# Scoping the Development of a Comprehensive mCDR Assessment Framework for California Coastal Waters

## Workshop Summary

October 7-8, 2024
Southern California Coastal Water Research Project, Costa Mesa, CA

### Attendees

Sree Gopal, CA Ocean Protection Council
Joseph Street, California Coastal Commission
Gabby Kitch, NOAA OAP
Alicia Karspeck, [C]Worthy
Erika La Plante, Equatic/UC Davis
Jess Adkins, Calcarea
Jeanine Ash, Capture6
Morgan Raven, Carboniferous/UCSB
Sophie Chu, Captura
David Koweek, Ocean Visions
Mattias Cape, Environmental Defense Fund
Alex Harper, Cal Poly Humboldt
Alyssa Griffin, UC Davis
Christina Frieder, SCCWRP
Daniela Faggiana Dias, UCSD/SIO
David Siegel, UCSB
Debora Iglesias-Rodriguez, UCSB
James Gately, UCSB
Jessica Cross, PNNL
Martha Sutula, SCCWRP
Noah Gluschankoff, Stanford
Sarah Smith, MLML
Yui Takeshita, MBARI
**Christina Frieder, SCCWRP***
**Steve Weisberg, SCCWRP***
**Kristen Davis, Stanford***
**Alex Harper, CeNCOOS***
**Lauren Linsmayer, OST***
**Kevin Travis, OST***
**Jill Harris, OST***

***workshop organizer**

# About the Workshop

The goal of the workshop was to explore the potential role of safe, responsible, and effective marine carbon dioxide removal (mCDR) in California coastal waters, with a specific focus on identifying possible environmental effects and prioritizing research needs. The workshop convened experts from scientific institutions, industry, NGOs, and government and was informed by the science needs of state agencies to ensure any products would have a ready audience. Participants gathered in-person for two days to develop a summary of anticipated environmental effects across mCDR approaches and begin to identify the components of an assessment framework to evaluate those effects. The focus was in California, with the goal of taking into consideration opportunities for regional collaborations.

## Organizing Committee

This workshop was organized by the co-leads of the Ocean Carbon and Biogeochemistry program's California Current Regional mCDR Node, in close partnership with the California Ocean Science Trust and hosted by the Southern California Coastal Water Research Project.

## Background

mCDR approaches to reduce atmospheric carbon dioxide ($CO_2$) are under development as part of a response to maintain global average temperature rise over the remainder of the century to under 2˚C. In the last several years, private companies, governmental agencies, and philanthropic organizations have invested hundreds of millions of dollars in research and technology development that is essential for advancing our understanding of the efficacy and scalability potential of mCDR technologies. However, the impacts of these technologies on marine ecosystems remain uncertain, requiring a proactive approach to research and monitoring for any future widespread adoption of mCDR.

mCDR has the potential to affect marine ecosystems and ocean users in multiple ways. Some mCDR techniques may offer co-benefits, such as improving local water quality and alleviating local ocean acidification. However, there are also concerns about potential adverse effects and whether California is a viable location for scaled implementation. These include, for example, environmental impacts from introducing new materials into marine ecosystems, installation of necessary infrastructure for mCDR operations, and unintended consequences on marine life and nutrient cycles. Advancing research to address these concerns is critically important for federal, state, and local agencies to make informed regulatory and policy decisions.

Moreover, scientists have yet to agree on a comprehensive scientific assessment framework to quantify environmental effects or socio-economic consequences of mCDR deployments. This is further complicated by many possible mCDR approaches, each with a different set of potential challenges and modes for assessing effects. To help guide and standardize research needs and accelerate shared understanding, a comprehensive assessment framework for mCDR that is adaptable and implementable by a range of users is needed.

## Additional Workshop Products:

- Journal manuscript (expected 2025)
- Briefings for policy-makers and regulators on the state of mCDR science (ongoing)

