Office of National Marine Sanctuaries
National Oceanic and Atmospheric Administration

Guidance for the Potential Application of Marine Carbon Dioxide Removal (mCDR) in U.S. National Marine Sanctuaries

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U.S. Department of Commerce
Gina Raimondo, Secretary

National Oceanic and Atmospheric Administration
Richard W. Spinrad, Ph.D., Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator

National Ocean Service
Nicole LeBoeuf, Assistant Administrator

Office of National Marine Sanctuaries
John Armor, Director

SUGGESTED CITATION

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Cover photo: Kelp, like this giant kelp forest, and other macroalgae are one of many mCDR techniques. Credit: Robert Schwemmer/NOAA.

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Executive Summary and Purpose

Executive Summary

In addition to ambitious efforts to reduce greenhouse gas emissions, multiple gigatons of atmospheric carbon dioxide (CO_2) will likely need to be removed to significantly curb the impacts of global climate change. According to the National Academies of Sciences, Engineering, and Medicine's (NASEM's) Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration, the marine environment is a key long-term carbon reservoir, and its sequestration potential may be enhanced through marine Carbon Dioxide Removal (mCDR) methods, thereby reducing atmospheric levels of CO_2.[1] The mCDR approaches reviewed in this document are considered based on their level of environmental impact: low risk, including ecosystem recovery and coastal blue carbon approaches; medium risk, including nutrient fertilization and alkalinity enhancement; and high risk, including seaweed cultivation and sequestration, artificial upwelling and downwelling, and electrochemical approaches.

Congressional and external stakeholder interest in mCDR is increasing. Results from a survey conducted with select Office of National Marine Sanctuaries (ONMS) staff found that there have been external inquiries about mCDR deployment in national marine sanctuaries, and that there is an interest among sanctuary staff and advisory council members in learning more about the subject. This guidance is meant to respond to that interest and facilitate future discussions about sanctuaries' engagement with mCDR by providing information on the basic characteristics and key considerations around different mCDR approaches.

For possible deployment of mCDR in national marine sanctuaries, sanctuary managers should consider the associated level of environmental risk in addition to the mCDR approach's alignment with the National Marine Sanctuaries Act mission and authority to protect nationally significant resources, as well as any site-specific missions or authorities. Ultimately, since all mCDR methods involve some level of environmental risk, it is important to consider whether the activity needs to be conducted in a sanctuary to achieve its purpose and whether the activity is aligned with the purposes of the NMSA and the goals of the sanctuary. Deploying a mCDR project, at any scale, would require satisfying federal, state, and international regulations outside of the purview of ONMS, for example Titles I and II of the Marine Protection, Research, and Sanctuaries Act (MPRSA), also referred to as the Ocean Dumping Act, which are administered by the Environmental Protection Agency (EPA).[2] The precise regulations to be satisfied would likely depend on the proposed project and location of deployment. If such regulations were to be satisfied, the majority of mCDR approaches may still trigger additional prohibitions under the NMSA and implementing regulations. Projects proposed in a sanctuary would need to be reviewed by ONMS staff (1) to coordinate with EPA or other federal or state entities to determine whether the project is subject to and could be permitted under federal statutes such as the MPRSA, the Clean Water Act, or the Rivers and Harbors Act, and then (2) to determine if they were eligible for approval through a sanctuary general permit, special use

[1] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

[2] https://www.epa.gov/ocean-dumping/permitting-mcdr-and-msrm

permit, certification, or authorization. Due to the resource protection goal of sanctuaries and the public sensitivity surrounding this topic, sanctuaries should consider if newer forms of mCDR are meeting a high standard for community engagement and scientific transparency and integrity. This document provides a series of questions for ONMS personnel to consider when approached with a particular mCDR inquiry or request and provides details on additional factors such as governance and social considerations, co-benefits, scalability, and more.

National marine sanctuary managers should consider if low environmental risk mCDR approaches in sanctuaries may align with the sanctuary's mission and promote a healthy ocean. Managers may also wish to consider medium risk methods at experimental scale, but should proceed with caution and fully understand the scope required and the extent of the risks and impacts before deployment. Sanctuary managers should consider disallowing high environmental risk approaches due to large-scale known and unknown physical and biological effects as well as associated risk with the involved equipment and associated impacts. High environmental risk approaches should be regarded with utmost caution and be consistent with the precautionary principle.

Purpose

The purpose of this document is to provide the foundational knowledge, awareness, and guidance on mCDR that sanctuary managers require to familiarize themselves with the topic and make key decisions regarding current inquiries and future planning around the deployment of mCDR in national marine sanctuaries. Furthermore, it aims to facilitate policy decisions, raise awareness on the nascent subject, and promote discussion. This document explores considerations related to mCDR through ONMS processes. Deploying any mCDR project, at any scale, would require satisfying other federal, state, and international regulations. The precise regulations to be satisfied would likely depend on the proposed project and location of deployment. A full exploration of these regulations is beyond the scope of this document, but readers can learn more by referring to relevant state, federal, and international regulatory literature. While this report directly focuses on the potential of mCDR deployment within sanctuaries, it also hopes to inform future discussions around the role that national marine sanctuaries may have in fostering research, education, international collaboration, and public involvement around mCDR. This document will be updated as more information becomes available for this rapidly evolving field.

Marine Carbon Dioxide Removal Background

Atmospheric carbon dioxide (CO_2) concentrations continue to reach record high levels, with present CO_2 concentrations greater than at any point in the last 800,000 years.[3] With elevated CO_2 levels contributing to anthropogenic climate change, marine and terrestrial ecosystems are experiencing detrimental impacts.[4] The Intergovernmental Panel on Climate Change's (IPCC) sixth assessment report stresses global climate-driven changes and influences are becoming more widespread, rapid, and intense and immediate action is required to reduce heat-trapping gasses and avoid worst-case scenarios. The report delineates a successful change will likely necessitate multiple strategies ranging from working together on local to federal to international levels.

In addition to reducing emissions, an estimated multi-gigatons per year of CO_2 will need to be removed from the atmosphere to induce a significant change in the trajectory of climate change. The potential exists for the marine environment, already the planet's largest long-term non-fossil carbon sink, to have its natural carbon sequestration capacity enhanced by ocean-based Carbon Dioxide Removal (CDR) technologies.[5] CDR approaches span a range of biotic and abiotic methodologies, but the aforementioned IPCC report uniformly defines CDR as "anthropogenic activities that deliberately remove CO_2 from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs, or in products. Carbon dioxide is removed from the atmosphere by enhancing biological or geochemical carbon sinks or by direct removal of CO_2 from the air." Ocean-based CDR, or marine CDR (mCDR), refers to intervention methods that occur primarily in ocean and coastal regions and extract CO_2 from the atmosphere or from seawater to reduce atmospheric CO_2, and durably store the extracted CO_2 for extended periods of time.[6] It is important to note the carbon removal potential and scalability potential of these approaches vary widely amongst the technologies. These factors will be discussed more extensively later in this report.

In addition to mCDR activities that use ocean or coastal-based processes to capture and store CO_2, there are proposals to use sub-seafloor geologic formations and depleted offshore oil and gas reservoirs to store CO_2 that is captured elsewhere, including via terrestrial processes. This technique is not mCDR, both because it does not directly draw down CO_2 and as it may involve terrestrial processes, and as such is not covered alongside the mCDR techniques discussed in

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[3] Blunden, J., Hartfield, G., Arndt, D. S., DUNN, R., TYE, M., Blenkinsop, S., ... & JACOBS, S. (2018). State of the Climate in 2017. *Bulletin of the American Meteorological Society, 99*(8), Si-S310. doi:10.1175/2018BAMSStateoftheClimate.1

[4] IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

[5] Aspen Institute Energy & Environment Program. (2021). *Guidance for Ocean-Based Carbon Dioxide Removal Projects: A Pathway to Developing a Code of Conduct*. (Washington, DC: Climate Institute). https://www.aspeninstitute.org/wp-content/uploads/files/content/docs/pubs/120721_Ocean-Based-CO2-Removal_E.pdf

[6] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

this report. However, as it may have impacts on marine ecosystems and resources, sub-seabed geologic storage is discussed in a separate section at the end of the main body of this report.

