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Selected Potential Considerations with Respect to Marine Carbon Dioxide Removal: In Brief

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The Intergovernmental Panel on Climate Change (IPCC) states in its *Sixth Assessment Report* that "human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming."[1] The IPCC projects average global warming "more likely than not" will continue to increase in the near term (through 2040) under the lowest greenhouse gas (GHG) emission scenarios considered.[2] Both the IPCC's *Sixth Assessment Report* and the U.S. Global Change Research Program's *Fifth National Climate Assessment* state that carbon dioxide removal (CDR) approaches, in addition to other efforts, are likely needed to mitigate rising atmospheric carbon dioxide (CO_2) and the associated impacts of climate change (e.g., increasing average global temperature, rising sea levels, increasingly severe weather events).[3] According to experts, to be effective, CDR approaches must remove CO_2 from the atmosphere and durably store carbon for prolonged periods of time.[4]

The ocean is a major component of the global climate system, serving as a planetary reservoir of heat, water, and carbon. The IPCC estimates with high confidence that the global ocean has absorbed more than 90% of the atmosphere's human-induced excess heat; since the 1980s, it has likely absorbed between 20% and 30% of total human-caused CO_2 emissions.[5] Scientists have investigated how *marine CDR* (mCDR, also referred to as *ocean* or *ocean-based CDR*) approaches may augment the ocean's natural ability to absorb atmospheric CO_2 and store carbon for extended periods of time in coastal and ocean environments.[6]

Interest from various stakeholders in the use of mCDR to mitigate rising atmospheric CO_2 levels is growing. For example, the National Oceanic and Atmospheric Administration's (NOAA's) Office of National Marine Sanctuaries reports that it has received an increased number of external inquiries about mCDR deployment in national marine sanctuaries.[7] To this end, in 2023, the Biden Administration identified obtaining new information about the "safest and most effective approaches" to mCDR as a high priority and established the Marine Carbon Dioxide Removal Fast Track Action Committee (MCDR-FTAC).[8] MCDR-FTAC's charter acknowledged the "urgent need to resolve key knowledge gaps for different [mCDR] techniques."[9] In the 118th

[1] For example, Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," in *Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. Core Writing Team, Hoesung Lee, and José Romero, 2023, p. 4.

[2] Ibid., p. 12.

[3] IPCC, "Chapter 3: Oceans and Coastal Ecosystems and Their Services," in *Climate Change 2022: Impacts, Adaptation and Vulnerability*, eds. Hans-Otto Pörtner et al., 2022, p. 464; and Steven J. Davis et al., "Chapter 32: Mitigation," in *Fifth National Climate Assessment*, eds. Allison R. Crimmins et al., 2023, p. 21.

[4] For example, see Prati Rosen et al., *Guidance for the Potential Application of Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries*, National Oceanic and Atmospheric Administration (NOAA), Office of National Marine Sanctuaries, June 2023, p. 3 (hereinafter Rosen et al., *Marine Carbon Dioxide Removal*); and Jessica N. Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research: A White Paper Documenting a Potential NOAA CDR Science Strategy as an Element of NOAA's Climate Interventions Portfolio*, NOAA Special Report, May 2023, p. 22 (hereinafter Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*).

[5] IPCC, "Summary for Policymakers," in *The Ocean and Cryosphere in a Changing Climate: A Special Report of the Intergovernmental Panel on Climate Change*, eds. Hans-Otto Pörtner et al., 2019, p. 9.

[6] For example, see National Academies of Sciences, Engineering, and Medicine (NASEM), *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration* (Washington, DC: The National Academies Press, 2022) (hereinafter NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*).

[7] Rozen et al., *Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries*, p. 1.

[8] White House, "Marine Carbon Dioxide Removal: Potential Ways to Harness the Ocean to Mitigate Climate Change," October 6, 2023, https://www.whitehouse.gov/ostp/news-updates/2023/10/06/marine-carbon-dioxide-removal-potential-ways-to-harness-the-ocean-to-mitigate-climate-change/.

[9] *Charter of the Marine Carbon Dioxide Removal Fast Track Action Committee of the Subcommittee on Ocean Science and Technology, National Science and Technology Council*, September 2023, p. 2. Hereinafter *MCDR-FTAC Charter*.

Congress, congressional interest in mCDR primarily has focused on advancing mCDR research, development, and demonstration (RD&D).[10]

The study of mCDR is a relatively new field. In light of growing interest in mCDR, this In Brief provides an overview of different mCDR approaches and discusses some outstanding related research questions. These questions may be informed by additional RD&D, including controlled field experiments. Congress also may consider laws applicable to the various mCDR approaches and the potential challenges, if any, researchers may encounter in conducting RD&D, including field experiments in the U.S exclusive economic zone (EEZ).[11]

Overview of Marine Carbon Dioxide Removal Approaches

mCDR approaches generally are categorized into those that enhance or accelerate marine *biological pathways* or *chemical pathways*.[12]

