonstrate that the technique being tested is likely to be effective and minimize harm to the surrounding environment. At the current stage of development, mCDR pilot projects and field trials should be only as large as needed to answer the research questions at hand. These pilot projects and field trials can collect data and information to inform subsequent decisions regarding further mCDR modeling, laboratory and mesocosm research, field testing or deployment. Federal agencies should encourage project developers receiving federal funding to comply with research best practices for meaningfully engaging local communities from the outset of a project and throughout the entire process.

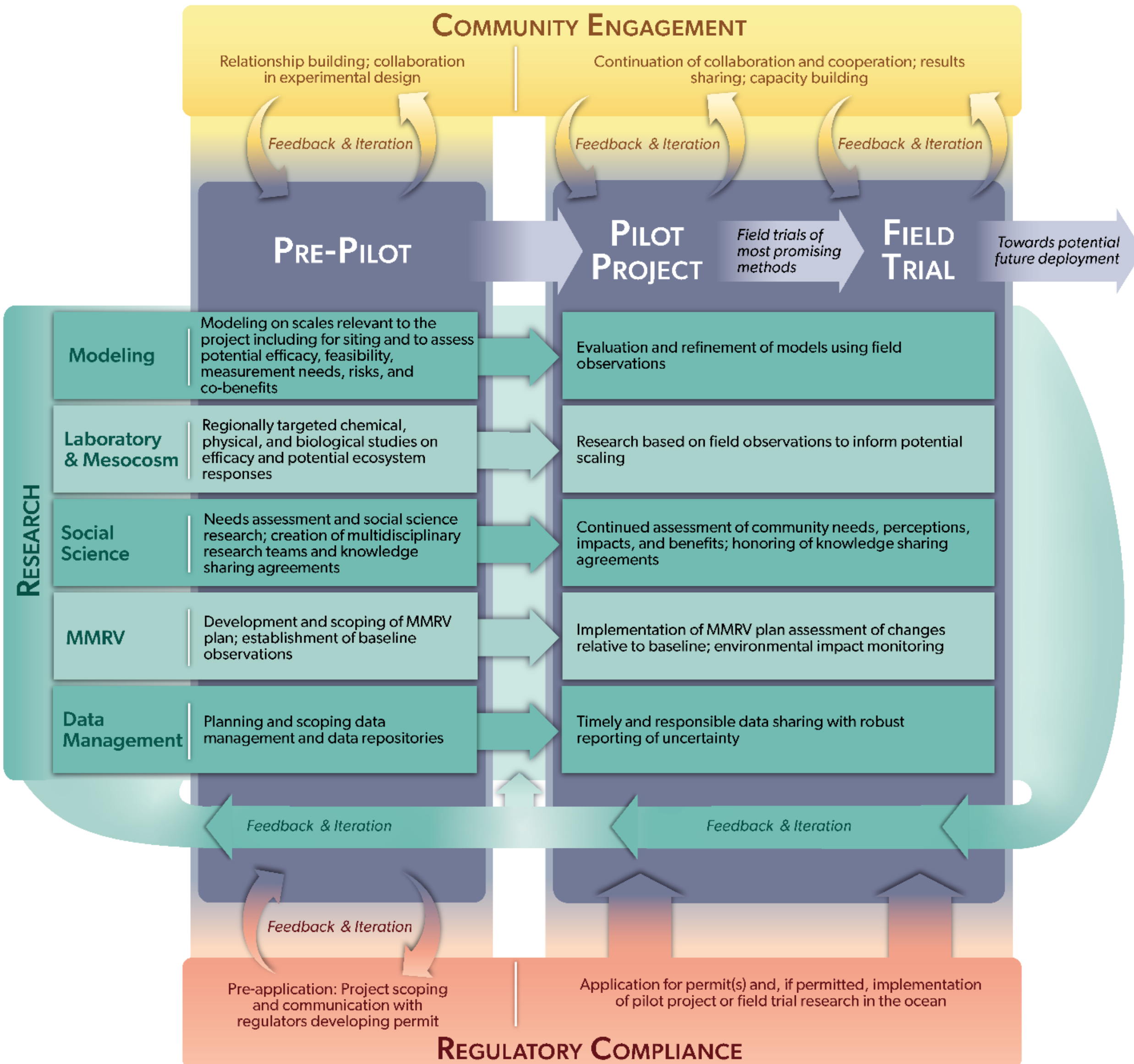

Figure 2. This schematic presents an overview of the key steps to enable mCDR research to progress from laboratory and mesocosm research to a pilot project, or initial scale-up to test an mCDR approach under real-world conditions, and field trial, or a larger-scale experiment designed to produce results representative of commercial-scale mCDR deployment. This process represents an informed and

iterative approach to advance sound science and the well-being of people and ecosystems. Figure by Chelsea Thompson, NOAA.

Objective 2: Strengthen interdisciplinary areas of research to answer key questions about mCDR safety and efficacy.

A comprehensive and interdisciplinary research agenda is needed to answer key research questions (see Box 2: Key research questions informed by recent syntheses of mCDR research) about the safety and efficacy of mCDR approaches, enabling eventual decision-making regarding their potential future deployment. Relevant modeling, strengthened empirical laboratory and mesocosm data (i.e., simulated natural environment data), and carefully designed pilot projects and field trials in well understood and monitored areas of the ocean will help determine efficacy and identify possible environmental risks of mCDR approaches. Integrating social science research into mCDR projects promotes responsible technology development that is socially acceptable, equitable, and aligned with local needs and values.

Box 2: Key research questions informed by recent syntheses of mCDR research[55,56]

- How many tons of carbon dioxide equivalents[57] can an mCDR approach remove from the atmosphere and/or surface ocean, including consideration of—
  - the amount of carbon dioxide uptake that would have occurred without intervention;
  - the amount of carbon dioxide that escapes back into the atmosphere;
  - the amount of time carbon dioxide is removed before being released back to the atmosphere, and;
  - the total greenhouse gas emissions that are produced directly or indirectly throughout the project's life cycle?
- How do ecosystems respond to the mCDR approach in question, including both co-benefits and negative adverse impacts on ocean ecosystems and culturally and economically important species?
- What cultural, public safety, economic, and other societal implications, both positive and negative, do mCDR approaches have for local communities?
- Where can an mCDR approach be most effectively deployed, and how might deployment impact the approach's contributions to advancing environmental justice?
- What resources are needed before, during, and after an mCDR project, and what is the ability of an approach to scale up, considering energy supply, need for minerals or other materials, waste disposal, etc.?

[55] See footnote 15.
[56] See footnote 19.
[57] A carbon dioxide equivalent is used to compare the emission or removal of various greenhouse gases based on how long they stay in the atmosphere and how much heat they can trap. For example, over a period of 100 years, 1 ton of methane will trap as much heat as 21 tons of carbon dioxide. Thus, 1 ton of methane removed is equal to 21 tons of carbon dioxide equivalents removed.

- How will carbon removal from potential mCDR approaches be reliably and independently measured and attributed to individual mCDR projects, considering that each mCDR project should be measured over a time period that allows for adequate assessment in the context of a complex and changing ocean, and that each ton of carbon dioxide equivalent removed must be real, additional,[58] and verifiable?