While many mCDR technologies currently exist, the most prevalent existing and proposed strategies include ecosystem recovery, coastal blue carbon, seaweed cultivation and carbon sequestration, nutrient fertilization, alkalinity enhancement, artificial upwelling and downwelling, and electrochemical approaches.[7] These mCDR methods can be defined as follows:

Ecosystem recovery is the protection and restoration of ocean and coastal ecosystems such as kelp forests and free-floating *Sargassum spp*. as well as the recovery of marine species such as fishes, whales, and other animals. These ecosystems and organisms have the potential to contribute to CO_2 removal by storing carbon in their bodies and enhancing the sequestration and export of carbon to long-term reservoirs.

Coastal blue carbon involves the preservation and restoration of carbon-sequestering coastal wetlands, including salt marshes, mangroves, and seagrasses. Through photosynthesis, these ecosystems remove CO_2 from the atmosphere and incorporate it into plant biomass, which is ultimately stored as dead organic matter in the soil for hundreds to thousands of years.[8]

Seaweed cultivation and carbon sequestration is the process by which macrophytes (seaweed) are farmed on large scales, which results in the production of organic carbon biomass through photosynthesis. The mass-production scale of seaweed aquaculture can assist with removing carbon from the atmosphere and the upper ocean and transporting it to the deep sea, where it can be stored for centuries to millennia.

Nutrient fertilization is the enhancement of the natural ocean biological carbon pump by the addition of micro- (e.g., iron) and/or macro-nutrients (e.g., nitrogen) to the upper (sunlit) layers of the ocean to stimulate naturally occurring photosynthesis by marine phytoplankton. The CO_2 that is taken up by phytoplankton during photosynthesis is then converted to carbon in the body of phytoplankters and, upon the death and sinking of the organism, transferred to the deep sea or sediments where it can be stored for periods of up to millennia under the right conditions.

Alkalinity enhancement involves the addition (by dissolution) of alkaline materials into the ocean to enhance seawaters' natural conversion of CO_2 from the atmosphere into stable bicarbonate and carbonate molecules; this further develops the conditions for the ocean to absorb more CO_2 from the atmosphere. Alkalinity enhancement is conducted through various methods such as enhanced mineral weathering and electrochemical or thermal reactions.

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[7] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

[8] National Academies of Sciences, Engineering, and Medicine. (2017). *Coastal Blue Carbon Approaches for Carbon Dioxide Removal and Reliable Sequestration: Proceedings of a Workshop—in Brief*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24965

Artificial upwelling and artificial downwelling utilize engineered methods, such as pipes and pumps, to push seawater between the surface and deep ocean. Artificial upwelling is the pumping of cooler, more nutrient- and CO_2-dense water from lower depths to the surface to increase local surface primary production. Artificial downwelling is the pumping of surface water downward below the pycnocline to counteract artificial upwelling and move carbon to the deep ocean, where it can be stored, while alleviating eutrophication and hypoxia following natural or enhanced CO_2 uptake at the surface.

Electrochemical approaches have similar desired output effects to ocean alkalinity enhancement, and some projects may even include alkalinity enhancement as an additional goal or co-benefit, but involve using constructed structures and technology to induce particular chemical reactions. An electrolytic approach uses an electric current to break down seawater and salt and rearrange the elements into a discarded acid, and a base that is returned into the ocean. The returned base increases the alkalinity of the seawater and induces more atmospheric CO_2 to be pulled into the ocean. The discarded acid can be used to facilitate an electrodialytic approach in which the acid is combined with seawater in a large, separate tank. The acid converts the inorganic carbon in seawater into CO_2 gas which can be removed. The resulting mixture is a base solution that can be added back into the ocean, increase ocean alkalinity, and absorb additional atmospheric CO_2.

Assessments of Environmental Concerns of mCDR

Small-scale mCDR research activities are already occurring in waters close to shore, including in the United States. As the demand for large-scale experimentation and implementation increases, mCDR has the potential to conflict with other ocean uses.[9] With the ocean so interconnected and the potential unintended consequences of mCDR relatively unknown, it is crucial to investigate the known (albeit with varying levels of confidence) and unknown impacts of these technologies. Based on the NASEM Ocean CDR report,[10] the mCDR approaches explored here have been categorized into three designations based on environmental risk—low, medium, and high,[11] as per the currently available knowledge at the time of the report publication. Readers should be aware that there is uncertainty around many mCDR approaches, given the emerging state of the science.

Tier 1: Low Environmental Risk

Ecosystem Recovery

The impacts of restoring degraded ecosystems and declining marine species are generally positive with abundant co-benefits such as improving ecosystem function and biodiversity, and the services they provide.

Coastal Blue Carbon

The impacts of preserving and restoring coastal blue carbon ecosystems are generally positive, often leading to improved ecosystem function and biodiversity and the services they provide (e.g., coastal flood protection, fish and wildlife habitat, water quality, etc.). Environmental impacts associated with wetland restoration include initial site priming processes such as sediment collection and delivery, nutrient management, and potential groundwater extraction.[12]

Tier 2: Medium Environmental Risk

Nutrient Fertilization

Excess nutrients, such as iron, in the ocean can result in bloom-associated eutrophication which reduces oxygen levels to below that needed by living marine organisms (hypoxia), lead to

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[9] Aspen Institute Energy & Environment Program. (2021). *Guidance for Ocean-Based Carbon Dioxide Removal Projects: A Pathway to Developing a Code of Conduct*. (Washington, DC: Climate Institute). https://www.aspeninstitute.org/wp-content/uploads/files/content/docs/pubs/120721_Ocean-Based-CO2-Removal_E.pdf

[10] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

[11] The high environmental risk approaches listed here are classified as medium-high risk by NASEM, that is the highest environmental risk rating given in the report to any of the mCDR techniques. This report has simplified the categorization to high risk for clarity. The low and medium risk classifications are directly provided by NASEM.

[12] National Academies of Sciences, Engineering, and Medicine. (2017). *Coastal Blue Carbon Approaches for Carbon Dioxide Removal and Reliable Sequestration: Proceedings of a Workshop—in Brief*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24965

changes in phytoplankton species potentially resulting in undesired algal blooms, and cause clouding at the surface.[13] Nutrient fertilization can also influence global nutrient distribution, affecting biological productivity and resulting in cascading effects up the food web—such as changes to the relative abundance, size structures, and diversity of various marine organisms. Resulting plankton blooms can warm the ocean's surface, leading to higher atmospheric temperatures and lowering the ability of seawater to hold dissolved CO_2. Moreover, enhanced surface water temperatures caused by plankton blooms resulting from nutrient fertilization can make surface water less dense. This change in density encourages stratification and discourages mixing with colder, deeper waters.

Many proposed nutrient fertilization initiatives would be deployed in shallower waters (<1000m), but at those depths, the additional CO_2 absorbed by the approach and converted into Particulate Organic Carbon (POC) is likely to return back to the surface on relatively short timescales (<100 years). This could increase local acidity and have cascading negative effects on various marine organisms. If nutrient fertilization occurred on the surface over deeper waters (>1000m), the POC would be more likely to settle at a depth where there is no significant mixing (i.e., below the pycnocline), allowing it to contribute to long-term carbon storage.[14] However, this could result in increased ocean acidification of deep waters. Moreover, the decomposition of the nutrient-induced algal bloom particles could cause deeper waters to be depleted of oxygen and enriched in nutrients, resulting in the production of nitrous oxide (denitrification) and methane, two prominent greenhouse gasses.[15]

Alkalinity Enhancement

Ecotoxicological risks associated with the release of trace metals through mineral dissolution could bioaccumulate up the food chain and pose a risk to human health. The level of toxicity is dependent on the type and concentration of the source rock. For example, silicate rocks are likely to have higher metal concentrations compared to carbonate rocks.[16] A shift may occur in phytoplankton community compositions from carbonate-shell producers (e.g., coccolithophores) to silica-shell producers (e.g., diatoms) based on the type of alkaline materials added. Carbonate-shell producers are vital contributors to the marine carbon cycle as they form their shells using CO_2 in the upper surface and their subsequent sinking to the deep ocean contributes to long-term carbon storage and enhances the alkalinity at the surface.[17]

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[13] Powell, Hugh (January 8, 2008.), What Are the Possible Side Effects?, Oceanus. Woods Hole Oceanographic Institute. https://www.whoi.edu/oceanus/feature/what-are-the-possible-side-effects/

[14] Pires, J. C. M., & da Cunha Gonçalves, A. L. (Eds.). (2019). *Bioenergy with carbon capture and storage: using natural resources for sustainable development*. Academic Press. https://doi.org/10.1016/B978-0-12-816229-3.00006-5.