Biological Pathway Approaches

Approaches that manipulate marine biological pathways enhance the uptake of atmospheric CO_2 by increasing the growth of marine plants (i.e., micro- and macroalgae). These mCDR biological pathway approaches include the following:

- **Artificial Upwelling**. This approach relies on a technological intervention to transport cold, nutrient-rich ocean waters from the deep ocean to the surface. Cold, nutrient-rich waters can stimulate primary producers (i.e., phytoplankton) to take up CO_2 via photosynthesis. Once dead, the primary producers may sink into the ocean, transporting carbon out of the surface ocean. A small portion of this carbon may be buried in ocean sediments for up to 100 years.[13]
- **Artificial Downwelling**. This approach relies on a technological intervention to transport relatively warm and CO_2-rich surface waters, as well as the primary producers (i.e., phytoplankton) living in the surface waters, to water depths below the *pycnocline* (generally between 500 and 1,000 meters below the ocean surface) for the purpose of storing downwelled CO_2 in the deep ocean and burying carbon associated with dead primary producers in ocean sediments for up to 100 years.[14]

[10] For example, see S. 1576, H.R. 5457/S. 2812, H.R. 7054, and H.R. 7797.

[11] For example, Clear Path, "Ocean CDR Permitting and Regulations 101," https://clearpath.org/tech-101/ocean-cdr-permitting-and-regulations-101/. Hereinafter Clear Path, "Ocean CDR Permitting and Regulations 101." The U.S. exclusive economic zone is the ocean area located generally between 3 and 200 nautical miles from the shoreline (White House, "Proclamation 5030: Exclusive Economic Zone of the United States of America," 48 *Federal Register* 10605, March 10, 1983).

[12] For example, Lennart T. Bach et al., "Implementation of Marine CO_2 Removal for Climate Mitigation: The Challenges of Additionality, Predictability, and Governability," *Elementa*, vol. 12, no. (1), pp.1-16, see p. 2 (hereinafter Bach et al., "Implementation of Marine CO_2 Removal for Climate Mitigation"); and Rosen et al., *Marine Carbon Dioxide Removal*, p. 3.

[13] For example, Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 22; and NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 111.

[14] For example, S. Zhou and P.C. Flynn, "Geoengineering Downwelling Ocean Currents: A Cost Assessment," *Climate Change*, vol. 71, no. 1 (2005), pp. 203-220, see p. 204; Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 22; and NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 111. The *pycnocline* is a layer in the ocean marking a sharp density (i.e., temperature and salinity) change.

- **Macroalgal (Seaweed) Cultivation**. This approach uses fast-growing marine plants to take up CO_2 via photosynthesis.[15] In order for this to be a successful mCDR technique, these plants cannot be harvested for food or other uses (e.g., fertilizers, feed and fuel for land activities), and, once dead, these plants must sink and be buried in ocean sediments.[16] Depending on the offshore environment, such carbon may be stored in ocean sediments for decades to millennia.[17]
- **Ocean Fertilization**. This approach adds micro- (iron) or macronutrients (nitrogen or phosphorous) to the surface ocean. These nutrients can stimulate primary producers (i.e., phytoplankton) to take up CO_2 via photosynthesis. Once dead, the primary producers may sink into the ocean, transporting carbon out of the surface ocean. A small portion of this carbon may be buried in ocean sediments for centuries to millennia.[18]

Chemical Pathway Approaches

Approaches that manipulate marine chemical pathways alter the natural air-sea gas exchange by changing seawater *alkalinity* (i.e., the ocean's ability to resist pH changes). These approaches aim to change seawater alkalinity so the ocean can absorb more CO_2.[19] mCDR approaches that augment marine chemical pathways include the following:

- **Direct Ocean Removal**. This approach relies on technologies to remove and capture CO_2 directly from seawater by changing the pH of the treated water. The treated (decarbonized) water is returned to the surface ocean, where it can absorb more CO_2.[20]
- **Ocean Alkalinity Enhancement (OAE)**. OAE alters seawater alkalinity either by adding alkaline minerals to increase the ocean's ability to absorb atmospheric CO_2 or by using electricity to split seawater into its acidic and basic components.[21] In the absence of processes that remove the added alkalinity, some have proposed OAE can sequester CO_2 on timescales of millennia or longer.[22]

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[15] For example, Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, pp. 34-35; and NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 3.

[16] Ibid. Seaweed harvested for food or fertilizer sequesters carbon on the order of months to a few years (i.e., shorter than the timeframe required for carbon dioxide removal [CDR]) and allows sequestered carbon to be reemitted back to the atmosphere. M. Troell et al., "Farming the Ocean—Seaweeds as a Quick Fix for the Climate?," *Reviews in Fisheries Science and Aquaculture*, vol. 31, no. 3 (2023), pp. 285-295.

[17] For example, Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 35; and Rosen et al., *Marine Carbon Dioxide Removal*, p. 4.

[18] For example, NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 77. For more information about ocean iron fertilization, see CRS Report R47172, *Geoengineering: Ocean Iron Fertilization*, by Caitlin Keating-Bitonti.

