Informational Item
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Item 7

Information Item:
Marine Carbon Dioxide Removal (mCDR) Considerations for California

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Location: Statewide

Strategic Plan Goals and Objectives: Goal 1: Safeguard Coastal and Marine Ecosystems and Communities in the Face of Climate Change, Objective 1.3: Improve Understanding of Climate Impacts on California's Coast and Ocean

Executive Summary:

Carbon Dioxide Removal (CDR) refers to technologies, approaches and practices that draws down carbon dioxide from the atmosphere and store it long-term on land, underground, or in the ocean. While greenhouse gas (GHG) emission reductions remain the primary mechanism to mitigate climate change, CDR has been identified as a critical strategy to reach the state's carbon neutrality goals. Marine CDR (mCDR) uses ocean processes to increase the amount of atmospheric carbon dioxide taken up by the ocean and stored either in the ocean or a geologic reservoir. These approaches include a range of techniques from ocean alkalinity enhancement (adding alkaline substances to seawater to enhance the ocean's natural carbon sink) to artificial upwelling (pumping up nutrient rich water to stimulate phytoplankton growth and carbon dioxide drawdown). Each of these approaches is at varying levels of technological maturity, has varying potential carbon benefits, and a wide range of potential environmental impacts that are dependent on the project site.

In this informational item, technological approaches to mCDR will be discussed. Blue carbon (i.e. restoration of natural habitats for carbon storage benefits), sometimes broadly included in the definition of mCDR, is not included here. Although mCDR has been at the center of recent local, national, and international interest and investment, it is still considered an emerging area of research and development with many unknowns. OPC is tracking mCDR research and experiments in California in alignment with the Council's mandate under the California Ocean Protection Act

(Pub. Res. Code section 35500 et seq.) to protect coastal and ocean ecosystems and ensure that the best available science informs state decisions. OPC remains committed to working closely with relevant state and external stakeholders to track and assess individual mCDR technologies and potential environmental impacts specific to California.

Background

Climate change is one of the most pressing threats to our coast and ocean. While GHG emission reductions remain the primary mechanism to mitigate climate change, additional strategies such as CDR are needed to reach net zero global emissions. The Intergovernmental Panel on Climate Change (IPCC) assessed a range of climate scenarios with varying levels of climate change mitigation needed to limit global warming to 1.5°C or 2°C increase from pre-industrial levels to the year 2100.[1] For all scenarios assessed by the IPCC, CDR was found to be necessary to support stabilizing global temperatures and mitigating impacts of climate change. The amount of CDR that will ultimately be needed to achieve this level of limited global warming is uncertain, but all pathways that limit global warming to 1.5°C in the IPCC report project the use of CDR on the order of 100–1,000 Gigatons of carbon dioxide ($GtCO_2$) over the 21st century.

In recognition of the science and need to drastically reduce GHGs and achieve carbon neutrality no later than mid-century to stabilize the climate, the California Legislature passed Assembly Bill 1279 (AB 1279) (Muratsuchi, Chapter 337, Statutes of 2022), paired with Senate Bill 905 (SB 905) (Caballero, Chapter 359, Statutes of 2022). SB 905 requires the California Air Resources Board (CARB) to create the Carbon Capture, Removal, Utilization, and Storage (CCUS) Program[2] to evaluate, demonstrate, and regulate CCUS and carbon dioxide removal (CDR) projects and technologies; AB 1279 establishes the policy of the state to achieve carbon neutrality as soon as possible, but no later than 2045 and to ensure that statewide anthropogenic GHG emissions are reduced at least 85 percent below 1990 levels by 2045. The bill also requires CARB to ensure that Scoping Plan updates identify and recommend measures to achieve carbon neutrality, and to identify and implement policies and strategies that enable CO_2 removal solutions and carbon capture, utilization, and storage (CCUS) technologies. In 2022, CARB approved the [2022 Climate

1 IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

2 https://ww2.arb.ca.gov/our-work/programs/carbon-sequestration-carbon-capture-removal-utilization-and-storage

Change Scoping Plan Update which lays out the path for California to achieve carbon neutrality by 2045 and includes a carbon dioxide removal target of 20 million metric tons of carbon dioxide ($MMTCO_2$) by 2030 and 100 $MMTCO_2$ by 2045.