[15] Ibid (Powell 2008)

[16] Bach, L. T., Gill, S. J., Rickaby, R. E., Gore, S., & Renforth, P. (2019). CO2 removal with enhanced weathering and ocean alkalinity enhancement: potential risks and co-benefits for marine pelagic ecosystems. *Frontiers in Climate*, *1*, 7. https://doi.org/10.3389/fclim.2019.00007

[17] Ferderer, A., Chase, Z., Kennedy, F., Schulz, K. G., & Bach, L. T. (2022). Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community. *Biogeosciences*, *19*(23), 5375-5399. https://doi.org/10.5194/bg-19-5375-2022

Possible ecological and geochemical effects of discharging high alkalinity or high pH waters include the precipitation (inorganic mineral formation) of carbonate. The dispersal of fine particles associated with such precipitation can influence local physical processes, such as the water column's particle concentration, turbidity, and optical characteristics. Moreover, potential changes in rates of particle deposition on the seafloor could lead to smothering or burial, and alter light availability and food web interactions.[18]

Tier 3: High Environmental Risk

Seaweed Cultivation and Carbon Sequestration

Local detrimental effects may be present where large-scale seaweed cultivation operations occur. Two significant immediate impacts are local reductions in light availability and nutrients, which could result in reduced net primary production, carbon export, and trophic transfers from processes other than the cultivated species.[19] Additionally, risks may be similar to those of other aquaculture practices such as the risk of disease and parasites, alteration of population genetics, introduction of non-native species, the release of large quantities of wastes (e.g., halocarbons and trace gasses), and enhanced noise pollution as a result of construction, machinery, and vessel traffic.[20]

Regarding impacts to physical processes, large-scale farming can increase stagnation of seawater and induce changes in small-scale circulation patterns. This may influence seawater's residence time in nearshore environments and ultimately affect the frequency and intensity of harmful algal blooms.[21] Deployment in locations where seaweed does not grow naturally could also result in marine megafauna entanglements, particularly in high traffic or migratory zones.[22]

Sinking and storing large quantities of macroalgae biomass into the deep ocean could cause various location-specific ecological and biogeochemical impacts, including increases in acidification, hypoxia, eutrophication, and carbon inputs.[23] Moreover, artificial upwelling, which

[18] "Ocean Alkalinity Enhancement: Environmental Risks." Ocean Vision's Ocean-Based Carbon Dioxide Removal: Road Maps. https://www2.oceanvisions.org/roadmaps/ocean-alkalinity-enhancement/state-of-technology/#environmentalrisks

[19] Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., ... & Stanley, M. (2019). The environmental risks associated with the development of seaweed farming in Europe-prioritizing key knowledge gaps. *Frontiers in Marine Science, 6*, 107. https://doi.org/10.3389/fmars.2019.00107

[20] Ibid.

[21] Frieder, C. A., Yan, C., Chamecki, M., Dauhajre, D., McWilliams, J. C., Infante, J., ... & Davis, K. A. (2022). A Macroalgal cultivation modeling system (MACMODS): evaluating the role of physical-biological coupling on nutrients and farm yield. *Frontiers in Marine Science, 9*, 214. https://doi.org/10.3389/fmars.2022.752951

[22] Ibid. (Campbell et al. 2019)

[23] "Macroalgae Cultivation and Carbon Sequestration: Environmental Risks." Ocean Vision's Ocean-Based Carbon Dioxide Removal: Road Maps. https://www2.oceanvisions.org/roadmaps/macroalgae-cultivation-carbon-sequestration/state-of-technology/#environmentalrisks

is sometimes proposed as a strategy to provide nutrients for macroalgae farming, brings additional risks (see below for further discussion).[24]

Artificial Upwelling and Downwelling

Artificial upwelling and downwelling can affect physical oceanic processes and cause ecological shifts resulting from the movement of colder, inorganic carbon- and nutrient-rich waters to the surface and vice versa. This artificial mixing can influence the ocean's density structure and could change ocean circulation on scales of tens of kilometers.[25] Since deep ocean water is rich in dissolved carbon, additional CO_2 may be outgassed from the ocean surface to the atmosphere.[26]

In stimulating biological productivity at the surface, the subsequent export of organic carbon to the water column can result in enhanced oxygen consumption (creating a hypoxic environment) and the production of respiratory CO_2 and other greenhouse gasses underlying these regions, which may have detrimental effects on marine life.[27] While surface waters may cool due to artificial upwelling and downwelling, enhanced heat storage in subsurface waters may occur, causing these regions to warm significantly.[28]

If artificial upwelling and downwelling are conducted on a large scale, construction of the technology could potentially result in material and noise pollution.

Electrochemical Approaches

Risks inherent to both electrodialysis and electrolysis include potential changes in the properties of the water column such as particle concentration, turbidity, and optical properties due to the precipitation of carbonate resulting from changes in local alkalinity and pH.[29] Moreover, elevated concentrations of bicarbonate and carbonate may pose risks if sustained in the environment. Associated increases in acidity or alkalinity may also cause shifts in phytoplankton, invertebrate, and vertebrate physiology, competition, and potential mortality.[30]

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[24] Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., ... & Chen, Y. (2016). Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences, 59*, 236-248. https://doi.org/10.1007/s11430-015-5195-2

[25] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

[26] Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., ... & Chen, Y. (2016). Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences, 59*, 236-248. https://doi.org/10.1007/s11430-015-5195-2

[27] Keller, D. P., Feng, E. Y., & Oschlies, A. (2014). Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nature Communications, 5(1), 3304. https://doi.org/10.1038/ncomms4304.

[28] Boettcher, M., Chai, F., Cullen, J., Goeschl, T., Lampitt, R., Lenton, A., ... & Wanninkhof, R. (2019). *High level review of a wide range of proposed marine geoengineering techniques*. eds. Boyd, Philip and Vivian, Chris. GESAMP Reports & Studies Series, 98. GESAMP, 144 pp.

[29] "Electrochemical CDR: Environmental Risks." Ocean Vision's Ocean-Based Carbon Dioxide Removal: Road Maps. https://www2.oceanvisions.org/roadmaps/electrochemical-cdr/state-of-technology/#environmentalrisks.

[30] Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. Reviews of *Geophysics, 55*(3), 636-674. https://doi.org/10.1002/2016RG000533.

The mechanism of the machine's seawater pumps and filters can also result in the mortality of surrounding marine life.

Discarded outputs from these reactions, such as large excesses of acid, will require safe consumption or neutralization, likely through reactions with alkaline minerals.[31] The production of excess gas, particularly chlorine, will also require treatment and safe disposal.[32] Reactions that split CO_2 gas from seawater risk potential leakage of the stored CO_2 back into the ocean or atmosphere.

Additional Considerations

It is crucial to note while each approach has varying levels of risks to the marine environment, some methods may also result in various associated external CO_2 emissions and environmental impacts. mCDR methods that have low inherent environmental risk are likely to have little to no associated external impacts. Site-specific approaches may produce CO_2 emissions due to boat travel to sites, construction, mining for particular minerals, etc. With intervention methods that depend on a consistent source of power (e.g., artificial upwelling and downwelling), the technology will likely require most of its power to be generated by non-fossil fuel sources to achieve a net positive removal of atmospheric carbon dioxide.