[19] Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 33; and Bach et al., "Implementation of Marine CO_2 Removal for Climate Mitigation," p. 3.

[20] For example, Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, pp. 40-41.

[21] U.S. Environmental Protection Agency (EPA), "About mCDR and mSRM," https://www.epa.gov/ocean-dumping/about-mcdr-and-msrm (hereinafter EPA, "About mCDR and mSRM"); NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 3; and Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 38.

[22] NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 185.

Considerations for Congress

Limited experimentation, including a lack of controlled field experiments,[23] for many mCDR approaches creates uncertainties regarding the efficacy, cost, potential co-benefits, and potential negative impacts of full-scale deployment of mCDR approaches.[24] On February 23, 2024, the National Science Foundation (NSF), acting through the MCDR-FTAC, sought input from all interested stakeholders to inform the development of an implementation plan to advance mCDR research.[25] In its notice, NSF stated, "As of yet, however, no marine CDR methods are considered ready for full-scale deployment or commercial application."[26] Some stakeholders contend that small-scale proof-of-concept field testing is necessary to quantify CDR potential (i.e., efficacy) as well as the potential co-benefits and negative impacts associated with different mCDR approaches.[27]

Federal RD&D and federally funded research may elucidate whether mCDR approaches are effective and at what scale.[28] Some stakeholders may question the relative priority of mCDR RD&D compared with other federal activities, such as existing programs that support more technologically mature CDR options or GHG emissions reductions.[29] Others may invoke a moral hazard argument against CDR because they prefer policies and actions to reduce GHG emissions prioritized over those aimed at removing emitted GHG from the atmosphere.[30] If Congress is interested in directing federal agencies to conduct and advance mCDR RD&D or to support nonfederal RD&D, it could consider several policy approaches, including identifying a permitting framework for mCDR RD&D in the U.S. EEZ.

Permitting for Marine Carbon Dioxide Projects

Some stakeholders contend that scaling and accelerating mCDR RD&D is unlikely to happen without a regulatory framework that facilitates controlled field experiments.[31] Either a field-based

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[23] For example, according to NASEM, artificial downwelling has never been tested in the field as means of CDR. NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 105.

[24] For example, see National Science Foundation (NSF), "Marine Carbon Dioxide Removal Research Plan," 89 *Federal Register* 13755-13757, February 23, 2024 (hereinafter NSF, "Marine Carbon Dioxide Removal Research Plan"); Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, pp. 13 and 17; and EPA, "About mCDR and mSRM."

[25] NSF, "Marine Carbon Dioxide Removal Research Plan." NSF sought feedback to advance a recommendation of the Biden Administration's *Ocean Climate Action Plan* (White House Ocean Policy Committee, *Ocean Climate Action Plan: A Report by the Ocean Policy Committee*, March 2023, pp. 41-43).

[26] NSF, "Marine Carbon Dioxide Removal Research Plan."

[27] For example, Hongjie Wang et al., "Simulated Impact of Ocean Alkalinity Enhancement on Atmospheric CO_2 Removal in the Bering Sea," *Earth's Future*, vol. 11, no. 1 (2022), pp. 1-17; and Clear Path, "Ocean CDR Permitting and Regulations 101."

[28] Article 2 of the Paris Agreement states that parties aim to "[hold] the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."

[29] For example, *direct air capture* (DAC) removes CO_2 from the atmosphere and stores the carbon in a stable or long-lived reservoir. For more information about DAC, see CRS In Focus IF11501, *Carbon Capture Versus Direct Air Capture*, by Ashley J. Lawson. As another example, *soil carbon sequestration* approaches, including certain land-use activities, involve removing CO_2 from the atmosphere (primarily mediated by plants through photosynthesis) and storing it in the soil carbon pool. For more information about soil carbon sequestration, see CRS In Focus IF11693, *Agricultural Soils and Climate Change Mitigation*, by Megan Stubbs.

[30] For example, Institute for Policy Integrity, *Consensus on Carbon Dioxide Removal: A Large-Sample Expert Elicitation on the Future of CDR*, July 2024, p. 36.

[31] Ocean Visions, "A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by (continued...)

demonstration or a fully deployed mCDR project likely would require compliance with certain state, federal, and/or international regulations, depending on the mCDR approach and the project's location. Proposals for mCDR projects within the U.S. EEZ could be subject existing laws, such as the Marine Protection, Research, and Sanctuaries Act (MPRSA; P.L. 92-532); the Coastal Zone Management Act (P.L. 109-58); Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. §403); the Clean Water Act (33 U.S.C. §1251 et seq.); and the Magnuson-Stevens Fishery Conservation and Management Act (MSA; 16 U.S.C. §1801 et seq.), among others. For example, the MSA requires federal agencies to consult with NOAA on activities that may adversely affect *essential fish habitat*.[32] As another example, the MPRSA, also known as the Ocean Dumping Act, regulates the transportation and "dumping" of any material—which may include alkalinity enhancement materials—into ocean waters (see textbox, below).[33]