Previous focus by the international community to advance CDR has largely been on terrestrial approaches, such as direct air carbon capture and storage (DACCS), afforestation, and bioenergy with carbon capture and storage (BECCS).[3] These technologies differ in terms of removal process, timescale of carbon storage and benefits or adverse side effects, which need to be appropriately managed through CDR governance and policies. For instance, with DACCS and BECCS, the carbon dioxide extracted is stored in geological formations deep underground, thereby providing long time scales of carbon storage.

In addition to land-based CDR techniques, carbon removal in the ocean (i.e. mCDR) has long been identified as a potential climate solution. These techniques include, but are not limited to:

1. **Altering seawater chemistry** to increase its alkalinity and enable additional absorption of carbon dioxide (Ocean Alkalinity Enhancement or OAE)
2. Using **electrochemical approaches** to remove dissolved carbon dioxide from seawater and sequestering it elsewhere (deep sea or geologic formations)
3. **Adding nutrients** such as iron to encourage phytoplankton growth (Ocean Iron Fertilization or OIF)
4. **Growing kelp** and **sinking** it to the deep ocean (macroalgal cultivation and deep ocean sequestration).

Technologies that advance **artificial upwelling** and **downwelling** are not included in this item since these do not currently have data on enhanced carbon sequestration even at pilot scales.[4] Upwelling, like nutrient fertilization, induces phytoplankton blooms by pumping nutrient-rich water to the surface, while downwelling increases the rate at which carbon is transported away from the surface ocean. There is limited science and data available (including modeling data) to know whether even persistent and effective deployment of millions of functional pumps across the global ocean would result in permanent CO_2 removals.[2] Further, these approaches are not

3 https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf
4 A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2022) https://nap.nationalacademies.org/read/26278/chapter/1

likely appropriate for California's offshore environment, given the natural upwelling and nutrient-rich waters that already occur off the California coast.

It is also important to note that blue carbon restoration (restoring wetlands, eelgrass and other coastal habitats) is not a focus of this informational item. Blue carbon as a CDR strategy has an extensive body of research and is considered through the lens of coastal habitat restoration. Blue carbon habitats in California are incorporated in the State's Natural and Working Lands Climate Smart Strategy; additionally, the California Natural Resources Agency, in consultation with CARB and an expert advisory committee legislated by Assembly Bill 1757 (Garcia, 2022), have already set targets for conserving and restoring these ecosystems. Therefore, these habitats will not be discussed further in this item.

History of mCDR

The 1960s-1990s marked the beginning of mCDR research, when scientific developments were made in global climate change and the role of the ocean in absorbing carbon dioxide was being better understood. This began with an initial purely scientific interest in ocean iron fertilization, followed by a call for caution.[5] In the 2000s to early 2010s there was a focus on experimentation on ocean iron fertilization and other approaches. However, lack of positive results related to commercial experiments resulted in a lull in mCDR activities, until renewed concerns over climate change rekindled the current era of interest around mCDR. This was not triggered by a technological breakthrough or reduction of scientific uncertainty, but rather a larger push for carbon removal in general and rise in commercial interests.

In the past decade, interest in mCDR has further accelerated; in 2021, the National Academies of Science, Engineering, and Medicine released A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration report, laying out the state of science and highlighting gaps.[4] This report was followed by the National Oceanic and Atmospheric Administration's (NOAA) Strategy for NOAA Carbon Dioxide Removal Research in 2023 that presented the benefits and risks of different land and ocean-based CDR techniques, followed by a $24.3M investment on advancing mCDR research. Additionally, a $45 million funding opportunity was announced by the Department of Energy to support validation of mCDR techniques. In November 2024, the White

5 Socio-historical analysis of mCDR and its three phases of history: *The rise, fall and rebirth of ocean carbon sequestration as a climate 'solution', de Pryck and Boettcher, Global Environmental Change, Volume 85, 2024*

House Office of Science and Technology Policy released a federal strategy outlining the policy direction for managing and governing mCDR, with a goal of determining if emerging mCDR approaches are viable climate solutions. These efforts, in combination with an influx of private funding, have renewed research activities on mCDR.