## Agenda Overview

**Day 1**

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| 9:00 am | **Introductions and Workshop Goals**<br>● Steve Weisberg, SCCWRP |
| 9:15 am | **State and federal agency perspectives on mCDR**<br>● Jenn Eckerle, OPC<br>● Karen Mogus, SWRCB<br>● Kevin Travis, OST<br>● Gabby Kitch, NOAA OAP |
| 10 am | **The current state of mCDR, a rapidly evolving industry**<br>● David Koweek, Ocean Visions |
| | **Experience of mCDR companies in California**<br>● Sophie Chu, Captura<br>● Erika La Plante, Equatic<br>● Morgan Raven, Carboniferous<br>● Jess Adkins, Calcarea |
| 1:00 pm | **Including Environmental Effects within the Information Priority Needs of Communities**<br>● Jessica Cross, PNNL |
| 1:15 | **Breakout Session 1:** Identifying Environmental Effects of mCDR |
| 2:45 pm | **Reconvene and Group Report Outs** |
| 3:15 pm | **Measuring environmental effects of mCDR**<br>● Experimental Approaches: Debora Iglesias-Rodriguez, UCSB<br>● Observational Approaches: Kristen Davis, Stanford<br>● Modeling Approaches: Alicia Karspeck, [C]WORTHY |
| 4:00 pm | **Breakout Session 2:** Measuring and Quantifying Environmental Effects of mCDR |
| 5:15 pm | **End of Day 1** |

**Day 2**

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| 8:30 am | **Continue Breakout Session 2** |
| 9:30 am | **Reconvene and Group Report Outs and Discussion** |
| 10:00 am | **Breakout Session 3:** Prioritizing Research Needs on mCDR Environmental Effects |
| 11:00 am | **Reconvene and Group Report Outs** |
| 1 pm | **Environmental Impact Assessment Framework: Open Call for Proposals**<br>● Dave Koweek, Ocean Visions |
| 1:15 pm | **Breakout Session 4:** Integration and Workshop Recommendations |
| 2:30 pm | **Reconvene and Group Report Outs: Synthesis and Next Steps** |
| 4:30 pm | **Adjourn** |

# Workshop Summary

***Disclaimer:*** *The resulting summary is issued under the auspices of the California Ocean Science Trust and attempts to capture the key messages, recommendations, and perspectives raised during the two-day workshop. It is not a comprehensive review of the state of the science on mCDR. No attribution of specific messages should be assigned to individuals or organizations who participated in the dialogues. Not all perspectives could be captured in this summary.*

## Marine Carbon Dioxide Removal (mCDR)

### Consideration of mCDR in California

California has set a goal to reach carbon neutrality by 2045, in significant part by cutting greenhouse gas (GHG) emissions at least 85% from 1990 levels. Due to residual emissions from hard-to-abate industries (e.g., transportation) and legacy carbon (historical GHGs already emitted in the atmosphere), California has indicated the need to responsibly advance a portfolio of carbon dioxide removal (CDR) strategies to achieve net-zero and negative emissions. State agencies, such as the California Air Resources Board, are developing programs to evaluate, demonstrate, and regulate CDR projects, and in the years ahead, fit-for-purpose science will play a critical role in decision-making. Currently, most CDR activities in California are land-based, but marine CDR (mCDR) activities could also contribute to California's climate goals.

**With increasing climate-driven impacts on California's communities and livelihoods, workshop participants emphasized the urgent need to both rapidly reduce emissions and safely remove atmospheric $CO_2$, highlighting that the projected impacts of insufficient climate action should be balanced against any potential risks associated with an effective and responsibly-scaled mCDR pathway.**

### State and Federal Perspectives

Prior to this workshop, the California Ocean Protection Council and the California Ocean Science Trust convened initial discussions among state partners on mCDR to share agency updates, identify science questions, and ensure early coordination on this emerging climate mitigation strategy. These efforts produced an initial list of priority questions from state agencies that were shared at the workshop to guide discussions. These priority questions included:

- **What are the effects on marine systems and how to avoid, minimize, and mitigate environmental impacts?**
- **Is the $CO_2$ removal and storage permanent, how is this verified, and what is the life cycle analysis of these methods?**
- **Can mCDR be measured or modeled, what is the uncertainty in each, and how are the models developed and validated?**

Significant investments, actions, and collaborations on the federal level have supported research into mCDR in recent years. At the workshop, the National Oceanic and Atmospheric Administration (NOAA) outlined their role and current assets available to expand research and build understanding on the efficacy and safety of mCDR approaches. For example, NOAA and partners invested $24.3M in FY2023 by leveraging the National Oceanographic Partnership Program (NOPP) to support a research portfolio of multi-sector mCDR research awards and public-private partnerships. In 2024, NOAA and the Department of Energy signed a Memorandum of Agreement to enhance coordination, research, and technology development to advance mCDR. After the workshop, an mCDR Fast Track Action Committee (or FTAC) composed of subject matter experts from across the federal government released the National mCDR Research Strategy, which set objectives to advance research on the benefits, risks, and tradeoffs of mCDR to inform potential future deployment decisions in the years to come.