Congress has not authorized mCDR projects in law. Should Congress support testing of mCDR projects, it could take different approaches. Congress could amend existing laws to specifically address mCDR broadly (or selected mCDR approaches). Alternatively, Congress could consider new legislation that provides a framework for mCDR projects deployed within the U.S. EEZ or regulates the scale and siting of a project to limit the potential impact on waters adjacent to the EEZ. H.R. 5457/S. 2812 in the 118th Congress would direct NSF, in collaboration with other federal agencies, to "award funding for research into governance frameworks for safe and sustainable experimentation" with mCDR.[34]

U.S. Environmental Protection Agency Permits for Ocean Alkalinity Enhancement

The U.S. Environmental Protection Agency (EPA) has clarified that marine carbon dioxide removal (mCDR) activities, such as ocean alkalinity enhancement (OAE), may require a permit under either the Clean Water Act (33 U.S.C. §1251 et seq.) or the Marine Protection, Research and Sanctuaries Act (MPRSA, also known as the Ocean Dumping Act; P.L. 92-532). The applicability of these EPA-administered statutes depends on case-specific aspects of the mCDR activity (e.g., the type and location).

In May 2024, EPA published a public notice of its tentative determinations to issue two research permits to Woods Hole Oceanographic Institution (WHOI) pursuant to MPRSA for a two-phased research study to collect information on the feasibility, potential benefits, and potential adverse impacts of a ship-based OAE project. The research study is proposed to take place at two locations offshore of Massachusetts. Under MPRSA, EPA may issue research permits for a period up to 18 months for the transportation and disposition of materials into the ocean as part of a research study when it is determined that the scientific merit of the proposed research study outweighs the potential environmental or other damage that may result from the activities (33 U.S.C. §1412; 40 C.F.R. §220.3(e)). If EPA finalizes the permits for WHOI, it would be EPA's first use of such research permits for mCDR activities.

Sources: EPA, "Permitting for mCDR and mSRM," https://www.epa.gov/ocean-dumping/permitting-mcdr-and-msrm; EPA, "Notice of Applications and Tentative Determinations for Marine Protection, Research and Sanctuaries Act Research Permits to Conduct a Two-Phased Ocean Alkalinity Enhancement Research Study Offshore of Massachusetts," https://www.epa.gov/system/files/documents/2024-05/whoi-loc-ness-public-notice.pdf; and WHOI, "The LOC-NESS Project," https://locness.whoi.edu/.

2030," p. 2. Hereinafter Ocean Visions, "A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030."

[32] 16 U.S.C. §1855(b). The Magnuson-Stevens Fishery Conservation and Management Act, under 16 U.S.C. §1802(10) defines *essential fish habitat* as "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity."

[33] The Marine Protection, Research, and Sanctuaries Act (MPRSA; P.L. 92-532, 33 U.S.C. §§1401 et seq.) defines *dumping* to mean the disposition of a "material," which the statute defines broadly as "matter of any kind or description," with some specific exclusions. The MPRSA authorizes the U.S. Army Corps of Engineers to issue permits under the MPRSA for dredged materials. EPA is the permitting authority for all other materials.

[34] §905 of H.R. 5457/S. 2812.

Federal Research for Marine Carbon Dioxide Removal

Several federal agencies have existing mandates, programs, and activities that intersect with mCDR research. NOAA has acknowledged that it has "capabilities that can be applied to understand and assess CDR."[35] For example, NOAA's Ocean Acidification Program conducts and funds research, monitoring, and other activities to develop mitigation strategies to address ocean acidification, among other purposes.[36] Some mCDR approaches, such as OAE, have the potential to mitigate ocean acidification.[37] The Department of Energy's (DOE's) Office of Fossil Energy and Carbon Management (FECM) identified CDR as a priority area.[38] For FY2025, DOE requested $237.5 million for CDR activities.[39] On June 6, 2024, DOE and NOAA signed a memorandum of agreement to collaborate on mCDR RD&D.[40]

Within agencies, Congress may consider designating an existing program (or office) or creating a new program to lead mCDR RD&D activities for the agency.[41] For example, within DOE, Congress could designate FECM, designate another office, or create a new office to lead mCDR activities. Several Members have introduced legislation in the 118th Congress that would direct certain agencies to establish mCDR RD&D programs (e.g., H.R. 5457/S. 2812, H.R. 7797) or amend existing programs to include mCDR approaches as part of their RD&D programs (e.g., S. 1576).

Congress also could designate a federal agency to coordinate federal mCDR RD&D activities or establish an interagency working group (IWG) for this purpose. Some stakeholders have proposed NOAA lead on federal mCDR research and coordination.[42] In the 118th Congress, S. 2002 and H.R. 9212 would establish the Interagency Group on Large-Scale Carbon Management in the National Science and Technology Council for the purpose of developing a federal strategic plan for CDR RD&D and coordinating federal CDR activities.[43] Alternatively, Congress could consider authorizing existing committees with a CDR-related focus, such as the MCDR-FTAC,[44] or amend existing laws to broaden the scope of an existing IWG, such as the IWG on Ocean

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[35] Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 17.