Comparison of mCDR approaches

The table below shows a comparison across the four mCDR approaches that are highlighted in the Background section of this Staff recommendation.[6] As mentioned previously, blue carbon restoration and artificial upwelling/downwelling are not included here. This table distills the potential scale of carbon dioxide removal, expected costs, risks, co-benefits, and geographical suitability for these four approaches.

6 Lebling, K., E. Northrop, C. McCormick, and E Bridgwater. 2022. Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. Report. Washington, DC: World Resources Institute. (Adapted)

Comparison of mCDR Approaches

Approach	How it works	Carbon removal potential (Empirical or modeled)	Cost of deployment	Geographic suitability and scalability	Potential co-benefits	Potential risks (not an exhaustive list) in California
Macroalgal (seaweed) cultivation	Carbon in cultivated seaweed can be sunk for sequestration in deep ocean water or seafloor sediment.	Estimated to be between 0.1 and 1 $GtCO_2$/year	\$65B/$GtCO_2$ to more than \$3,000B/ $GtCO_2$	Suitability depends on nutrient availability at cultivation sites. Limited scalability in California waters given scaling area needed and competing ocean uses.	Potential co-benefits include reduced acidification in surface waters locally and uptake of excess nutrients.	Nutrient depletion and diversion from other habitats; competition for light; changes in oxygen, CO_2, pH levels; introduction of non-native species; competition for space; durability of infrastructure.
Ocean Iron Fertilization (Increasing phytoplankton growth)	Addition of iron, to iron-depleted areas to promote phytoplankton growth; some fraction of this moves to the deep sea for storage where it is sequestered.	Ranging from 0.1-1 $GtCO_2$/yr. Scientific evidence is lacking to demonstrate the transfer of organic matter to deep ocean and uptake of atmospheric carbon.	Estimated to be \$8B-\$80B/$GtCO_2$	Only locations where iron is a limiting nutrient, with largest opportunity internationally in the Southern Ocean. Likely not suitable for scaling in nutrient rich waters such as in California.	Potential increased fish-stocks from increased phytoplankton growth, in suitable environments.	Ecological impacts like reduced oxygen, nutrient depletion and reduced light, changes to populations of grazer and predator marine organisms. Upstream lifecycle considerations of iron acquisition including mining and transportation to OIF location. Additionally in CA, there is a significant risk of increasing frequency and intensity of Harmful Algal Blooms (HABs).

Ocean alkalinity enhancement (altering seawater chemistry)	Addition of alkaline materials that react with dissolved CO_2, which then drives the uptake of atmospheric CO_2 until a new equilibrium between the ocean and atmosphere is reached.	Uncertain; estimates vary widely from 0.1 $GtCO_2$/yr up to 1.0 $GtCO_2$/yr	Estimated to be \$100B-\$150B/$GtCO_2$, not including the additional monitoring costs that would be required.	No consensus exists yet, but possible criteria for selecting a location include season, upwelling velocity, and the possibility of providing co-benefits.	Potential co-benefit of locally reduced acidification.	Changes to biogeochemistry and food systems, changes to the species composition and growing locations of phytoplankton, introduction of trace minerals; expanded mining; risk of driving secondary precipitation of calcium carbonate minerals which might, in turn, cause the net release of CO_2 into the atmosphere or at least reduce atmospheric CO_2 uptake potential of ocean alkalinity enhancement.
Electrochemical techniques (altering seawater chemistry)	Using electricity to remove CO_2 from seawater or producing alkalinity for a variant of alkalinity enhancement.	Uncertain; estimates vary from 0.1 $GtCO_2$/yr to 1.0 $GtCO_2$/yr	Expected to be high as electrochemical processes are capital intensive; estimated costs range from \$150B to \$2,500B/ $GtCO_2$ removed.	Criteria including ocean access, energy availability, synergies with existing infrastructure like desalination plants and/or infrastructure to transport and sequester CO_2.	Potential co-benefit of locally reduced acidification.	Risks are similar to those of alkalinity enhancement, with additional risk from manipulating and intake of large volumes of seawater (risk of mortality to marine life) and risks from effluent discharge. Further risks include mining material inputs and safely managing chemical byproducts like chlorine gas and hydrogen.