[31] Ibid. ("Electrochemical CDR: Environmental Risks")
[32] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

National Marine Sanctuaries Act and Permitting

Location-specific and project-specific requirements may apply in some sanctuaries, including regulatory requirements of federal or state regulations outside the purview of ONMS. For example, certain mCDR activities, including research activities, may require authorization under more than one federal statute, including the EPA-administered or Army Corps-administered statutes like, Titles I and II of the MPRSA, Clean Water Act, or Rivers and Harbors Act.[33] The precise requirements would depend on the specific location and nature of the proposed project. A comprehensive review of these requirements is beyond the scope of this document. Proposed projects would need to be reviewed by ONMS staff (1) to coordinate with EPA or other federal or state entities to determine whether the project is subject to and could be permitted under federal statutes such as the MPRSA, the Clean Water Act, or the Rivers and Harbors Act, and then (2) to determine if they were eligible for approval through a sanctuary general permit, special use permit, certification, or authorization if deployed in a sanctuary.

The United States National Marine Sanctuaries Act (16 USC §§ 1431 et seq.) provides a coordinated and comprehensive legislative approach to conserving and managing certain areas of the marine environment of national significance. National marine sanctuaries protect places with significant natural and cultural resources—particularly breeding and feeding grounds for endangered species such as whales; habitats such as coral reefs and kelp that support a variety of life; and historically important areas that contain shipwrecks and archaeological resources. With relevance to the deployment of mCDR in national marine sanctuaries, the Act cites the authority to:

- Provide for comprehensive and coordinated conservation and management of these marine areas, and activities affecting them, in a manner which complements existing regulatory authorities.
- Maintain the natural biological communities in the national marine sanctuaries, and to protect, and, where appropriate, restore and enhance natural habitats, populations, and ecological processes.
- Support, promote, and coordinate scientific research on, and long-term monitoring of, the resources of these marine areas.
    - Develop and test methods to enhance degraded habitats or restore damaged, injured, or lost sanctuary resources
- Issue special use permits for the conduct of specific activities in a national marine sanctuary deemed necessary for access to and use of any sanctuary resource.

The Act authorizes the Secretary of Commerce to designate and protect marine areas of national significance, and their management has been delegated to NOAA's Office of National Marine Sanctuaries (ONMS). As the managing entity, ONMS may encounter inquiries, proposals, and requests for conducting mCDR experiments in national marine sanctuaries. The mCDR approaches may involve activities that are otherwise prohibited by sanctuary regulations. See 15

[33] https://www.epa.gov/ocean-dumping/permitting-mcdr-and-msrm

CFR Part 922 for all ONMS regulations. The current list of regulatory prohibitions that exist across most of the sanctuaries include:

- Discharging material or other matter into the sanctuary
- Disturbance to, construction on, or alteration of the seabed
- Disturbance to cultural resources
- Exploring for, developing, or producing oil, gas or minerals
- Causing disturbances to marine mammals and other organisms

ONMS may issue permits (including general permits, special use permits, certifications and authorizations) to allow activities that are otherwise prohibited by sanctuary regulations. An activity must fall within an existing category of permit and meet certain review criteria (relative to the specific permit tool) in order to be eligible for a permit. Permit categories and review criteria are set forth in ONMS regulations and in the case of special use permits, the NMSA. In all cases, permit eligibility would be conducted on a case-by-case basis and would be based on the specifics of the mCDR activities being proposed. Upon receipt of a permit application, ONMS may request such additional information necessary to evaluate the application and the applicable review criteria, to make a permitting decision, and to inform permit terms and conditions. If a project is found eligible for a permit, ONMS applies special terms and conditions to permits to avoid, minimize or otherwise mitigate adverse effects to sanctuary resources. ONMS regulations also set forth the ability to amend, suspend, or revoke a permit for good cause. ONMS permit decisions may be administratively appealed to the National Ocean Service Assistant Administrator.

ONMS permitting is a tool that can potentially be used to allow various mCDR activities in sanctuaries should they align with ONMS mission and values. mCDR permitting decisions would be made on a case-by-case basis based on the permit application and the specific authorities and regulations of each site. The table below provides a description of relevant permitting tools, with notes on how they could relate to mCDR.

Table 1. ONMS Permitting tools and their applicability to mCDR. In some instances, the list of criteria may be shortened to only include relevant information relating to mCDR. Provided is an asterisk (*) with a link to more information.

Permitting Tool	Description	Criteria	mCDR Applicability
General Permit	ONMS may issue a sanctuary general permit for otherwise prohibited activities, if the proposed activity falls within one of the general permit categories or any site-specific permit categories, and provided that the regulatory review criteria are met. The most commonly used ONMS general permit categories	ONMS general permits must meet the following regulatory review criteria: (1) The proposed activity will be conducted in a manner compatible with the primary objective of protection of national marine sanctuary resources and qualities, taking into account the following factors: The extent to which the conduct of the activity may diminish or enhance national marine sanctuary resources and qualities; and any indirect or cumulative effects of the activity; (2) It is necessary to conduct the proposed	A proposed mCDR activity would need to meet one of the categories of a sanctuary general permit. ONMS could consider limited mCDR research applications under the research general

Permitting Tool	Description	Criteria	mCDR Applicability
	are*: (1) Research - activities that constitute scientific research on or scientific monitoring of a national marine sanctuary resource or quality; (2) Education - activities that enhance public awareness, understanding, or appreciation of a national marine sanctuary or national marine sanctuary resource or quality; and (3) Management - activities that assist in managing a national marine sanctuary. *https://www.ecfr.gov/current/title-15/subtitle-B/chapter-IX/subchapter-B/part-922/subpart-D/section-922.30	activity within the national marine sanctuary to achieve its stated purpose; (3) The methods and procedures proposed by the applicant are appropriate to achieve the proposed activity's stated purpose and avoid, minimize, or otherwise mitigate adverse effects on sanctuary resources and qualities as much as possible; (4) The duration of the proposed activity and its effects are no longer than necessary to achieve the activity's stated purpose; (5) The expected end value of the activity to the furtherance of national marine sanctuary goals and purposes outweighs any potential adverse impacts on sanctuary resources and qualities from the conduct of the activity; (6) The applicant is professionally qualified to conduct and complete the proposed activity; (7) The applicant has adequate financial resources available to conduct and complete the proposed activity and terms and conditions of the permit; (8) There are no other factors that would make the issuance of a permit for the activity inappropriate; including if the activity does not meet the requirements of other applicable statutes such as Titles I and II of the Marine Protection, Research, and Sanctuaries Act; and (9) For Olympic Coast National Marine Sanctuary, the activity as proposed does not adversely affect any Washington Coast treaty tribe.	permit. For scientifically-proven applications that would also contribute to the purposes and policies of the NMSA and site-specific priorities, ONMS could consider mCDR activities, such as activities associated with preservation and restoration of ecosystem and coastal blue carbon, under the management general permit category. If a proposed mCDR activity is determined to meet a general permit category, the activity is then evaluated against the regulatory review criteria. A proposed mCDR activity's environmental risks and expected benefits would be important parts of assessing if a specific activity proposal may qualify for a general permit. Of all the review criteria, the necessity of conducting the proposed activity within a national marine sanctuary could be a challenge for many mCDR applications.