### Strengthening Science Capacity in California on mCDR

This workshop provided an opportunity to build community across sectors spanning mCDR research, development, and demonstration to strengthen science capacity at a regional level for future consideration of mCDR as a climate mitigation strategy. Through breakout group discussions, participants explored the state of science on environmental effects from mCDR pathways most relevant to California coastal waters to begin scoping the considerations and research needs for a comprehensive environmental assessment framework. Other important considerations for mCDR, such as project efficacy and feasibility to scale in California, were not prioritized in this workshop. Workshop discussions were framed by the questions, concerns, and roles of federal and state representatives engaged during and prior to this workshop, which provided an opportunity to produce recommendations to responsibly advance mCDR science in California.

## Enumerating and Measuring Environmental Effects of mCDR Approaches

A range of mCDR approaches were discussed during the workshop, all of which seek to enhance the ocean's natural ability to take up carbon dioxide and draw down atmospheric carbon dioxide. Numerous mCDR and carbon capture and storage (CCS) projects have branched out of academic and science institutions in recent years (see Box 1 for entities highlighted at workshop), including some operating small-scale field testing in California state waters. Participants agreed that California is conducive to advancing research into a variety of mCDR approaches, in part due to the existing coastal infrastructure and resources, leading scientific institutions, and long-term observing systems and datasets.

Because mCDR pathways differ in methodology and in how they interact with the environment, breakout groups at the workshop were separated by mCDR approach, and discussions varied between groups. The mCDR approaches (outlined below) were selected by workshop organizers and participants in consideration of the following: representative of abiotic-to-biotic approaches, recent advancements in technology, relevance to California coastal waters, and the diversity of expertise present at the workshop. The choice of approaches discussed does not indicate mCDR pathway prioritization generally or in California, as achieving climate-relevant scales of CDR will likely require a portfolio of effective and safe approaches.

**Box 1: mCDR/CCS entities highlighted at workshop to represent mCDR pathways**

Equatic

Captura

Carboniferous

Calcarea

Capture6

Breakout groups were tasked with reviewing an initial list of possible environmental effects for their assigned mCDR approach and identifying scientific capabilities and research needs to measure and/or model the environmental effects in California. While breakout groups were guided by pre-determined discussion prompts, each group approached the task in a manner that was reflective of their specific mCDR pathway, relevant mCDR project case studies, and the interest and expertise of group participants. To bound conversations on the current state and needs of the mCDR industry, breakout groups primarily discussed oceanic environmental effects in the context of 'pilot' projects or small-scale field testing (see Box 2 about the role and opportunity of mCDR pilot projects). At times, discussions considered commercially scaled operations and how environmental effects at scale may influence research priorities. Breakout groups noted but did not discuss externalities (e.g., power source, transportation, mining, infrastructure, pollution) associated with each mCDR method or transportation and storage of $CO_2$ for mCDR approaches for which $CO_2$ is a waste product (e.g., Direct Ocean Capture).

The following sections summarize possible environmental effects for each pathway discussed at the workshop, accompanied by what would be needed to measure or monitor those effects. It does not distinguish environmental effects by positive, negative, or neutral impact, as workshop participants ultimately felt that further examination with a more diverse representation of marine users is required to make such assessments. The discussion summaries are a non-exhaustive list of environmental effects for each pathway and reflect the direction each breakout group approached the discussion prompts.

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## Ocean Alkalinity Enhancement (OAE; Electrochemical or Substance-based)

OAE references abiotic pathways that increase the alkalinity of ocean waters to enhance the ocean's capacity to durably store carbon and enable more carbon dioxide to be absorbed from the atmosphere. The approach involves the introduction of alkaline minerals or solutions to ocean waters and/or the use of electrochemical techniques to equivalently modify water chemistry .[1] Participants discussed environmental effects applicable to both OAE methods (electrochemical and substance-based), emphasizing that further discussions should consider these separately.

<u>Discussion Summary of Potential Environmental Effects</u>:

- Impacts to fisheries and biodiversity: variability in reproduction, respiration, shell formation via pH changes and/or increased trace metals; disease and increased mortality via ecotoxicological risks; ocean noise impacts
- Habitat alterations: changes in sedimentation rates; turbidity and light attenuation
- Human considerations: seafood safety via bioaccumulation of trace metals; recreational water quality; increased infrastructure (coastal development, ocean use/industrialization)
- Moderate increases in pH could be a short-term co-benefit by ameliorating the negative effects of ocean acidification for vulnerable marine life (also applies to Direct Ocean Capture)
- For electrochemical OAE, the intake of seawater can lead to both impingement and entrainment of marine life and discharge could lead to various environmental effects (also applies to Direct Ocean Capture)

<u>Measuring Environmental Effects</u>:

*Approaches and considerations discussed:*

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[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.