Notes (Table Above): Abbreviations: $GtCO_2$/yr =Gigatons per year= billion metric tons of carbon dioxide per year; tCO_2 = metric tons of carbon dioxide; CO_2 = carbon dioxide. B = Billion (cost of deployment). The IPCC special report on global warming estimates the need for removal on the order of 100–1000 gigatons ($GtCO_2$) of carbon dioxide removal by the end of the century, almost equivalent to the total U.S. emissions of carbon dioxide from 1990 to 2010.

Pilot Projects in California

MCDR pilot experiments and projects have been conducted in California from 2022, including but not limited to:

- Kelp cultivation and sinking in Santa Barbara Basin in offshore federal waters (one study concluded July 2023, two concluded June 2024). These are data collection experiments to inform potential future CDR efforts.
- OAE mCDR pilot in Port of Los Angeles, onshore and open system (100 ton/year pilot, ongoing)
- Electrolysis-based mCDR pilot project in Port of Los Angeles, onshore and open system (100 kg per day pilot, ended 2024)

There are significant information gaps that exist both globally and specific to California waters for each of the proposed technologies in terms of efficacy and environmental safety when scaled, impacts to the coastal environment, marine life, fisheries, tribal cultural resources, and coastal communities. Critically, procedural and knowledge gaps exist in the current regulatory regime for all mCDR activities. Permitting considerations for pilot and to-scale approaches will be technology-specific and involve multiple state agencies, depending on the location and potential impacts of the project. In addition, since mCDR has the potential to impact coastal communities both positively and negatively, the state should require engagement and coordination to evaluate and address these impacts and engage communities through the design and execution of future research related to mCDR.

Conclusion: Interagency Coordination is Essential

The interdisciplinary nature of mCDR research, identified gaps in science and the sequestration potential of specific approaches, potential significant impacts of specific approaches to California's coastal and marine environments and adjacent communities, and the need for comprehensive environmental impact assessment of these technologies make it imperative that multiple state and federal agencies coordinate to enable informed decision-making, and avoid regrettable impacts to California's coastal and ocean environments.

OPC initiated interagency collaboration on mCDR given the Council's mission to align state efforts and its mandate to protect the coast and ocean. OPC has convened, in partnership with the Ocean Science Trust (OST), initial engagement discussions with state agencies including CARB, State Lands Commission, California Department of Fish and Wildlife, California Coastal Commission, State Water Resources Control Board and Regional Water Quality Control Boards (Water Boards), San Francisco Bay Conservation and Development Commission (BCDC), and the State Coastal Conservancy. The goal of these discussions was to share the current state of the science and identify information needs specific to California. OPC, along with other state agencies, academics, and practitioners also participated in a workshop on exploring the potential role of safe, responsible, and effective mCDR in California, with a specific focus on identifying possible environmental effects and prioritizing research needs.

OPC has statutory authority under the California Ocean Protection Act to evaluate and advise state agencies on ocean carbon removal approaches; the Council's role and focus is to protect ocean and coastal ecosystems and the communities that rely on them. CARB is the lead agency to evaluate the efficacy, safety, and viability of carbon management technologies as mandated by SB 905, and OPC is committed to supporting these efforts as appropriate. OPC will continue to facilitate collaboration with state agencies and external partners to track ocean carbon removal technologies, share information regarding the state of the science and knowledge gaps, and consider the potential co-benefits and risks of this emerging technology. Additionally, the state should continue to engage closely with federal and external partners, including NOAA and practitioners, to ensure the execution of an efficient and transparent scientific decision-making framework for mCDR in California to inform pilot projects and before projects are brought to scale.