Modeling

Models can help determine the best mCDR methods, strategies, and potential pilot project and field trial locations. Numerical modeling is an essential tool for exploring mCDR feasibility, siting, processes, measurement needs, technologies, uncertainties, and potential risks and co-benefits, including assessing the overall effect on climate change mitigation at various spatial and temporal scales. Modeling is also critical to considering mCDR in the context of the ocean as a whole, and it can assess potential ecosystem responses to mCDR in the deep ocean. Additionally, modeling can help determine the necessary scale of project implementation, quantify the likely amount and durability of carbon dioxide removal, and assess potential impacts to ecosystems and communities.[59] Modeling can help expand the resolution of baseline observational data and determine what observations are necessary to enable meaningful MMRV of carbon dioxide removal.

Recommendations:

- **Maintain and improve existing oceanographic models to inform pilot projects and field trials.** Regional models with high spatial resolution will be needed to plan and evaluate the impacts of small-scale mCDR pilot projects, while global models will be needed to assess larger-scale field trials. Models at all scales need to be evaluated under baseline conditions (i.e., without the use of mCDR) to ensure that they are reliable. Fully coupled hydrodynamic-biogeochemical models should be used to produce baseline data[60] and provide insights into ecosystem function. Many existing model frameworks can be adapted for mCDR, and model intercomparisons using standardized input datasets are essential. Key agencies: NOAA, National Aeronautics and Space Administration (NASA), USGS, NSF.
- **Use models to answer questions surrounding mCDR research and deployment,** utilizing existing proposal funding mechanisms where appropriate. Models may provide insight into questions around scale and duration, assessment of the likelihood and magnitude of unintended consequences, determination of energy needs, and informed monitoring design. Incorporating mCDR approaches into global climate and Earth system models can advance understanding of the overall impacts of and responses to scaling up proposed methodologies. Empirical field observations should be used to evaluate and improve models. Key agencies: NOAA, NSF, DOE, USACE, NASA.

[58] Additional removal refers to the net removal of carbon dioxide equivalents, assessment of which requires a) measurement of a counterfactual baseline, b) measurement of gross removal, and c) calculations that account for the emissions in the production and supply chain of the removal project.

[59] See footnote 15.

[60] Baseline data are environmental observations and model output that reflect the physical, chemical, and biological characteristics of a location prior to mCDR intervention.

- **Enable model intercomparison and consistency** by reporting uncertainties and sharing data on a common, curated repository. Research agencies should then develop a government-led comparison project. Key agencies: NOAA, National Institute of Standards and Technology (NIST), NASA, DOE, USACE.
- **Conduct life cycle analyses (LCAs)[61] and techno-economic assessments (TEAs)[62]** to assess the feasibility and sustainability of mCDR approaches and projects across their life cycles, incorporating models that are rigorously evaluated. LCAs and TEAs are tools to assess life cycle emissions, energy needs, waste disposal requirements, etc., of mCDR approaches generally, in order to help compare these approaches to each other and to other possible climate solutions. Federal funding agencies should require LCAs at early research stages in their funded projects. Key agency: DOE.

Laboratory and Mesocosm Research

Laboratory and mesocosm settings can test the chemical, physical, and biological effects of mCDR interventions under controlled conditions without harm to the marine environment or communities. This information can answer key research questions, inform model development and application, support field trial permit application processes, and strengthen community engagement and responsiveness.

Recommendations:

- **Tailor laboratory and mesocosm experimental designs to specific regions,** utilizing existing proposal funding mechanisms to better set the foundation for field research where possible. Laboratory and mesocosm research should consider local oceanographic conditions, as well as conditions that are perturbed by mCDR approaches and relevant regional marine species at various life stages. Key agencies: NOAA, DOE, USGS.
- **Facilitate intercomparison between laboratory and mesocosm experiments** by publicly sharing experimental methods and key parameters for observation. Consistent experimental design and data management can allow for results to be compared across similar projects to avoid bias and facilitate syntheses across the field. Key agencies: NOAA, DOE, USGS, IWG-mCDR.

Social Science

Social, behavioral, and economic sciences (SBES) and interdisciplinary methodologies are important aspects of any responsible mCDR research project. SBES methodologies can be used to help identify and characterize the perceptions of interested parties about the use of mCDR, estimate local impacts or benefits, and identify economic or market opportunities of mCDR research, especially for local communities. Integrating SBES research into the design and implementation of mCDR projects facilitates responsible and effective technology development that is socially acceptable, equitable, and aligned with local needs and values. The federal government and partners have developed resources

[61] LCA is a methodology for assessing the environmental impacts associated with the entire life cycle of a product or process.

[62] TEA is a methodology for assessing technology states against a fixed reference case in terms of economic performance, as well as the discovery, design and operation of a process.

and guidance documents for incorporating SBES into similarly complex issues that may inform how to integrate SBES into mCDR research.[63,64,65,66,67] Co-design and iterative needs assessments for mCDR projects would ensure that research aligns with community priorities, honoring knowledge-sharing agreements and integrating diverse ways of knowing. Additionally, SBES research and needs assessments, combined with interdisciplinary teams, enhance research outcomes by incorporating varied perspectives and expertise.

Recommendations:

- **Support incorporation of SBES research and techniques early** in a project's development to assess community needs, priorities, motivations, and perceptions of mCDR research, using existing proposal-funding mechanisms. Research teams should be interdisciplinary and include researchers from the social, behavioral, and/or economic sciences to determine known and unknown impacts throughout a project's life cycle. Key agencies: NSF, NOAA, DOE.
- **Encourage the creation of knowledge sharing agreements with community collaborators or other local knowledge holders** that are transparent about data shared, data collected, and the use and availability of the data beyond the originally intended purpose (also see Objective 1, Best Practices for mCDR Research). Key agency: NOAA.
- **Integrate the many ways of knowing, including Indigenous Knowledge, local and place-based knowledge, and historical knowledge**, that may inform mCDR research. The unique knowledge and expertise held by Tribal Nations and other Indigenous Peoples should be recognized and included with appropriate consent and respect for confidentiality (also see Best Practices for mCDR Research).[68] Key agencies: NOAA, DOE, NSF, USGS.
- **Prioritize place-based research methodologies and experimental co-design principles,** including ethnographic and qualitative methods, interviews, reviews of archival materials, and considerations of local values and spaces of significance to advance understanding of community needs and concerns and to help avoid environmental, social, or cultural harm or injustices. These practices should occur for each mCDR approach in conjunction with each potentially affected community. Key agencies: NOAA, DOE, USGS.

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[63] Hawai‘i Sea Grant. 2019. Kulana Noii Community Based Research. https://seagrant.soest.hawaii.edu/kulana-noii/

[64] NOAA National Estuarine Research Reserve System Science Collaborative. Guide to Collaborative Science. 2022. nerrssciencecollaborative.org/guide

[65] See footnote 30.

[66] See footnote 31.

[67] OSTP. 2023. Blueprint for an AI bill of rights. https://www.whitehouse.gov/ostp/ai-bill-of-rights/

[68] See footnote 46.