Permitting Tool	Description	Criteria	mCDR Applicability
Special Use Permits	Activities authorized under a special use permit (SUP) must fall within one of the SUP categories and must meet the statutory criteria established in NMSA section 310. ONMS establishes specific categories of activities subject to SUPs by publishing them in the Federal Register and soliciting public comment on the categories and the associated fees that could be assessed for those permits. Currently, the list of special use permit categories includes: (1) The placement and recovery of objects associated with public or private events on non-living substrate of the submerged lands of any national marine sanctuary. (2) The placement and recovery of objects related to commercial filming. (3) The continued presence of commercial submarine cables on or within the submerged lands of any national marine sanctuary. (4) The scattering of cremated human remains for burial at sea within or into any national marine sanctuary, when authorized under the Marine Protection, Research, and Sanctuaries Act. (5) Recreational diving near the USS Monitor. (6) Fireworks displays. (7) The operation of aircraft below the minimum altitude in restricted zones of national marine sanctuaries.	In evaluating proposed activities to be conducted pursuant to an SUP, ONMS may authorize the conduct of specific activities in a national marine sanctuary if it determines such authorization is necessary: (1) to establish conditions of access to and use of any sanctuary resource; or (2) to promote public use and understanding of a sanctuary resource. ONMS SUPs must meet the following statutory criteria: (1) Activity is compatible with the purposes for which the sanctuary is designated and with protection of sanctuary resources; (2) Activity may only be permitted for a period of 5 years; (3) Activities conducted under an SUP may not destroy, cause the loss of, or injure sanctuary resources; and (4) The permittee must maintain comprehensive general liability insurance.* *www.sanctuaries.noaa.gov/management/permits/special.html.	There is currently no SUP category that specifically applies to any mCDR approach. However, it is possible that some components of an mCDR project may fall within the existing categories of SUPs. That said, ONMS would need to evaluate the entirety of the mCDR project against applicable permit tools and review criteria. Meeting the SUP review criteria may be challenging for most mCDR applications. In particular, only the low risk mCDR approaches may be eligible under the criterion that specifies that a SUP activity may not destroy, cause the loss of, or injure sanctuary resources.

Permitting Tool	Description	Criteria	mCDR Applicability
	(8) The continued presence of a pipeline transporting seawater to or from a desalination facility in the Monterey Bay National Marine Sanctuary		
Certifications	As part of sanctuary designation, expansion, or regulatory review, ONMS evaluates pre-existing leases, permits, licenses, and rights of subsistence use or access for any intersection with new regulatory prohibitions. Pursuant to the NMSA, ONMS may further regulate the exercise of those rights consistent with the purposes for which the sanctuary is being designated or expanded through a process called certification.	Terms and conditions may be applied to certifications to ensure activities are consistent with the purpose of the sanctuary and to protect sanctuary resources.	ONMS certifications for mCDR approaches would only be applicable if there was a mCDR project previously permitted by a federal, state, or local agency within an area where a new sanctuary is designated or where an existing sanctuary is expanded. ONMS would evaluate whether the mCDR approach was consistent with the purposes and policies of the NMSA and any site-specific goals. ONMS would consider whether further regulation of those activities would further protect sanctuary resources.
Authorizations	ONMS may authorize a person to conduct an otherwise prohibited activity if such activity is specifically allowed by any valid federal, state, or local lease, permit, license, approval, or other authorization. Such authorizations may only be issued for activities in the following six national marine	The applicant for an authorization is required to notify ONMS of their request for an authorization and do so within specific timelines and procedures. In making a decision whether to authorize another agency's permit, ONMS must consider and evaluate the same regulatory review criteria that are established for general permits. See above for the full list of regulatory review criteria.	ONMS authorization of mCDR activities would require that the project involves an otherwise prohibited activity and has a nexus to an underlying federal, state, or local permit. Similar to

Permitting Tool	Description	Criteria	mCDR Applicability
	sanctuaries: Florida Keys, Flower Garden Banks, Monterey Bay, Stellwagen Bank, Olympic Coast, and Thunder Bay national marine sanctuaries. For some sanctuaries, there are specific regulatory limitations on this authority.		sanctuary general permits, the activity would be evaluated against the regulatory review criteria, which may be challenging for certain mCDR approaches to meet.

With mCDR as an emerging field, evaluating the appropriate permit type and assessing whether any given project meets applicable regulatory review criteria may be complex, and will ultimately depend on the authorities and regulations of each site and the specifics of the mCDR activity being proposed. Generally, low risk approaches may be more likely to meet regulatory review criteria, which emphasize the careful analysis of potential impacts of an activity. However, ultimately, since all mCDR methods involve some level of environmental risk, it is important to consider whether the activity needs to be conducted in a sanctuary to achieve its purpose and whether the activity is aligned with the purposes of the NMSA and the goals of the sanctuary.

While the NMSA is the primary legislative authority that can best facilitate ONMS decisions, other existing state, federal, and international regulatory frameworks can provide further guidance on discerning whether mCDR experimentation or implementation is likely to meet applicable regulatory standards other than those that apply under the NMSA and is appropriate in sanctuaries.

Considerations for mCDR in National Marine Sanctuaries

The capacity for carbon removal in terrestrial environments is not alone capable of absorbing sufficient volumes of CO_2 at the timescale necessary to meet global climate mitigation goals. Therefore, growing a diverse portfolio of existing potential carbon removal technologies is necessary. mCDR is an important part of the portfolio that is rapidly gaining traction, and as a consequence there is a rising necessity to research mCDR's environmental effects. mCDR leaders may turn to U.S. national marine sanctuaries (NMS) as potential locations for larger scale testing and implementation. Potential benefits for carrying out scientific research on mCDR in sanctuaries include: (1) some approaches to mCDR may provide co-benefits within the sanctuary, (2) sanctuaries possess diverse marine life and habitats and can serve as undisturbed "control sites" which allow early warning capabilities to various threats, and (3) extensive existing scientific background data may exist on the physical and biological properties of the region that can help provide a scientific baseline for project data collection.

As sanctuary managers are already receiving inquiries from businesses and other stakeholders on mCDR deployment in sanctuaries, they may find themselves needing to determine whether these technologies belong in protected waters. When making that determination, it is critical to keep in mind that mCDR projects in sanctuaries need to comply with federal, state, and international requirements other than those under NMSA, and sanctuaries should consult with those regulatory authorities when considering mCDR projects. It is also important to note that sanctuaries are protected areas that encompass significant natural and cultural features and therefore are held at higher standards for protection, and for consideration of permitting activities, particularly for potentially risky or large-scale approaches like those associated with mCDR.

The nature of sanctuaries may limit the scalability potential for many mCDR approaches. Moreover, sanctuaries should consider holding newer forms of mCDR, particularly medium and high environmental risk approaches, to a high standard in terms of community engagement and scientific transparency and integrity—including long-duration measurement, reporting, and verification (MRV), meeting international standards, and reporting back to the host sanctuary and community—if such activities are permitted within sanctuaries. There is public sensitivity and controversy surrounding mCDR's potential deployment, especially with regards to meeting certain transparency and scientific integrity requirements. However, external support does exist for the experimentation and deployment of more mCDR approaches in coastal and ocean regions to maximize marine carbon mitigation potential.

Based on current knowledge regarding mCDR approaches, sanctuary managers and staff could apply the following framework when assessing proposals to implement mCDR in sanctuaries:

Consider in NMS

1. *Ecosystem recovery*
    a. Little to no negative environmental impacts exist.
    b. May not trigger existing regulations/may require few permits.
    c. Promotes a healthy ocean and aligns with the ONMS mission.
    d. Questions to consider:

i. To what extent is mCDR occurring at the ecosystem level and will it result in any unacceptable imbalances?
ii. After how long will potential mCDR effects become quantifiable?
iii. How vulnerable is this approach to a changing climate?
iv. What is the potential for reversibility of this approach?
v. What is the likelihood these approaches can restore targeted processes on a timescale relevant to climate mitigation?
vi. Will potential curbing of human activities in one area result in their increase in another?

2. *Coastal blue carbon*
    a. Similar rationale as ecosystem recovery.
    b. Special consideration should be taken for environmental impacts of site priming and overall construction.
    c. Questions to consider:
        i. How long will it take for potential mCDR effects to become quantifiable?
        ii. How vulnerable is this approach to a changing climate?
        iii. What is the potential for reversibility of this approach?
        iv. What is the likelihood these approaches can restore ecosystem processes on a policy relevant timescale?
        v. Will potential curbing of human activities in one area result in their increase in another?
        vi. What preventative measures are in place to ensure site priming has minimal environmental impacts?