[36] NOAA requested $17.1 million for its Integrated Ocean Acidification line item for FY2025 (NOAA, *FY2025 Congressional Budget Justification*, p. OAR-58). In 2022, Congress passed the Coastal and Ocean Acidification Research and Innovation Act of 2021 (P.L. 117-167, Division B, Title VI, Subtitle E), which amended Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act; P.L. 111-11). As amended, FOARAM Act directed the Secretary of Commerce to establish an ocean acidification program (33 U.S.C. §3705). For more information, see CRS Report R47300, *Ocean Acidification: Frequently Asked Questions*, by Caitlin Keating-Bitonti and Eva Lipiec.

[37] Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 39.

[38] Department of Energy (DOE), Office of Fossil Energy and Carbon Management (FECM), "Mission," https://www.energy.gov/fecm/mission. For more information on FECM's carbon dioxide removal activities, see CRS In Focus IF11861, *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs*, by Ashley J. Lawson.

[39] CDR funding would be drawn from DOE's Office of Fossil Energy and Carbon Management ($130.2 million), Office of Energy Efficiency and Renewable Energy ($13.3 million), and Office of Science ($94.0 million). DOE, *FY2025 Congressional Justification*, vol. 2, March 2024, p. 241.

[40] NOAA, "NOAA, DOE Sign Agreement to Advance Marine Carbon Dioxide Removal," June 6, 2024, https://www.noaa.gov/news-release/noaa-doe-sign-agreement-to-advance-marine-carbon-dioxide-removal.

[41] For example, see Center for the Blue Economy, *Turning the Tide*, p. 39.

[42] Ibid.

[43] The agencies responsible for focusing on mCDR activities under the Interagency Group would be NOAA, National Aeronautics and Space Administration, Department of Defense, NSF, Department of the Interior, and EPA.

[44] The MCDR-FTAC is to terminate by November 15, 2024, unless renewed by the National Science and Technology Council Subcommittee on Ocean Science and Technology. See *MCDR-FTAC Charter*.

Acidification, to explicitly include mCDR research activities.[45] In addition to reducing potential duplication across federal agencies, improved federal coordination on mCDR activities could yield research results that inform whether mCDR approaches are effective.[46]

The private sector may be reluctant to fund mCDR activities until the risks and benefits are better understood. In the absence of private sector support, agencies such as DOE, NOAA, and NSF have provided funding to support external and/or joint (federal and nonfederal) projects aimed at advancing mCDR RD&D.[47] Some Members introduced legislation in the 118th Congress that would direct certain federal agencies to provide funding for nonfederal research. For example, Section 101 of H.R. 5457/S. 2812 would direct DOE's FECM to provide competitive demonstration awards for mCDR projects within the U.S. EEZ, and Section 903 would direct NSF, in collaboration with other federal agencies, to provide funds for mCDR research. Some stakeholders contend that recipients of federal funding should be required to abide by a code of conduct designed to ensure researchers avoid, minimize, mitigate, and monitor the environmental impacts of mCDR activities,[48] as with DOE's Responsible Carbon Management Initiative.[49]

What Is the Effectiveness of Marine Carbon Dioxide Removal?

Results of some laboratory and modeling studies indicate that mCDR may be effective at absorbing atmospheric CO_2 and storing it in the ocean for prolonged periods of time.[50] Some stakeholders contend that controlled field experiments are needed to determine whether mCDR approaches can lead to a net increase in ocean carbon storage.[51] A controlled field experiment may include (1) quantifying the rate at which carbon is taken up by the ocean (i.e., sequestration rate); (2) monitoring and verifying carbon sequestration; (3) determining the permanence of carbon sequestration; and (4) monitoring ecological and environmental shifts to demonstrate that the approach is effective while minimizing impacts. This research may be challenging, because "extremely precise measurements are required to detect a small [carbon] removal signal."[52]

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[45] 33 U.S.C. §3703. See Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*, September 2023, p. 19.

[46] For more information about existing interagency working groups and committees as well as federal coordination on research related to coastal CDR and mCDR, see CRS Report R48148, *Coastal Blue Carbon as a Carbon Dioxide Removal Approach: Selected Issues for Congress*, by Caitlin Keating-Bitonti and Eva Lipiec.

[47] For example, NOAA, "Announcing $24.3M Investment Advancing Marine Carbon Dioxide Removal Research," September 7, 2023, https://oceanacidification.noaa.gov/fy23-nopp-mcdr-awards/; DOE, "DOE Announces $36 Million to Advance Marine Carbon Dioxide Removal Techniques and Slash Harmful Greenhouse Gas Pollution," October 26, 2023, https://www.energy.gov/articles/doe-announces-36-million-advance-marine-carbon-dioxide-removal-techniques-and-slash; DOE, "U.S. Department of Energy Announces $45 Million to Validate Marine Carbon Dioxide Removal Techniques," February 16, 2023, https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-45-million-validate-marine-carbon; and NSF, "mCDR 2023: Data Requirements for Quantifying Natural Variability and the Background Ocean Carbon Sink in Marine Carbon Dioxide Removal (mCDR) Models," https://www.nsf.gov/awardsearch/showAward?AWD_ID=2333608.