Environmental responses

mCDR approaches have the potential to impact basic ecosystem functioning and resilience. Moving from models, laboratory, and mesocosm experiments to *in situ* testing of mCDR approaches requires a robust understanding of ecosystem and environmental baseline conditions and relevant processes and a scientific basis for assessing potential changes or impacts to the environment. Research specifically targeted at understanding likely environmental responses to different mCDR approaches will be vital to building the knowledge base needed to guide potential regulatory actions and mCDR deployment decisions. This research will inform decision-making by federal, Tribal, state, territorial, and local governments and is critically needed to inform communities about mCDR. Existing community-based research networks can lay the foundation for regional environmental response research.[69] Potential impacts and risks will vary by location and mCDR approach, so project design should be carried out in concert with determining a proposed field trial site, which is, in turn, informed by community-centered, site-, and mCDR approach-specific scientific research. Such research is needed to assess the spatial and temporal scales of environmental response to mCDR both for single projects and for the cumulative response to multiple projects, in the context of other human activities in the marine environment (e.g., co-location of mCDR research with offshore renewable energy sites).

Recommendations:

- **Strengthen characterization of physical, chemical, and ecological baselines** and relevant ocean processes, utilizing existing proposal-funding mechanisms, needed to assess the magnitude and nature of changes that result from mCDR experiments. Research may include sustained measurements, field and satellite monitoring, laboratory and *in situ* studies, and modeling, and should consider potentially impacted habitats (e.g., benthic, pelagic, nearshore, and deep sea). Key agencies: NOAA, NSF, NASA, USACE, EPA, USGS.
- **Assess local, regional, cumulative, and longer-term impacts**, including chemical, physical and biological responses. Laboratory, modeling, and field data, including from autonomous platforms and remote sensing, should be used to inform an understanding of potential impacts that large-scale or long-term mCDR projects and approaches could have on the marine environment. Key agencies: NOAA, NASA, NSF, DOE, USACE, EPA.
- **Understand environmental impacts on culturally, ecologically, and economically important species and their ecosystems**, including the effects of mCDR on species physiology, reproduction, and behavior, as well as ecosystem structure, function, processes, and services. Involving local communities can help identify culturally, ecologically, and economically important species, and potential impacts should be investigated through laboratory, mesocosm, remote sensing, and modeling efforts prior to advancing to pilot projects and field trials. Key agencies: DOI, BOEM, NOAA, NASA, EPA, NSF, USACE.
- **Encourage mCDR project development teams to have the necessary local knowledge and multi-disciplinary expertise,** when appropriate, to evaluate potential impacts to local physical,

[69] For example, the U.S. ocean acidification community uses Regional Vulnerability Assessments to work closely with invested parties and NOAA's Ocean Acidification Program to identify regional vulnerabilities to ocean acidification and establish long-term modeling.

chemical, and biological conditions and to assess potentially complex changes to ecosystem dynamics. Key agencies: NOAA, DOE, NSF, USGS, EPA, IWG-mCDR.

Pilot Projects and Field Trials

Pilot projects and field trials in the ocean may be necessary to determine the efficacy of mCDR approaches and ecosystem responses, including the potential for adverse effects. The federal government may consider identifying well-studied and well-instrumented areas of the ocean as test beds, i.e., priority areas for mCDR research, when doing so will not significantly limit other co-uses or negatively impact protected areas (see Box 3: Case Study – lessons from marine energy test beds). Allocating resources to advance testing capabilities in test beds may accelerate mCDR research by taking advantage of existing environmental baseline data, maximizing the value of long-term investments in modeling and monitoring systems, encouraging interdisciplinary collaboration, and potentially lowering the barrier to in-water testing without compromising safety or robust public engagement.

The implications of potentially developing mCDR test beds should be carefully considered by federal funding and permitting agencies. For example, researchers would need to demonstrate to permitting agencies that co-location of mCDR pilot projects or field trials is scientifically sound, consistent with regulations, and does not conflict with overall public interest.

Box 3: Case study – lessons from marine energy test beds

DOE's experience with marine energy test beds may provide useful considerations for future mCDR test beds. Similar to mCDR, many marine energy technologies are in the early stages of readiness. They face many similar questions, including about cost, social acceptance, and potential environmental impacts. Answering these questions will require a broad range of research, legal, and public relations skills. The federal agencies involved in mCDR research should consider the lessons learned from marine energy technologies, and could even consider potential synergies between existing marine energy testing capabilities and future mCDR testing needs. Two DOE marine energy test bed programs for possible consideration include the Testing and Expertise for Marine Energy (e.g., TEAMER) facility, an example of a test facility accessibility program intended to help ease the financial and time commitments required to graduate beyond lab experiments,[70] and PacWave South, a more ambitious facility that in the near future will offer an open-ocean test site for larger-scale testing.[71] These efforts and their associated investments were made possible by Congressional directive.

Recommendations:

- **Assess potential synergies between mCDR field trials and other ocean uses and activities,** including offshore wind, marine energy, or other renewable energies; desalination; wastewater

[70] TEAMER. Testing and Expertise for Marine Energy. https://teamer-us.org/

[71] Water Power Technologies Office. PacWave: Offshore Wave Energy Test Site. https://www.energy.gov/eere/water/pacwave-offshore-wave-energy-test-site

treatment; ecosystem restoration; fisheries; beach nourishment; sub-seabed carbon sequestration; and the overall reuse of existing offshore infrastructure. Energy-intensive electrochemical approaches may be particularly well-suited for co-location with renewable energy sources. Key agencies: DOE, BOEM, NOAA, USACE, EPA.

- **Consider siting coastal mCDR research test beds in observation- and data-rich areas of the ocean** to facilitate the measurement of physical and environmental effects of mCDR experiments and comparison with baseline conditions. Researchers should leverage ongoing observations, where appropriate, while recognizing the value in preserving unperturbed systems with long-term observations. Observations should enable researchers to correctly attribute the effects of specific mCDR experiments. Existing observing systems, including for active ecosystem management, navigation, and flood risk management, may be helpful in evaluating mCDR research being conducted nearby. Key agencies: NOAA, DOE, USGS, NSF, USACE, EPA.
- **Investigate promising field locations and set appropriate lifetimes for mCDR test beds.** Research areas might be selected according to a number of factors, including coastal and oceanographic characteristics, relevant expertise, institutional knowledge, baseline ecosystem data, physical infrastructure, emergency response logistics, and community support. These facilities should be long-lived, under continuous management by regulated organizations, and continue to collect data after field trials are complete. Key agencies: DOE, NOAA, USGS, BOEM, EPA, USACE.

Objective 3: Advance reliable and accurate MMRV of mCDR and the sharing of research results.

As an emerging set of ocean-based technologies and approaches, mCDR is dependent upon the collection and dissemination of new forms of reliable and accurate ocean data. MMRV will be vital to evaluate and compare mCDR pilot projects and field trials and crucial to any potential future mCDR deployment.