Consider in NMS with Caution at Experimental Scales

1. *Nutrient fertilization*
    a. Numerous environmental consequences that pose unknown cascading risks.
    b. Requires various permits.
    c. According to the United Nations General Assembly Ocean Resolution 2021,[34] nutrient fertilization should only be considered for legitimate scientific research and assessed on a case-by-case basis using an assessment framework created by the London Convention and Protocol. In accordance with the precautionary approach, nutrient fertilization activities should not be carried out until there is:
        i. Adequate scientific justification for the activities which includes an assessment of associated risks.
        ii. A global, transparent and effective control and regulatory mechanism is in place for this activity.
    d. Questions to consider:
        i. How far and at what magnitude will the effects in the ocean be experienced under various scenarios?
        ii. How can outcomes be optimized based on varying factors such as location, season, duration, type of delivery (pulsed vs. continuous)?

[34] United Nations General Assembly resolution 67/72. Oceans and the law of the sea, A/RES/76/72 (20 December 2021.

iii. What are the effects on planktonic food webs and fisheries? What are the impacts on higher marine trophic levels and how would they be recognized? On what timeline would impacts be observed?
iv. What guidance and code of conduct should be followed for nutrient fertilization research?

2. *Alkalinity enhancement*
    a. Various environmental consequences that have unknown risks.
    b. Ocean alkalinity enhancement may require permitting under federal or state statutes, depending on the specifics of the proposed project, including the location of the activities.
    c. Potential for controlled, small-scale experiments (e.g., mesocosm study) in NMS.
    d. Questions to consider:
        i. What are the optimal locations for ocean alkalinity deployment?
        ii. What is the ideal rate of addition? How far and at what magnitude will affects in the ocean be experienced?
        iii. What indicators can be used to identify physiological effects, marine communities and ecosystems response, and undesirable impacts?
        iv. What conditions may lead to undesirable effects such as particle aggregation as particles are spread throughout the surface, and reverse weathering in which acidity is generated as marine organisms consume the alkaline material for clay formation?

Consider in NMS with Significant Caution at Experimental Scales

1. *Seaweed cultivation*
    a. Potential for cultivation to be deployed on a small scale.
    b. Requires careful management to prevent large uncontrollable effects.
    c. Sinking or burial of seaweed in the seafloor should only occur in areas where bottom habitat impacts are minimal, although more research is needed about impacts on, and distribution of, benthic habitats within sanctuaries.[35]
    d. Likely to require various permits.
    e. Questions to consider:
        i. What spatiotemporal scale would be optimal for macroalgae cultivation and sequestration?
        ii. What are the local and downstream effects of macroalgae cultivation?
        iii. What are the levels of acceptable impacts to disposal sites?
        iv. Are there disposal options that don't involve significant environmental impacts (e.g., product uses, terrestrial applications)?
        v. What is the likelihood of these farms interfering with human activities such as becoming a hazard to navigation or displacing fishing due to ecosystem effects?

[35] In order for farmed biomass to be considered carbon removal, it needs to be sunk in the deep ocean. Biomass used on land for feed and fuel does not sequester carbon for long-term.

vi. At what scale will this approach need to be tested to achieve quantifiable results?

Regard with the Extreme Caution in NMS and Apply the Precautionary Approach

1. *Artificial upwelling and downwelling*
    a. Has detrimental effects on both physical and biological ocean properties and its effects are large-scale.
    b. Requires equipment that may malfunction and/or have detrimental construction impacts, and that could contribute to greenhouse gas emissions.
    c. Questions to consider:
        i. How much additional carbon sequestration will occur with this method?
        ii. What is the optimal siting of this approach? What are the potential conflicts with other ocean uses such as shipping lanes and fishing effort?
        iii. Should artificial pumping be intermittent or continuous?
        iv. What is the potential of carbon outgassing to occur and at what scale?
        v. Are there termination effects such as pressure differentials, circulation compensation, and geochemical effects that may lead to undesired consequences?
2. *Electrochemical approaches*
    a. Affects both the physical and biological properties of the ocean.
    b. Requires equipment that may malfunction and/or have detrimental construction impacts.
    c. Questions to consider:
        i. What is the potential of extracted CO_2 leakage? What are the protocols in place for prevention and treatment of such an event?
        ii. How are unwanted byproducts minimized? Will byproducts be treated and disposed of properly? Have environmental impact assessments or life-cycle assessments been conducted to understand the efficacy and impact of this approach?
        iii. What is the optimal siting of such processes and plants?
        iv. Are there unintended impacts on the ecosystem if this process was terminated at any point?

Other Considerations

Although sanctuary managers should consider certain questions most pertinent to each approach, these general questions should additionally be considered as overall guidance:

Regulatory Considerations

1. Are the project proponents engaging with the appropriate regulatory agencies to ensure compliance with applicable legal frameworks and regulations?

2. Does the project have appropriate authorization (e.g., a permit) or other evidence of compliance with applicable local, state, or federal regulations or policies other than those administered by ONMS?

Office of National Marine Sanctuaries Mission Alignment

1. Does the mCDR project's goals and objectives align with ONMS' mission, objective, and goals?
2. How much additional carbon will be removed if the intervention method is implemented?
3. Why does the project need to be conducted in a national marine sanctuary and not a similar marine site? Can the expected outcomes be achieved in other locations or by other methods?
4. How will ONMS and NOAA scientists be involved, including during stakeholder engagement processes?
5. What are the project's funding sources and how do these sources align with the mCDR's ultimate purpose?

Technical Project Questions

1. Does substantial supporting evidence exist for this project concept? Has this technology previously been verified in laboratory settings or small field sites before being proposed in or scaling up to larger *in situ* experiments in NMS?
2. Does peer-reviewed literature exist that provides support for or concerns about the proposed technology or concept?
3. Will any project activities violate existing laws and regulations, therefore requiring a special local, state, or federal permit? How are researchers engaging with regulatory agencies to ensure compliance with legal frameworks and regulations?
4. Have the project's previous experiments undergone a public engagement opportunity?
5. What protocols does the project have in place to ensure responsible operations when using new approaches and technologies, or operating in geographies, not fully covered by existing laws and regulations?

Environmental Considerations

1. Have an Environmental Impact Statement or other environmental analyses or consultations been conducted, or will they be completed before the start of deployment?
2. Is the scope of the mCDR project proportionate to the current state of scientific knowledge about potential risks? Does the project adhere to the precautionary principle? To what extent has this project been designed to avoid, minimize and mitigate detrimental environmental impacts?
3. What are the potential environmental implications of ending the activities (i.e., decommissioning) after the project has started, such as CO_2 storage impacts, pollution, or ecosystem impacts?
4. Is the project's location, scope, scale, and duration appropriate based on its potential effects to the sanctuary's resources?

Engagement, Equity, and Justice Considerations

1. Does the project's proposed engagement process incorporate and account for community involvement? How does the proposed engagement process incorporate priorities of diversity, inclusion, accessibility and participation?
2. Would the project impact resources of local cultural or economic significance?
3. How does the project account for the inequitable impacts of environmental issues and climate change?

Considerations on Consultation and Government-to-Government Engagement with Tribes and Indigenous Communities

1. Would the project impact resources of Indigenous, cultural, and tribal significance?
2. Have impacts to tribes been adequately considered and should government-to-government consultation be conducted?
3. Does the project's proposed engagement process incorporate and account for local, tribal, and Indigenous communities' involvement?

Additional Factors to Consider in Relation to mCDR Deployment

While the level of environmental risk is a primary concern of sanctuary managers, it may be beneficial to also consider other factors associated with mCDR to gain a comprehensive view of this emerging field. Sanctuary managers may want to specifically consider the efficacy and scalability of the approach, co-benefits, and governance and social conflict considerations associated with the approach. This section and the associated explanatory table provide a high-level assessment of how each mCDR approach measures against these considerations.

The content of this section, including the relative ratings of mCDR in the table below, are based on a recent NASEM comparative report and research strategy on mCDR.[36] This section summarizes NASEM's findings, and builds on them to discuss specifics not directly assessed or scored in the NASEM report. It includes how each mCDR approach's varied characteristics intersect with key governance and social concerns that may be of particular importance to sanctuaries. The results of this effort are summarized in the table below.