[48] Center for the Blue Economy, *Turning the Tide*, pp. 38-39.

[49] The Responsible Carbon Management Initiative encourages developers to "pursue the highest levels of safety, environmental stewardship, accountability, community engagement, and societal benefits in carbon management projects." DOE, "Notice of Intent and Request for Information Regarding Launching a Responsible Carbon Management Initiative," 88 *Federal Register* 54608, August 11, 2023.

[50] For example, Bach et al., "Implementation of Marine CO_2 Removal for Climate Mitigation, p. 4.

[51] For example, Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, pp. 38, 40, 67; NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, p. 239; Ocean Visions, "A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030," pp. 2-4.

[52] Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 20.

Several federal agencies have established programs to collect ocean data that may be applicable to monitoring and verifying carbon removal (e.g., NOAA, National Aeronautics and Space Administration, U.S. Geological Survey).[53] To accelerate the development of "marine carbon sensor technologies operating across spatial and temporal scales broad enough to sufficiently understand mCDR," among other research questions, the Advanced Research Projects Agency-Energy established the Sensing Exports of Anthropogenic Carbon Through Ocean Observation (SEA-CO2) program.[54] SEA-CO2 has supported at least 11 projects.[55] Congress may consider whether the current federal investment in ocean monitoring and observational instruments is sufficient to provide accurate information about the efficiency of mCDR.

What Is the Cost of Marine Carbon Dioxide Removal?

Experts have estimated the cost per ton of carbon removal ($/t$CO_2$ removed) for future at-scale deployment for the different mCDR approaches.[56] Approaches proposed to have a low-to-moderate cost include macroalgal cultivation ($25-$125/tCO_2 removed), ocean alkalinity enhancement ($25-$160/tCO_2 removed), and ocean fertilization ($50-$125/tCO_2 removed).[57] Artificial upwelling and downwelling are proposed to have a moderate cost ($100-$150/tCO_2 removed), and direct ocean removal is proposed to have a high cost ($400-$600/tCO_2 removed).[58] Direct air capture CDR is estimated to cost $40-$1,000/tCO_2 removed.[59] Some stakeholders may contend the cost for full-scale deployment of mCDR should be compared with the costs of a no-action alternative, such as the economic costs associated with climate-related risks and impacts.[60]

Some stakeholders have proposed goals for cost per ton of carbon removal for CDR. H.R. 7054, introduced in the 118th Congress, would direct DOE to determine if technologies to remove CO_2 directly from ambient air or seawater are economically feasible and provide a roadmap for decreasing the cost per ton of carbon removal to no more than $150 by 2035, among other research objectives.[61] DOE's Negative Carbon Shot aims to advance technologies that reduce the cost of CDR approaches to less than $100/t$CO_2$-equivalent removed.[62]

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[53] For an overview of federal programs engaged in ocean research, see CRS Report R47021, *Federal Involvement in Ocean-Based Research and Development*, by Caitlin Keating-Bitonti.

[54] The Advanced Research Projects Agency-Energy is a DOE office authorized by the America COMPETES Act (P.L. 110-69) to support transformational energy technology research projects. DOE, "Sensing Exports of Anthropogenic Carbon through Ocean Observation," https://arpa-e.energy.gov/technologies/programs/sea-co2.

[55] Ibid.

[56] Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 22; and NASEM, p. 256.

[57] Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research*, p. 22.

[58] Ibid.

[59] Ibid.

[60] For example, Climate Policy Initiative, "The Cost of Inaction," https://www.climatepolicyinitiative.org/the-cost-of-inaction/.

[61] §2(d)(1) of H.R. 7054 in the 118th Congress would consider CDR "economically feasible if such removal can be accomplished" under five different scenarios with specific timeframes with a cost per ton of carbon removal ($/t$CO_2$) removed (e.g., not more than $750/t$CO_2$ removed in FY2024-2025).

[62] DOE, "Carbon Negative Shot," https://www.energy.gov/fecm/carbon-negative-shot. For any quantity and type of greenhouse gas (GHG), *CO_2 equivalent* signifies the amount of CO_2 which would have the equivalent global warming impact based on the global warming potential of the GHG.

What Are Potential Co-benefits and Negative Impacts of Marine Carbon Dioxide Removal?

Limited experimentation for many mCDR approaches provides uncertainties regarding the potential *ecological* and *environmental* co-benefits and impacts associated with mCDR.[63] For example, over the past 30 years, at least 16 ocean fertilization experiments have taken place in the open ocean.[64] No field experiments have taken place for other mCDR approaches.[65] Results from these experiments led some stakeholders to assert that such efforts will have "unknown, unpredictable, and potentially highly damaging impacts on the food web in marine ecosystems."[66] The specific interactions and degree of impact of potential deleterious effects on the marine food web and other ecological interactions remain unknown.