Ocean Observations

All levels of mCDR research, from modeling to field trials, depend upon ocean measurements and ongoing observations. Ocean observing is critical for mCDR MMRV (see Box 4: MMRV) and assessing environmental responses to mCDR technologies. Targeted expansion of coastal, open, and deep ocean observing capabilities and its associated workforce capacity will be required to meet the needs of a growing mCDR field. Technological development and investment in ocean observing systems advance national security and economic growth, all while increasing foundational knowledge of the ocean. Observing needs, including the spatial and temporal scales of monitoring, differ depending on the mCDR approach employed and the relevant spatial and temporal scales needed to evaluate efficacy and impacts. Robust experimental design will anticipate observing and MMRV needs through *in situ*, near-field and far-field remote sensing methods, complemented with modeling as necessary and appropriate.

Box 4: MMRV

As mCDR research progresses to field trials, research teams must validate the efficacy of a project over its lifetime. Such validation occurs through robust MMRV via direct measurements of marine waters, as well as models informed by empirical data throughout the scaled research process. Effective MMRV includes measuring the amount of net greenhouse gases removed by an mCDR project (accounting for potential release of greenhouse gases during a project's life cycle), monitoring carbon drawdown, reporting these findings to a third party, having the third party verify the finding, and making the data openly available for independent verification and research.[72] This iterative process is needed to produce reliable information regarding the efficacy of carbon dioxide removal and help assess the environmental soundness of mCDR approaches and techniques. Research and development of new MMRV technologies will be essential to furthering mCDR research and the potential deployment of mCDR on a climate relevant scale.

Recommendations:

- **Maintain and expand observing infrastructure** to address mCDR observing needs. Examples of existing ocean observing infrastructure of relevance to mCDR include, but are not limited to, the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP),[73] the Global Ocean Acidification Observing Network (GOA-ON),[74] OneArgo (i.e., Argo/BGC-Argo/Deep Argo),[75] NOAA's Surface Ocean CO_2 Observing Network (SOCONET),[76] NOAA's Integrated Ocean Observing System (IOOS),[77] NSF's Ocean Observatories Initiative,[78] ocean satellites such as NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission,[79] the NOAA Ocean Acidification Observing Network (NOA-ON),[80] NOAA Coastal Ocean Acidification Cruises,[81] and local and regional coastal monitoring efforts. This ocean observing infrastructure produces the critical baseline data that determine how future mCDR efforts might change the marine carbon cycle and impact ecosystems and ocean uses. Key agencies: NOAA, NSF, NASA.
- **Support the development of trusted MMRV** through the production and curation of certified reference materials, calibration schemes, databases, documentary standards, and possible proficiency testing and/or quality assurance programs. These resources will reduce uncertainty

[72] U.S. Voluntary Carbon Markets Joint Policy Statement and Principles. 2024. https://www.whitehouse.gov/wp-content/uploads/2024/05/VCM-Joint-Policy-Statement-and-Principles.pdf

[73] Global Ocean Ship-based Hydrographic Investigations Program. https://www.go-ship.org/

[74] Global Ocean Acidification Observing Network. https://www.goa-on.org/

[75] ARGO. https://argo.ucsd.edu/; GO-BGC. https://www.go-bgc.org/

[76] NOAA. 2020. Surface Ocean CO_2 Observing Network. https://www.aoml.noaa.gov/ocd/gcc/SOCONET/

[77] NOAA. Integrated Ocean Observing System. https://ioos.noaa.gov/

[78] NSF. Ocean Observatories Initiative. https://oceanobservatories.org/

[79] NASA. PACE-NASA Science. https://science.nasa.gov/mission/pace/

[80] NOAA. Developing innovative tools to connect stakeholders with NOAA's Ocean Acidification Observing Network (NOA-ON). https://oceanacidification.noaa.gov/funded-projects/developing-innovative-tools-to-connect-stakeholders-with-noaas-ocean-acidification-observing-network-noa-on/

[81] NOAA. Ocean Acidification Research Cruises. https://oceanacidification.noaa.gov/ocean-acidification-research-cruises/

and enable reproducibility and calibration across geography, time, laboratory, and practitioner. Key agencies: NIST, NOAA.

- **Delineate monitoring needs for high-quality MMRV** for each mCDR technique, including frequency of measurements and idealized modeling resolution for near-field and far-field dynamics. High-quality MMRV will assess whether mCDR is occurring as expected, and is quantifiable, additional, unique, attributable, and durable. Key agencies: NIST, IWG-mCDR.
- **Support and leverage next-generation computational and technological advances** to enable new sensing and measurement technologies that are more accurate, scalable, efficient, and affordable (see Box 5: Partnerships in ocean observing below). Key agencies: DOE, NOAA, BOEM.
- **Request MMRV plans from researchers during federal funding opportunities**, utilizing existing proposal-funding mechanisms, to track the efficacy of pilot projects and/or field trials. To the extent possible, funding agencies should develop MMRV plan requests with input from regulatory agencies to assess how MMRV and compliance measures can overlap. Key agencies: NOAA, DOE, NSF, EPA, USACE.

Box 5: Partnerships in ocean observing

At present, sustained ocean observations are largely supported by public funding, with minor to moderate investments by the private sector. Differences in observational approaches, including data accessibility, have been obstacles to the full integration of multi-source ocean observation investments. mCDR provides an opportunity to leverage multi-sector resources to meet critical monitoring needs. Multi-sector (e.g., federal, private, academic) partnerships can enhance carbon observing networks through the following:

- Technology Advancement: DOE's Advanced Research Projects Agency–Energy (ARPA-E)'s Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-CO2) program[82] invites multi-sector awardees to develop the next generation of ocean carbon sensors. The program also provides critical support in the technology-to-market transition in which private capital can phase in to support technologies after concept design. Private partners, especially those with existing platforms or field trials, are also critical in the testing development stages of such programs.
- Platform Infrastructure: To collect continuous measurements, *in situ* and satellite sensors need to be planned for uninterrupted presence in the ocean and in space. In recent years, autonomous platforms such as uncrewed surface vehicles, underwater gliders, and Argo floats, as well as ocean color satellite sensors, have been critical to understanding carbon dynamics. Federal programs often collaborate with or contract industry and academic partners with broader resources to execute such work. Such contractors may also be leveraged for private-sector monitoring needs, potentially presenting another avenue for multi-sector partnerships. For example, core platform networks under OneArgo (i.e.,

[82] ARPA-E. Sensing Exports of Anthropogenic Carbon through Ocean Observation. https://arpa-e.energy.gov/technologies/programs/sea-co2

Argo/BGC-Argo/Deep Argo)[83] rely on multi-sector frameworks, including backing from public funding.

- Seagoing Support: While autonomous and satellite remote sensing capabilities are growing, the field is not at a point where those measurements are fully linked to seawater sample analysis from shipboard studies. Programs such as the interagency sustained GO-SHIP program,[84] NOAA's Coastal Ocean Acidification Research Cruises,[85] and NASA's EXport Processes in the Ocean from Remote Sensing (EXPORTS)[86] campaign provide carbon measurements over a broad expanse of the ocean and collect high-quality data that ensure growing remote and autonomous capabilities are accurate and robust. These efforts can be expanded by collaborative partnerships with private vessels[87] that can work with federal partners to outfit seagoing investments to study relevant baseline conditions for mCDR. For example, NOAA's Ship of Opportunity Consortium[88] collects many ship-based ocean carbon measurements.