Table 2. Rating of mCDR approaches with respect to various factors. * Signifies that associated ratings are directly from NASEM Ocean CDR Report;[37] ** signifies that associated ratings are based on the NASEM Report; *** signifies that the NASEM Report does not explicitly cover coastal blue carbon, the assessment here is based on NASEM ecosystem recovery assessment and author knowledge.

mCDR Impact	Ecosystem Recovery	Coastal Blue Carbon***	Seaweed Cultivation & Sequestration	Nutrient Fertilization	Alkalinity Enhancement	Artificial Upwelling & Downwelling	Electrochemical
1. Environmental risk*	Low	Low	Medium - High	Medium	Medium	Medium - High	Medium – High
2. Efficacy of mCDR benefits*	Low – Medium	Low – Medium	Medium	Medium – High	High	Low	High
3. Governance Challenges**	Low	Low	Medium	High	High	High	High
4. Social Conflicts**	Low	Low	Low	Medium	Medium	High	High
5. Co-benefits*	High	High	Medium - High	Medium	Medium	Medium- High	Medium – High
6. Scalability*	Low – Medium	Low – Medium	Medium	Medium – High	Medium – High	Medium	Medium – High

1. **Environmental risk**, undesirable intended and unintended environmental consequences, is detailed earlier in this report but is included in the above table to compare its rating against other factors. The ratings given are from the NASEM report, and should be considered alongside

[36] National Academies of Sciences, Engineering, and Medicine. (2022). *A research strategy for ocean-based carbon dioxide removal and sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278

[37] Ibid.

the detailed environmental concerns summarized earlier in this report. Since environmental protection is the core of the ONMS mission, the lower risk mCDR approaches may align more closely with the ONMS mission than riskier approaches; however, all mCDR projects will need to be considered on a case-by-case basis.

2. **The efficacy of mCDR** is defined as the level of confidence that a mCDR approach will remove atmospheric CO_2 and result in a net increase in ocean carbon storage.

Due to the diversity of ecosystem recovery and coastal blue carbon approaches, mCDR efficacy is likely to be variable. The NASEM report determines that, of the ecosystem recovery approaches, kelp forest restoration, marine protected areas, fisheries management, and restoration of key blue carbon habitats have particular potential. While seaweed cultivation and sequestration should likely lead to net mCDR, little is known about its potential effect on net primary production that exists downstream and there is only medium confidence in its efficacy.

For nutrient fertilization approaches, NASEM notes medium-high confidence in its efficacy. Greater success has been demonstrated in experiments that occur over deeper waters where carbon can sink below the depth of annual winter mixing and be considered sequestered; however, uncertainty still exists with respect to impact and permanence. Lack of field experiments for ocean alkalinity enhancement makes it difficult to determine its efficacy; more knowledge is needed on factors such as dissolution rates and the fate of mineral particles in the ocean. However, NASEM reported high confidence in this approach's ability to deliver a net increase in ocean carbon storage. Modeling studies of artificial upwelling suggest that large-scale upwelling would not be an effective mCDR method and upwelling of deep water could release CO_2 into the atmosphere. NASEM records high confidence in the efficacy of electrochemical approaches, but the efficacy of those approaches is dependent on the use of renewable energy for the machinery and the ability to produce valuable co-products, such as potential fuel products.

3. **Governance considerations** are the levels of rules and regulations that would apply to any given approach. The NASEM report did not include ratings specifically for governance considerations, though it discusses governance readiness in the context of social considerations, and therefore the assessment for this category is based on information in the NASEM report as well as research conducted for this guidance document. An additional consideration beyond the NASEM report is that deploying any mCDR project, at any scale, would require satisfying regulations and authorities outside of the mission and authorities of ONMS such as other federal, state, and international regulations, for example the MPRSA. The precise regulations to be satisfied would likely depend on the proposed project and location of deployment. A full exploration of these regulations is beyond the scope of this document, but readers can learn more by referring to relevant state, federal, and international regulatory literature.

Ecosystem recovery and coastal blue carbon mCDR approaches do face governance challenges. However, given the lower environmental risk associated with ecosystem recovery and coastal blue carbon, and previous experience navigating the rules and regulations associated with these approaches, they face less of a governance burden than other more novel mCDR approaches.

The legal considerations around seaweed cultivation and sequestration are unclear, sequestration methodologies such as the purposeful sinking of biomass to the seafloor may require permitting to satisfy relevant policies and regulations.

Nutrient fertilization activities, ocean alkalinity enhancement activities, artificially upwelling, and artificially downwelling may be considered a "discharge" as defined under NMSA, and as such may be prohibited in national marine sanctuaries. Further, the construction and placement of subtidal infrastructure associated with these methods may further trigger regulations.

4. **Social conflicts** include factors such as tribal and Indigenous considerations and engagement, public perception, public access, jobs and livelihoods, public health, and more. The NASEM report did not have ratings for social conflicts, though it discussed social considerations. The assessment below is a summary of information in the NASEM report and synthesis of some concerns raised by sanctuaries' staff and partners, as a measure of social acceptance.

Similar to governance considerations, there is generally a positive social attribution to ecosystem recovery and coastal blue carbon approaches as there is minimal disturbance to the community and the environment. While seaweed cultivation and sequestration approaches could result in job creation, social acceptance from local stakeholders around conducting this work may pose a challenge.

There are also social acceptance concerns relevant to nutrient fertilization and ocean alkalinity enhancement, along with the hurdle of developing proper, peer-reviewed experiments that support the deployment of these techniques. Additional social considerations for ocean alkalinity enhancement include issues associated with the expansion of land-based mining production for source materials and associated impacts on public health and the economy.

Unlike other approaches, the open-ocean infrastructure and large-scale effects associated with artificial upwelling and downwelling may cause potential conflict with other ocean uses such as shipping, fishing, and recreation. Electrochemical approaches have similar social considerations to ocean alkalinity enhancement with the additional challenge of the public perception around and conflicting use with developing infrastructure near the coastal marine environment.

5. **Co-benefits** indicate the benefits that might accrue from a project in addition to the main goal of mCDR. The level of co-benefits for ecosystem recovery and coastal blue carbon approaches is very high as they contribute to enhanced biodiversity conservation; increase fisheries habitat; restore degraded ecosystems and their functions; preserve existence, spirituality, and additional non-use values; and increase tourism.

Seaweed cultivation and sequestration may have potential co-benefits if facilities are placed adjacent to fish or shellfish aquaculture to create a more closed-loop system in the aquaculture field. Moreover, cultivated seaweed may be repurposed into feed and fuel for land activities. However, the biomass used for these other activities likely does not contribute to carbon removal objectives. The co-benefits of artificial upwelling include the potential to locally reduce sea surface temperature, support fisheries and aquaculture, and contribute to cloud-formation through dimethyl sulfide production. The co-benefit of electrochemical approaches is the local reduction in ocean acidification. NASEM rated the significance and reliability of co-benefits for all three of these approaches as medium-high.

Little experimental evidence exists for the co-benefits of nutrient fertilization, but potential benefits include the increase in fish stocks through the enhancement of primary production, temporary reduction in local ocean acidification, and the production of dimethyl sulfide, which can lead to the formation of a cloud condensation above the ocean and potentially reduce local temperatures. Similarly, ocean alkalinity enhancement may have the potential to reduce ocean acidity and increase fish stocks locally; however, little experimental evidence exists to support these co-benefits. NASEM rated the significance and reliability of co-benefits for these two approaches as medium.

6. **Scalability** is a measure of the carbon removal potential of the mCDR approach if deployed at a global scale. Scalability is based on each approach's carbon removal capacity, how that capacity changes if scaled, and its ability to scale given resource demands and operational and physical limitations.

Both ecosystem recovery and coastal blue carbon have a low-medium scalability, based on the NASEM report. The scalability of ecosystem recovery is impacted by the comparatively lower carbon removal potential at global scales, a finite but significant area and number of degraded ecosystems, and the ever-changing nature of these ecosystems. In contrast, while coastal blue carbon ecosystems are highly efficient at sequestering and storing carbon, the limited global area appropriate for the restoration and expansion of these ecosystems limits the scalability of this approach.