Some scientists, primarily through laboratory and modeling studies, have identified a range of effects associated with mCDR approaches. Depending on the approach, these effects include potential reduction in deep-sea oxygen levels,[67] reduction in ocean acidification,[68] and changes to biochemical cycling with potential repercussions on marine ecosystems (**Table 1**). A study by NOAA's Office of National Marine Sanctuaries evaluated the level of risk associated with mCDR approaches based on their level of potential negative environmental impacts. The study identified ocean fertilization and OAE via accelerated weathering as having medium environmental risk. It identified macroalgal cultivation, artificial upwelling and downwelling, and OAE via electrochemical acid removal as having high environmental risk.[69] Some bills introduced in the 118th Congress would direct federal agencies to either conduct research examining the potential impacts of mCDR or provide funding to nonfederal researches investigating these impacts (e.g., H.R. 5457/S. 2812, S. 1576, and H.R. 7797).

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[63] In this context, *environmental* primarily refers to the physical and chemical (i.e., abiotic) environment and *ecological* refers to biological interactions with the abiotic environment. A discussion of the social impacts and governance challenges associated with mCDR are beyond the scope of this product. For an overview of social impacts and governance challenges associated with mCDR, see NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*.

[64] Geoengineering Monitor, "Geoengineering Technology Briefing: Ocean Fertilization," January 2021, p. 1, https://www.geoengineeringmonitor.org/wp-content/uploads/2021/04/ocean-fertilization.pdf.

[65] Ibid.

[66] Ibid., p. 2.

[67] Anand Gnanadesikan et al., "Effects of Patchy Ocean Fertilization on Atmospheric Carbon Dioxide and Biological Production," Global Biogeochemical Cycles, vol. 17, no. 2 (2003), pp. 1-17.

[68] For example, see ibid., pp. 37 and 39; and NASEM, *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, pp. 6 and 200.

[69] Rozen et al., *Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries*, pp. 6-10.

Table 1. Selected Potential Co-benefits and Negative Impacts of Marine Carbon Dioxide Removal Approaches

(listed in alphabetical order)

Approach	Potential Co-benefit(s)	Potential Negative Impact(s)
Artificial downwelling	Increase ventilation of oxygen-poor deepwater, countering *hypoxia*[a] and *eutrophication*[b]	Alter food web interactions Alter physical oceanic processes, including ocean circulation and density structure (i.e., stratification)
Artificial upwelling	Increase prey for fishes and higher-order consumers (e.g., marine mammals) in the marine food web Reduce thermal stress in coral ecosystems with cold upwelled deepwater and abate coral bleaching	In addition to the impacts listed above, Alter atmospheric circulation and precipitation patterns due to changes in surface ocean temperatures Increase surface temperature and atmospheric CO_2 to higher than pre-welling conditions following the cessation of artificial upwelling Release deepwater CO_2 to the atmosphere prior to the onset of primary production
Direct ocean removal[c]	Captured CO_2 can be turned into commercial products Captured CO_2 can be used to neutralize alkaline wastewater or alkaline stormwater Counter *ocean acidification*[d]	Alter phytoplankton, invertebrate, and vertebrate physiology, community composition, and ecological interactions
Macroalgal (seaweed) cultivation	Enhance *closed-circuit* finfish, shellfish, and seaweed aquaculture, if cultivation occurs near existing aquaculture facilities[e] Counter *ocean acidification* (i.e., increase pH by 0.01 unit per decade) in certain geographic regions[d]	Alter small-scale seawater processes, including seawater exchange rates (i.e., between water masses) in a given area Bury seafloor life with macroalgae Cause deepwater *hypoxia*[a] and *eutrophication*[b] Entangle marine animals Increase seawater stagnation (i.e., inability for seawater to mix with other water masses) Introduce disease, invasive species, and/or parasites Produce *halocarbons* by macroalgae[f] Reduce light availability Reduce nutrient availability Reduce phytoplankton productivity with potential impacts to higher-order consumers throughout the water column
Ocean alkalinity enhancement	Benefit calcifying organism (e.g., coccolithophores) if carbonate-derived alkaline minerals are applied[g]	Alter food web interactions

Approach	Potential Co-benefit(s)	Potential Negative Impact(s)
	Benefit nitrogen-fixing organisms (e.g., cyanobacteria) if the mineral olivine is applied	Alter natural chemical cycling and seawater chemistry
	Benefit organisms that grow silicate structures (e.g., diatoms) if the mineral olivine is applied	Alter phytoplankton, invertebrate, and vertebrate physiology and potential mortality
	Counter *ocean acidification*[d]	Increase *turbidity* and alter light availability[h]
	Increase the sinking rate of feces of organisms that ingest mineral particles, thereby enhancing the export of carbon to the deep ocean	Release trace metals, if alkaline minerals are sourced from certain mines and industry
Ocean fertilization	Counter *ocean acidification*[d] Increase prey for fishes and higher-order consumers (e.g., marine mammals) in the marine food web Enhance deep-sea biomass in certain regions (due to increased supply of organic matter on the seafloor) Increase oxygen production in surface waters temporarily	Alter food web interactions Bury seafloor life due to increased rates of particle deposition Cause deepwater *hypoxia* or *anoxia*[a] Cause e*utrophication*[b] Cause *nutrient robbing*[i] Cause deepwater *ocean acidification* (i.e., decrease pH by 0.1 unit) due to moving atmospheric CO_2 into the deep ocean[d] Cause toxic algal blooms Enhance stratification due to the phytoplankton bloom increasing seawater temperature Increase *turbidity* and alter light availability during the resulting phytoplankton bloom[h] Introduce toxic mine tailings to seawater if iron filings are used Produce GHGs (e.g., nitrous oxide, methane)