Data Management

Data will inform deployment decisions, so data management and transparency are critical as mCDR research continues to grow. Researchers should strive to manage mCDR data under findable, accessible, interoperable, and reusable (FAIR)[89] data principles, which provide for data interoperability and compatibility, discovery and access, data citation through long-term data preservation, compliance with uniform metadata and data standards, and controlled vocabularies. Similarly, following the collective benefit, authority, responsibility, and ethics (CARE)[90] principles, as appropriate, promotes equitable co-design and co-development of mCDR data best practices with Indigenous communities. Data management infrastructure will be important to facilitate robust synthesis activities and technological advancement that can help bridge the gap between observations and the subsequent research, analysis, and decision support, including potential MMRV. Usable, reliable, and public data management infrastructure will be critical to ensuring that research results are effectively communicated and research efforts are not needlessly duplicated. To this end, investment and multi-sector partnerships in data management represent a critical component of mCDR research.

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[83] See footnote 75.

[84] See footnote 73.

[85] See footnote 81.

[86] Export Processes in the Ocean from RemoTe Sensing. https://oceanexports.org/index.html

[87] NOAA and OceanX. 2023. Memorandum of Understanding (MOU) between NOAA and OceanX. https://www.noaa.gov/media-release/oceanx-and-noaa-join-to-advance-ocean-exploration-and-mapping.

[88] NOAA. AOML's Ocean Chemistry and Ecosystems Division. https://www.aoml.noaa.gov/ocd/ocdweb/occ.html

[89] FAIR: Findable, Accessible, Interoperable, and Reusable. For more information, see Wilkinson, M. D., et al. 2016. The FAIR guiding principles for scientific data management and stewardship. https://doi.org/10.1038/sdata.2016.18

[90] CARE: Collective Benefit, Authority, Responsibility, and Ethics. For more information, see Research Data Alliance International Indigenous Data Sovereignty Interest Group. 2019. CARE principles for Indigenous data governance. https://www.gida-global.org/care

The multi-sector nature of mCDR research requires clear guidelines for how proprietary data are handled. All public and private data that captures both successful and unsuccessful research should be shared in long-term public archives. As the multi-sector collaborative mCDR space grows, it is critical to develop data management tools that work for all partners and allow data to be easily integrated into different data systems. Private partners generating substantial data are encouraged to collaborate with agencies to accelerate progress. As discussed under Best Practices for mCDR Research, both public and private sector mCDR researchers will be vital in promoting responsible data management.

Recommendations:

- **Increase data accessibility and foster trust and transparency** by leveraging existing user-friendly, centralized, publicly accessible data platforms and creating new platforms as appropriate. Data should be searchable, secure, and preserved in a long-term public archive. Detailed metadata should provide vital contextual information regarding modeling or experimental parameters. Key agencies: IWG-mCDR, NOAA.
- **Require federally funded mCDR projects to implement data management plans** that consider the cost of data management, research data management personnel, and infrastructure, and that mandate public release of mCDR research data and information, where applicable. Projects should adhere to all existing federal data management and accessibility requirements. Key agencies: IWG-mCDR, NOAA, DOE, NSF, USGS.
- **Require federally funded researchers to work with agencies to make data freely available in a timely manner**, particularly information that shows consequences or benefits to local communities and ecosystems, in keeping with federal guidance.[91] Use existing repositories for pre-publication or unpublished reports. Key agencies: NOAA, DOE, NSF, USGS, NASA.
- **Allow and promote, as appropriate, knowledge sharing agreements** with community collaborators and local public and private institutions to advance transparency and provide co-benefits such as environmental monitoring to communities. Key agencies: NOAA, DOE, NSF, USGS.
- **Responsibly manage the inclusion of Indigenous Knowledge in mCDR research** to ensure that projects are more effective and engage multiple ways of knowing. The use and management of data related to and containing Indigenous Knowledge should be built upon the principles of free, prior, and informed consent for the use of Indigenous Knowledge; honoring Indigenous Knowledge sovereignty where appropriate; ensuring that knowledge holders are aware of the limitations of the ability to maintain confidentiality before they decide whether to share knowledge; and avoiding harm. Key agencies: NOAA, DOE, NSF, USGS.

[91] NSTC. 2022. Guidance for implementing national security presidential memorandum 33 (nspm-33) on national security Strategy for United States government-supported research and development. https://www.whitehouse.gov/wp-content/uploads/2022/01/010422-NSPM-33-Implementation-Guidance.pdf

Objective 4: Prioritize research towards mCDR approaches that show the greatest promise of achieving specific benchmarks for safety, efficacy, and other criteria.

Resources must be strategically allocated to produce sufficient mCDR knowledge to guide deployment decisions by 2030. Ideally, federal research and funding should be allocated to the experiments most likely to advance promising mCDR approaches that minimize adverse impacts on human health, the marine environment, coastal communities, and ocean uses. At the same time, approaches that are not currently feasible due to technological or financial constraints may become more feasible in the future.

If any mCDR approach is to become a scalable climate solution, the approach should demonstrate that it is both safe and effective at removing carbon dioxide from the atmosphere for a long duration of time. mCDR field trials should limit impacts to local communities and others who rely upon ocean resources, and any potential future deployment at a larger scale should strive for public acceptance. To be deployed commercially, mCDR should be cost-effective and able to produce real, additional, and verifiable carbon removal. Materials for and energy to support mCDR should be ethically and accountably sourced, and waste and byproducts should be disposed of appropriately in ways that do not add to the burdens of already overburdened communities or ecosystems. Practitioners should also consult with interested and affected communities to assess their risk tolerance and support for mCDR approaches and projects. Those methods which show the most promise in meeting the criteria outlined in this Strategy should be considered for prioritization for limited federal funding.

The federal government should employ a multi-dimensional approach for the prioritization of mCDR research funding and federal research. Projects to examine an mCDR approach should be evaluated holistically by funding agencies according to the extent in which they meet the criteria presented in Table 1. Some of these criteria for federal funding and research are most relevant at the pilot project and field trial level, while others are more applicable to mCDR approaches in general. As mCDR research progresses and new information is acquired, some approaches may be ruled out and efforts may be redirected elsewhere. Regardless of prioritization, proposed projects must demonstrate that they can meet regulatory requirements under applicable federal, Tribal, state, territorial, local, and international laws, regulations, and policies.

These considerations are technology-agnostic and adaptive to varying priorities among decision-makers. This flexibility will allow decision-makers across sectors to identify, design, evaluate, and accelerate mCDR technologies for climate change solutions in a methodical, accountable, and balanced manner. While these criteria are intended to inform federal funding decisions regarding mCDR research, the criteria could also be considered during future decision-making regarding potential mCDR deployment.

Table 1. Considerations for the prioritization of federal mCDR research funding for proposed mCDR approaches and research projects. Proposed mCDR approaches and testing should be prioritized according to the extent to which they may ultimately meet the criteria listed. In some cases, research must be done to determine if a project meets certain criteria prior to performing pilot studies and field trials, highlighting the importance of an informed and iterative research approach.