Nutrient fertilization has medium-high scalability as a result of its high carbon removal potential and the large areas of the global ocean that have suitable conditions to deploy this approach. However, in the United States, this approach's scalability will be in part dependent on any use restrictions applying to national waters that limit the available deployment area. There is a similar reasoning for ocean alkalinity enhancement, which NASEM also gives a medium-high scalability rating, and in addition, more research is needed on consequences of nutrient aggregation on carbon removal potential. Electrochemical approaches also have medium-high scalability potential but would require abundant machinery, more testing, and may be limited by water and energy requirements.

Seaweed cultivation has a medium rating for scalability since it has a high carbon removal potential but to be effective, it would require many millions of hectares of farms which may result in logistical or financial issues.

Artificial upwelling and downwelling has a medium rating for scalability as it has the potential to be combined with aquaculture. However, research and pilot trials are needed to test the approach’s durability in the open ocean and would necessitate the deployment of up to hundreds of millions of pumps to enhance carbon sequestration.

Sub-Seafloor Geologic Storage of CO_2

Sub-seafloor geologic storage of CO_2, sometimes also referred to as sub-seafloor geologic "sequestration," is the action of injecting captured CO_2 into geologic formations deep below the seabed. This approach is not itself CDR, but can be a critical component to ensure that carbon captured from terrestrial and marine CDR technologies such as direct air capture and electrochemical approaches is stored for timescales that are meaningful for climate change mitigation. CO_2 is captured and compressed into a supercritical fluid and injected into a geologic formation that is typically 1 km or more below the sediment surface where it can be stored for upwards of thousands of years.[38] These techniques may involve either new drilling or injection into already bored wells.

While sub-seabed geologic storage does not remove atmospheric CO_2, demonstration projects and modeling studies suggest this technique is likely to be highly effective in storing CO_2 once it has been captured by a different CDR technique. Further, it is estimated that the total global sub-surface (terrestrial and marine) geologic storage potential is about 10,000 GT, more than 1,000 GT of which is in the USA alone.[39] In U.S. offshore areas, injection of CO_2 into saline aquifers and depleted oil and gas reservoirs is being evaluated[40] with total estimated storage capacities on the order of tens of gigatons.[41] Given the high potential effectiveness and scalability of this storage technique, it is gaining attention as a piece of the U.S. climate mitigation strategy.[42]

Despite its potential utility, sub-seafloor geologic storage techniques could have impacts on coastal and marine resources and ecosystems. When considering just the storage of captured CO_2, leakage and spilling (during transport) are the most prominent risks associated with the storage of CO_2 in geologic formations. The risks of leakage and spillage are highest during transport and injection, and are higher for storage in sub-seafloor formations than terrestrial locations as the CO_2 must be transported, sometimes long distances, via ship or pipeline to the injection site.[43] Leakage could also occur after the CO_2 has been injected through failed or faulty

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[38] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259

[39] Nabuurs, G-J., R. Mrabet, A. Abu Hatab, M. Bustamante, H. Clark, P. Havlík, J. House, C. Mbow, K.N. Ninan, A. Popp, S. Roe, B. Sohngen, S. Towprayoon. (2022). *Agriculture, Forestry and Other Land Uses (AFOLU)*. In *IPCC, 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* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.009

[40] Bureau of Ocean Energy Management "Carbon Sequestration" https://www.boem.gov/about-boem/regulations-guidance/carbon-sequestration

[41] National Energy Technology Laboratory "Offshore Characterization field Projects" https://www.netl.doe.gov/carbon-management/carbon-storage/offshore

[42] Ocean Policy Committee. (2023). *Ocean Climate Action Plan*. https://www.whitehouse.gov/wp-content/uploads/2023/03/Ocean-Climate-Action-Plan_Final.pdf

[43] de Coninck, H., & Benson, S. M. (2014). Carbon dioxide capture and storage: issues and prospects. *Annual Review of Environment and Resources, 39*, 243-270. https://doi.org/10.1146/annurev-environ-032112-095222

seals, faults in geologic formations connecting to the storage reservoir, or wells in other areas of the reservoir that may have faulty caps (a particular concern when storage occurs in depleted oil and gas reservoirs). Migration out of the intended storage reservoir into other areas through unmapped sub-seafloor faults or permeable geologic formations is also possible, potentially leading to leakage into a reservoir that was not intended to store the CO_2. If a spill or leak were to occur, it could result in localized, but potentially significant, ocean acidification with impacts to organisms in the vicinity. Concerns have also been raised that injection could result in seismic activity, which has been detected at demonstration projects but only at very low levels far below the surface and detectable only by sensitive instruments.[44]

To ensure that geologic storage will be safe and effective in a given location, it is necessary to confirm that injection wells do not leak, measure the pressure in the reservoir, and track the plume of injected CO_2.[45] Monitoring the plume often requires seismic imaging[46] which, depending on method, could result in ocean noise. Further, ongoing monitoring at and near the reservoir site may be necessary to ensure that leakage and migration do not occur throughout the lifetime of storage.

In addition to direct potential impacts, sub-seafloor geologic storage will likely face social acceptance hurdles. It is also possible that CO_2 injection could be considered as discharge, pollution, or disturbance to the seabed under certain legal standards (including NMSA), even when such activities would occur well below the seafloor (often > 1km) rather than in the water column. The Bureau of Ocean Energy Management (BOEM) is currently developing regulations associated with carbon sequestration in the sub-seabed on the Outer Continental Shelf as directed by the Infrastructure Investment and Jobs Act. EPA and/or states authorize geologic sequestration of CO_2 onshore and offshore in state ocean waters. Regardless of legal standing, CO_2 injection may be seen as "dumping" by some communities and both transport and injection infrastructure may cause potential conflict with other ocean uses. Additionally, the capture and transport of CO_2 on land can directly impact communities. There may also be other land-based impacts associated with the CDR technique employed to capture the CO_2 being stored, potentially resulting in opposition to the storage by affected communities and stakeholders.

In spite of the environmental concerns, several demonstration projects, two of which took place offshore, have successfully stored injected CO_2[47] and overall leakage rates of this technique are estimated at less than 0.001 percent per year. [48]

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[44] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259

[45] Ibid.

[46] Ibid.

[47] Ibid.

[48] Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., ... & Haszeldine, R. S. (2018). Estimating geological CO2 storage security to deliver on climate mitigation. *Nature communications, 9*(1), 2201. https://doi.org/10.1038/s41467-018-04423-1

Based on the information above, and similar to mCDR techniques described elsewhere in this report, sanctuary managers and staff could apply the following framework when assessing proposals to implement sub-seafloor geologic storage of CO_2 in sanctuaries:

1. *Sub-seafloor Geologic Storage*
    a. Potential to store large volumes of CO_2 in sub-seafloor reservoirs beneath sanctuaries.
    b. Potential for localized ecological impacts if a leak occurs.
    c. Requires ongoing monitoring which may involve seismic imaging.
    d. May disturb the seafloor if a new injection site is needed.
    e. Will require various permits or authorizations.
    f. Questions to consider:
        i. What is the risk of leakage in the sanctuary?
        ii. Will a new injection site need to be drilled or will old or abandoned wells be repurposed for injections?
        iii. Will pipelines or other infrastructure need to be installed in the sanctuary to transport CO_2 to the injection site?
        iv. Is there a risk that seismic monitoring will disturb marine life?
        v. At what scale will this approach need to be tested to achieve quantifiable results?
        vi. Is the CO_2 being stored transported overland? Are there onshore impacts the sanctuary should be aware of?

Conclusions

mCDR methods are gaining momentum as a tool to combat climate change. Since mCDR is a nascent field, there is insufficient knowledge on the comprehensive impacts of these methods on the marine environment. The existing scientific research on mCDR impacts and trade-offs with other climate response approaches indicates varying levels of environmental risk. Research, both in laboratory and field settings and multiple scales, is necessary to better understand the potential of the approaches and anticipate adverse impacts on the marine environment and other ocean uses. However, the known and unknown environmental effects will discern which methods may be appropriate to test or deploy in national marine sanctuary waters. Sanctuary managers require essential background information and guidance on this topic to ensure optimal decisions are made regarding mCDR deployment in their sanctuary.

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