Sources: Mustafa Babiker et al., "Cross-Sectoral Perspectives," in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds. Priyadarshi R. Shukla et al. (Cambridge, UK: Cambridge University Press, 2022), pp. 1245-1354; Lennart T. Bach et al., "Implementation of Marine CO_2 Removal for Climate Mitigation: The Challenges of Additionality, Predictability, and Governability," *Elementa*, vol. 12, no. (1), pp. 1-16; Manon Berger et al., "Ocean Dynamics and Biological Feedbacks Limit the Potential of Macroalgae Carbon Dioxide Removal," *Environmental Research Letters*, vol. 18, no. 2 (2023), 024039, pp. 1-13; Jessica N. Cross et al., *Strategy for NOAA Carbon Dioxide Removal Research: A White Paper Documenting a Potential NOAA CDR Science Strategy as an Element of NOAA's Climate Interventions Portfolio*, NOAA Special Report, May 2023, pp. 1-81; National Academies of Sciences, Engineering, and Medicine, *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, (Washington, DC: The National Academies Press, 2022); Prati Rosen et al., *Guidance for the Potential Application of Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries*, National Oceanic and Atmospheric Administration (NOAA), Office of National Marine Sanctuaries, June 2023; U.S. Environmental Protection Agency, "About mCDR and mSRM," https://www.epa.gov/ocean-dumping/about-mcdr-and-msrm; and Jiajun Wu, David P. Keller, and Andreas Oschlies, "Carbon Dioxide Removal via Macroalgae Open-Ocean Mariculture And Sinking: An Earth System Modeling Study," *Earth System Dynamics*, vol. 14, no. 1 (2023), pp. 185-221.

Notes: CO_2 = carbon dioxide; GHG = greenhouse gas; mCDR = marine carbon dioxide removal. The table does not identify upstream or other lifecycle effects from the mCDR approach.

a. *Hypoxia* refers to water conditions that have dissolved oxygen levels below 2 milligrams per liter, and *anoxia* refers to waters that are depleted of dissolved oxygen (NOAA, "Hypoxia," https://oceanservice.noaa.gov/hazards/hypoxia/).

b. Some experts define *eutrophication* as "an increase in the rate of supply of organic matter to an ecosystem," which can promote the growth of algae through nutrient enrichment of coastal and marine systems. Eutrophication may lead to hypoxia, fish kills, turbidity, and other consequences. For example, see Scott W. Nixon, "Eutrophication and the Macroscope," *Hydrobiologia*, vol. 629, no. 1 (2009), pp. 5-19.

c. In theory, the infrastructure for direct ocean capture can be deployed offshore to avoid competitive nearshore use and also be powered by renewable energy sources. Some have proposed these two deployment strategies as potential benefits of this mCDR approach.

d. The increased uptake of atmospheric CO_2 by the ocean alters the chemistry of seawater by decreasing its pH in a process referred to as *ocean acidification*. One pH unit decrease equates to 10 times increase in seawater acidity. For more information, see CRS Report R47300, *Ocean Acidification: Frequently Asked Questions*, by Caitlin Keating-Bitonti and Eva Lipiec.

e. Some experts define *closed* (i.e., closed circuit or closed recirculating systems) aquaculture systems as those where the water is reconditioned and recirculated to the culture unit(s) (e.g., tank or pond). For example, see Thomas B. Lawson, "Aquaculture in Open Systems," in *Fundamentals of Aquaculture Engineering* (Norwell, MA: Kluwer Academic Publishers Group, 1995), p. 58.

f. *Halocarbons* are compounds that contain carbon, contain one or more halogens (e.g., fluorine, chlorine, bromine), and may contain hydrogen. Their emissions are associated with stratospheric ozone depletion. See O. Hodnebrog, K. Shine, and T. Wallington, "Halocarbons: What Are They and Why Are They Important?," *EOS*, vol. 101 (2020); and "H2," in *Bretherick's Handbook of Reactive Chemical Hazards*, ed. P. G. Urben, 8th ed. (Cambridge, MA: Elsevier, 2017), pp. 1247-1260.

g. Enhanced calcification could have an increasing or decreasing effect on carbon removal.

h. *Turbidity* is a measure of the relative clarity of the water. Increased particles (e.g., sediment, phytoplankton) in the water will increase the turbidity.

i. *Nutrient robbing* may occur when nutrients used by ocean fertilization biological production are not available for biological production and CO_2 uptake by surface ocean waters elsewhere.

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