Consideration	Description	Criteria
Environmental response	Potential risks that an mCDR technology could pose to the environment.	• Prior to pilot projects and field trials, potential environmental risks to the marine, coastal, and human environment are well characterized and estimated to have low probability of severe adverse impacts, as determined by regulatory bodies. • Prior to pilot projects and field trials, research demonstrates that there is minimal anticipated harm to ecosystems, particularly species that are vulnerable or of particular social, cultural, ecological, or economic interest. Monitoring is sufficient to identify harmful impacts. • Material sourcing, energy needs, and disposal of potential byproducts are monitored and pose limited risk of harm to the environment.
Social impacts	Effects on communities and people who rely upon ocean resources.	• Where possible, proposed projects are co-developed with local communities and project developers have invested in meaningful community engagement. • Proposed projects do not face major opposition by local communities and others who rely upon ocean resources. • Research efforts are designed to minimize risk and maximize benefits for local communities.
Efficacy	The degree to which an mCDR technology may produce net carbon dioxide (or equivalent greenhouse gas) removal.	• Prior to pilot projects and field trials, research indicates carbon dioxide removal will be effectively measured, monitored, reported, and verified, where possible. • Carbon dioxide removal at pilot project, field trial, and deployment scale is projected to achieve net removal[92] relative to the greenhouse gas emissions emitted over the life cycle of the effort, including consideration of the escape of carbon dioxide back to the atmosphere and the natural carbon dioxide sink that the ocean provides.

[92] See footnote 15.

		• Energy demands are met by renewable and natural energy sources to the extent possible. • The entirety of the project's life cycle, including supply chain of materials and emissions is considered (for example, through an LCA). Emissions are reduced when possible. • Research and data advance future MMRV capabilities.
Durability	Duration that removed carbon dioxide is isolated from the atmosphere or surface ocean.	• The approach has the potential to remove carbon dioxide for at least 100 years.[93] • The carbon dioxide is likely to remain isolated from the atmosphere regardless of changing oceanographic conditions.
Scalability	Viability as a tool for significant climate change mitigation.	• The approach has the potential to remove carbon dioxide (or equivalent) equal to or exceeding 1.0 Gigaton of carbon dioxide (or equivalent) per year. • The approach or project includes responsible and cost-effective management of the energy, materials, and waste-disposal needs that can be met cost-effectively, demonstrating meaningful progress towards the goal of $100/net ton removed.[94]
Potential benefits	Net-positive impact on ecosystems and communities.	• The approach or project has the potential to provide ecosystem services or co-benefits beyond carbon dioxide removal, including ocean acidification mitigation and ecosystem restoration. • The approach or project has the potential to result in co-benefits for communities, such as driving the creation of high-quality jobs and capacity-building efforts to increase scientific capital.
Resource considerations	Resources needed to sustain a project throughout its life cycle.	• Limited resources such as raw materials, human labor, and coastal and open ocean space are used efficiently. • Efforts consider other ocean uses and take advantage of opportunities for co-location with current or legacy marine infrastructure.

[93] Ibid.
[94] DOE. Carbon Negative Shot. https://www.energy.gov/fecm/carbon-negative-shot

Knowledge base	Confidence in foreseen and unforeseen consequences of project activities.	• The proposed project is designed to address research needs and advance understanding of efficacy and impacts of the mCDR approach. • There is a high degree of confidence in the range of possible outcomes for pilot projects and field trials, including both risks and benefits. • Pilot projects and field trials are supported by appropriate modeling, laboratory and mesocosm experiments, and local and Indigenous Knowledge.

Recommendations:

- **Create a numerical decision-support tool for the evaluation and prioritization of federally funded mCDR research**, using these criteria as a starting point. Key agencies: IWG-mCDR.
- **Encourage resources to address cross-cutting mCDR research needs** through federal grant processes and broad agency announcements. Key agencies: IWG-mCDR, NOAA, DOE, NSF, NASA.

Objective 5: Ensure mCDR research is efficiently and effectively permitted under applicable laws and regulations.

Testing mCDR approaches in the ocean may be necessary to determine whether specific approaches that have shown promise in laboratory and mesocosm experiments are effective and safe. An efficient, participatory, and science-informed permitting process is essential to protect the marine environment, human health, and other ocean uses, and to foster public trust. Whether experiments in the ocean are small-scale pilot projects or larger field trials, they must meet the regulatory requirements of applicable statutes.

The requirements that might apply to a given mCDR experiment depend on the experiment's design and location. Researchers seeking to conduct any mCDR research in the ocean should communicate with the EPA or the USACE early in the planning process to understand the regulatory requirements and permitting processes for their proposed mCDR pilot project or field trial. In general, researchers developing mCDR experiments that involve adding materials into the ocean must obtain authorization under a permit from the EPA under the Marine Protection, Research, and Sanctuaries Act (MPRSA),[95, 96] from the EPA or an authorized state agency under the Clean Water Act (CWA) Section 402 National Pollutant Discharge Elimination System (NPDES),[97] or from the USACE under the CWA Section 404

[95] References to the MPRSA in this Strategy specifically refer to Title I and II of the MPRSA, codified at 33 U.S.C. §§ 1401–1445. Title III of the MPRSA is referred to as the National Marine Sanctuaries Act, codified at 16 U.S.C. §§ 1431–1445c.

[96] EPA. Permitting for mCDR. https://www.epa.gov/ocean-dumping/permitting-mcdr-and-msrm

[97] EPA. NPDES Permit Basics. https://www.epa.gov/npdes/npdes-permit-basics

permitting programs.[98] Researchers developing experiments that could obstruct navigability may require a permit from the USACE under Section 10 of the Rivers and Harbors Act (RHA).[99] States may also have the authority to regulate certain mCDR activities in ocean waters.

To illustrate how the MPRSA, CWA and RHA may apply, a proposed mCDR experiment that involves—

- Transporting and releasing alkaline or iron materials, or sinking biomass, into ocean waters may require an MPRSA permit from the EPA.[100]
- Discharging alkaline materials into a bay or harbor through an outfall structure from a wastewater treatment facility may require a permit under the CWA Section 402 from the EPA or an authorized state agency.
- Drawing seawater from the ocean, enhancing its alkalinity through electrochemical or other processes, and discharging it back into a bay or harbor may require a permit under CWA Section 402 from EPA or an authorized state agency.
- Placing sand that contains solid alkaline material into a bay landward of its mouth may require a permit under the CWA Section 404 from the USACE.
- Construction of a permanent or temporarily fixed structure in an estuary or the ocean to monitor an mCDR experiment may require an RHA Section 10 permit from the USACE.

The permitting processes under these statutes generally require an applicant to provide information to demonstrate that the proposed activities will not unreasonably degrade the marine environment or human health, or harm protected species, and that it complies with other applicable criteria and regulations. In addition, these permitting processes generally include opportunities for public review and comment on proposed activities or proposed permitting actions.

Permitting agencies may also consult, coordinate with, or notify other federal, Tribal, state, territorial, or local government agencies, or other countries and relevant international bodies during the permitting processes under these statutes. For example, the EPA or USACE may also coordinate with the Department of Defense and the U.S. Coast Guard to prevent conflicts with navigation, defense, and homeland security missions.

Some federal statutes require federal agencies to consult or develop specific analyses for actions that the agency may fund, permit, or conduct. Some statutes place similar requirements on the applicant before an MPRSA, CWA, or RHA permit can be issued. For example, depending on the nature of the proposed experiment, including its location and potential impacts, additional federal statutes could apply, including the National Environmental Policy Act, the Endangered Species Act,[101, 102] the Marine Mammal Protection Act,[103] the Magnuson-Stevens Fishery Conservation and Management Act,[104] the

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98 USACE. Regulatory Program and Permits. https://www.usace.army.mil/Missions/Civil-Works/Regulatory-Program-and-Permits/

99 Ibid.

100 The permit application process is described in the MPRSA regulations at 40 C.F.R. parts 221 and 222.

101 USFWS. ESA Section 7 Consultation. https://www.fws.gov/service/esa-section-7-consultation

102 NOAA Fisheries. Understanding Permits and Authorizations for Protected Species. https://www.fisheries.noaa.gov/insight/understanding-permits-and-authorizations-protected-species

103 Ibid.

104 NOAA Fisheries. Consultations for Essential Fish Habitats. https://www.fisheries.noaa.gov/national/habitat-conservation/consultations-essential-fish-habitat

Coastal Zone Management Act (CZMA),[105] the National Marine Sanctuaries Act,[106] the National Historic Preservation Act,[107] or other statutes. State agencies issuing permits may have other requirements. Coordination with EPA and USACE early on can help researchers understand the permitting processes under the MPRSA and the CWA and may raise awareness of other agencies that implement statutory and regulatory requirements that may apply.

Federal agencies honor Tribal treaty and other rights by ensuring meaningful and timely input by Tribal officials in the development of any mCDR permitting action that may have implications for Tribes. Federal agencies advance environmental justice by considering disproportionate and adverse human health and environmental effects of mCDR permitting and by providing opportunities for meaningful engagement in the mCDR permitting process, in accordance with relevant rules, executive orders,[108,109,110] and agency policies, as appropriate.

Recommendations:

- **Develop resources to help potential permittees navigate the permitting process** such as educational materials, training, and tools. Consider the development and publication of a permitting handbook or other explanatory materials to further clarify the end-to-end permitting process. Key Agencies: EPA, USACE, NOAA, U.S. Fish and Wildlife Service (USFWS), DOI.
- **Develop and publish training materials for Tribal, state, and territorial governments** to build their capacity in evaluating mCDR research applications and participating in the permitting process, including consistency requirements under the CZMA. Leverage existing regional coalitions such as NOAA Regional Ocean Partnerships[111] and Regional Associations of the Integrated Ocean Observing System[112] to provide technical assistance and capacity building as appropriate. Key agencies: NOAA, EPA, USACE, NOAA, USFWS, DOI.

[105] NOAA Office for Coastal Management. Applying for Federal Consistency. https://coast.noaa.gov/czm/consistency/applying/

[106] NOAA Office of National Marine Sanctuaries. 2023. Guidance for the Potential Application of Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries. https://nmssanctuaries.blob.core.windows.net/sanctuaries-prod/media/docs/guidance-for-potential-application-of-marine-co2-removal-us-nms.pdf

[107] Advisory Council on Historic Preservation. An Introduction to Section 106. https://www.achp.gov/protecting-historic-properties/section-106-process/introduction-section-106#:~:text=If%20a%20federal%20or%20federally-assisted%20project%20has%20the,these%20matters%20before%20a%20final%20decision%20is%20made.

[108] E.O. 12898. Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations. 1994. https://www.archives.gov/files/federal-register/executive-orders/pdf/12898.pdf

[109] E.O. 13175. Consultation and Coordination With Indian Tribal Governments. 2000. https://www.federalregister.gov/documents/2000/11/09/00-29003/consultation-and-coordination-with-indian-tribal-governments

[110] See footnote 30.

[111] NOAA Regional Ocean Partnerships. https://www.noaa.gov/infrastructure-law/infrastructure-law-climate-data-and-services/regional-ocean-partnerships

[112] IOOS Regional Associations. https://ioos.noaa.gov/about/regional-associations/

Objective 6: Promote coordination across diverse sectors with interests in mCDR research.

Producing sufficient knowledge to guide decisions regarding mCDR deployment by 2030 will require extensive collaboration between different levels of government and across academia, industry, and philanthropy. New and existing mechanisms for coordination should be leveraged to promote knowledge sharing, support mCDR workforce development, enable the emergence of a strong domestic mCDR community of practice, and responsibly accelerate research progress. Integration across mCDR research activities will advance transparency, build public trust, and make efficient use of limited resources.

U.S. Regional Collaboration

Partnerships that bring federal, Tribal, state, territorial, and local partners together with industry, academia, and nongovernmental organizations could accelerate the progress of safe and responsible mCDR research. Domestic regional partnerships in particular could bring interdisciplinary expertise together with the place-based knowledge required for productive research. One way of promoting regional partnership could be for the government to establish regional mCDR research hubs.[113] These hubs could allow researchers to pool funding, infrastructure, observational capacity, and expertise, including on permitting, to make efficient use of limited resources from government, industry, and the philanthropic sector. Research hubs that are self-organized or managed by a government agency could promote innovation and collaboration across multiple scientific disciplines and strengthen the scientific rigor of the research effort (e.g., see DOE Energy Innovation Hubs[114]). Research hubs could also efficiently grow the community of experienced practitioners and leverage efforts in related fields, such as renewable energy, wastewater treatment, or desalination.

If located near mCDR test beds, research hubs could help maximize the long-term value of local investments in infrastructure, technical workforce development, and community engagement. Regional hubs could be particularly helpful in establishing long-term relationships between researchers and community members, developing community awareness, building capacity at the state and local level and among Tribes, and providing a locus for community collaboration on mCDR projects. These hubs could include as members, or partner with, established, trusted regional organizations like the Regional Ocean Partnerships[115] or Regional Associations of the U.S. Integrated Ocean Observing System.[116]

Recommendations:

- **Promote regional collaboration among a diversity of sectors in the mCDR research community.** Consider establishing regional mCDR research hubs or centers of excellence, including by scoping funding and resource requirements for mCDR regional research hubs, and identify program support from the federal government that could be directed towards the establishment and operation of mCDR research hubs. NOAA and DOE have already established a

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[113] See footnote 19.

[114] DOE. Hubs. https://www.energy.gov/hubs

[115] NOAA. Regional Ocean Partnerships. https://www.noaa.gov/infrastructure-law/infrastructure-law-climate-data-and-services/regional-ocean-partnerships

[116] See footnote 112.

Memorandum of Agreement[117] under which the agencies will direct federal researchers to scope and plan testing sites that would address critical needs of research hubs. Explore collaboration with the private sector in initiating the development of regional research hubs. Key agencies: NOAA, DOE, NSF.

- **Enable Tribal Nations to engage with regional hubs.** Explore ways of supporting the participation of Tribal Nations in regional collaborations, including through Regional Ocean Partnerships.[118] Key agency: NOAA.

Effective Interagency Coordination and Advice

Given the interdisciplinary and cross-cutting nature of mCDR research and engagement, multiple federal agencies have authorities and equities that should contribute not only to permitting, but also to future decision-making processes. Interagency coordination and collaboration of mCDR efforts are essential for efficiently implementing this Strategy. This Strategy recommends the creation of an IWG-mCDR to continue the work of the mCDR FTAC. Activities of the IWG-mCDR will include public engagement and efforts, as appropriate, with interested non-federal parties to ensure broader collaboration with the community and utilize mechanisms for input, such as through Requests for Information. When possible, the IWG-mCDR will leverage existing Federal Advisory Committees to provide guidance and recommendations on mCDR policy and research.

Recommendations:

- **Establish an Interagency Working Group to support the implementation of this Strategy,** including: promoting coordination among funding, research, and regulatory agencies; tracking progress in implementing the Strategy; and evaluating and updating the Strategy, as appropriate. Key agency: OSTP.
- **Continue and enhance communication and coordination among permitting agencies**, including those with roles in the interagency consultation process. Include representatives from agencies with regulatory authorities, such as NOAA Fisheries and USFWS, in the IWG-mCDR. Consider developing or expanding agreements among agencies with relevant regulatory authorities to facilitate the mCDR permitting process. Key Agencies: EPA, USACE, NOAA, DOI, USFWS.
- **Establish agreements or other arrangements among research/funding and permitting agencies** to facilitate the sharing of information, expertise, and resources. Consider planning joint research and funding initiatives, such as through the National Oceanic Partnership Program (NOPP). Key agencies: IWG-mCDR, NOAA, DOE, NSF, EPA, USACE, USGS.
- **Leverage existing Federal Advisory Committees to provide multi-sector guidance and recommendations on mCDR policy and research.** Engaging groups such as the Carbon Dioxide Capture, Utilization, and Sequestration Permitting Task Force[119] and the Ocean Research Advisory

[117] NOAA. 2024. NOAA, DOE sign agreement to advance marine carbon dioxide removal. https://www.noaa.gov/news-release/noaa-doe-sign-agreement-to-advance-marine-carbon-dioxide-removal

[118] See footnote 53.

[119] The White House. 2022. Biden-Harris Administration Creates New Task Forces to Inform Responsible Development and Deployment of Carbon Capture, Utilization, and Sequestration. https://www.whitehouse.gov/ceq/news-updates/2022/07/27/biden-harris-administration-creates-new-task-

Panel[120] as resources for advising mCDR research mechanisms such as the mCDR regional research hubs. Key agencies: IWG-mCDR.

Encouraging Public-Private Partnership in Financing mCDR Research

Funding, resources, and expertise across sectors must be strategically leveraged to produce sufficient knowledge to guide potential deployment decisions by 2030. The National Academies of Sciences, Engineering, and Medicine estimate that a comprehensive research agenda to advance the understanding of mCDR would require several hundred million dollars per year over a 5-to-10-year period.[121] Funding by governments around the world increasingly supports mCDR research.[122] The U.S. government has recently increased funding for mCDR research[123,124] and should continue leading the field.

Private funding from both commercial and philanthropic sources is also growing and plays a key role in mCDR research. Philanthropy in particular can play a catalytic role, jumpstarting efforts to develop technologies, engaging and educating communities, and raising public awareness. There may be many opportunities for high-quality research to be co-designed by industry, academia, philanthropy, and government agencies, such as through NOPP.

Commercial entities may also contribute valuable mCDR research, and federal action has the potential to spur funding from the private sector for additional research. For example, high-integrity carbon markets have the potential to support and accelerate decarbonization efforts, including mCDR.[125] mCDR entrepreneurs are already leveraging commitments from investors to purchase credits for carbon removal in the future, should they meet standards that purchasers set, to unlock the private capital entrepreneurs need to operate and develop mCDR technologies today. Research funded wholly by investors or purchasers, including through voluntary credit markets, should fully comply with the guidelines identified in or developed under this Strategy, and sellers should demonstrate that any credits sold meet robust integrity standards.

Recommendations:

- **Facilitate multi-sector funding partnerships through mechanisms such as NOPP**. Such mechanisms allow the federal government to invest in priorities that fall between agency missions or are too large for any single agency to support. Key agencies: IWG-mCDR.
- **Engage carbon market standards bodies to encourage the development of robust standards for mCDR.** Carbon dioxide removal from mCDR must be real, additional, unique, verifiable, and attributable to specific mCDR projects to be eligible for purchase programs by the U.S.

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forces-to-inform-responsible-development-and-deployment-of-carbon-capture-utilization-and-sequestration/

[120] NOAA. Ocean Research Advisory Panel. https://www.noaa.gov/ocean-research-advisory-panel

[121] See footnote 15.

[122] Smith, S. M., et al. The State of Carbon Dioxide Removal 2024. https://doi.org/10.17605/OSF.IO/F85QJ

[123] See footnote 28.

[124] See footnote 29.

[125] U.S. Voluntary Carbon Markets Joint Policy Statement and Principles. 2024. https://www.whitehouse.gov/wp-content/uploads/2024/05/VCM-Joint-Policy-Statement-and-Principles.pdf

government, such as DOE's CDR Purchase Pilot Prize,[126] or by voluntary carbon market actors, such as industry groups and civil society organizations. Key agencies: DOE, NOAA, EPA, NIST, USGS.

International Coordination

mCDR is increasingly discussed in multilateral and bilateral fora and among governments, academia, and civil society around the world. Some governments, including the United States, have begun to finance and permit mCDR research, while others are watching cautiously. The U.S. government should continue to engage internationally, as appropriate, to promote a common international understanding of developments in mCDR research, including the potential benefits and challenges of various mCDR approaches. International engagement can help promote responsible mCDR research, socialize best practices (such as adhering to a code of conduct), and discourage irresponsible experimentation or deployment. International engagement could also help shape expectations regarding responsible research and how mCDR could effectively be regulated if research were to demonstrate that it could be deployed safely and effectively as a solution to help address the climate crisis.

Federal agencies and civil society organizations will likely consider engaging in appropriate international cooperation on mCDR research, given the global nature of ocean-climate issues and the benefits of maximizing the value of scarce resources. International cooperation could involve one or more areas of mCDR research or strategies and could range from modest (e.g., convening an exchange of experts) to more comprehensive (e.g., organizing an international consortium).

Conclusion

mCDR has the potential to be a viable climate solution. Given the urgency of the climate crisis, research into the potential safety, efficacy, and tradeoffs of potential mCDR deployment is warranted. However, this research cannot come at the cost of people, ecosystems, or public trust. The recommendations outlined in this Strategy could ultimately inform decision-making regarding potential mCDR deployment at climate-relevant scales, while also advancing U.S. leadership in innovation and competitiveness. Potential future decisions regarding mCDR deployment will also be informed by complex considerations including domestic and international policymaking, societal acceptance, and other factors. Discussion on these topics should occur alongside the mCDR research described here, and future updates to this Strategy may elaborate upon the framework necessary to prepare for potential deployment decisions.

This Strategy will help accelerate the pace and scale of strategic and effective action to maximize success, collaboration, and innovation in mCDR research. Regardless of the potential deployment of mCDR as a climate solution, implementation of this Strategy will strengthen understanding of ocean ecosystems, improve ocean literacy, develop the ocean workforce, strengthen relationships between researchers and local communities, and more. By implementing this Strategy, the United States can advance its commitment to equitably steward a healthy and sustainable ocean and planet.

[126] See footnote 28.