- The source, method, and siting of alkalinity introduction determine the level of environmental risk (e.g., presence of trace metals; effects of seawater pumping and filtration at large volumes)
- When designing a pilot project, the mixing zone surrounding the alkalinity addition should be determined (via methods to estimate perturbation from ambient conditions) to establish both the most impacted area and a zone to prioritize measurements of any possible acute impacts
- The concept and definition of an initial mixing zone for effluent is well established in water quality guidelines and regulatory practices. Workshop participants suggested applying those existing concepts to guide where to prioritize limited resources for OAE measurements
- To ensure OAE is safe at scale, public and private sectors could co-design 'sentinel' networks with observing and modeling tools to maximize pilot projects (and resources) and coordinate long-term, publicly available data on priority environmental effects
- Baseline surveys to understand biodiversity and environmental conditions before field testing (applies to all mCDR pathways)

*Measurements and methods needed to advance research on potential environmental effects:*
- Changes in pH, and carbonate chemistry parameters (carbon dioxide, bicarbonate ions, carbonate ions, the saturation state of carbonate)
- Changes to reproductive success of fish and protected species through sampling and laboratory studies
- Phytoplankton abundance, diversity, and toxicity through sampling and laboratory studies
- Changes in turbidity
- Changes to benthic community structure from benthic sampling and measuring downward biogeochemical fluxes

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### Direct Ocean Capture (also referred to as Direct Ocean Removal)

This mCDR technique removes dissolved carbon dioxide from seawater by various engineered processes and returns carbon dioxide-depleted water to the surface of the ocean, where $CO_2$ is removed from the atmosphere via air-sea gas exchange. The carbon dioxide removed from seawater is durably stored through carbon sequestration in geologic formations or existing infrastructure.[1]

<u>Discussion Summary of Potential Environmental Effects</u>:

- Environmental effects could result from the intake and discharge of treated seawater (also applies to electrochemical OAE)
    - The intake of seawater can lead to both impingement and entrainment of marine life
    - Among potential other changes, the discharged seawater is depleted in dissolved inorganic carbon (DIC) and possible environmental effects may include:
        - Changes in water column particle concentrations, turbidity, and optical properties if local increases in pH lead to precipitation of carbonates
        - Direct effects on lower trophic ecosystems, such as reduced photosynthesis of some phytoplankton groups under DIC limitation resulting in shifts in phytoplankton communities
        - Indirect effects on lower trophic ecosystems, such as changes in bacterial populations and nitrifiers due to shifts in inorganic nitrogen constituents from changes in pH

- ■ Moderate increases in pH could be a co-benefit by ameliorating the negative effects of ocean acidification for vulnerable marine life (also applies to OAE)
- Depending on the scale and duration of the project, lower trophic level changes could potentially result in cascading effects on upper trophic levels

Measuring Environmental Effects:

*Approaches and considerations discussed:*
- There is precedent in California for how to consider environmental effects of facilities with seawater intake and discharge pipes, such as water treatment plants, desalination plants, and aquaculture facilities
- Baseline surveys to understand biodiversity and environmental conditions before field testing (applies to all mCDR pathways)

*Measurements and methods needed to advance research on potential environmental effects:*
- Numerical ocean models can be used as a tool to conduct site assessments to inform monitoring needs before piloting activities
- For pilot projects, autonomous sensor platforms can be used to measure the effluent. Priority measurements should include pH and turbidity accompanied by easy-to-measure seawater properties like salinity and temperature
- Laboratory and mesocosm exposure studies can be used to test for direct effects on marine life

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### Macroalgae Cultivation and Biomass Sinking

This technique involves capturing $CO_2$ via photosynthesis, either by growing seaweed in the surface ocean or by harvesting terrestrial plants, and transporting that biomass to the deep ocean.[1] Due to time constraints, participants prioritized discussions on the environmental effects of cultivating seaweed with less time spent discussing the subsequent sinking of biomass. Participants noted that the potential for net CDR occurs after sinking the cultivated biomass in a location where it can be durably stored, and the benthic impacts associated with sinking must be seriously considered (see Roberts et al., 2024 for more).

***Note:*** *Biomass-based mCDR is sometimes defined as including 'blue carbon' habitat restoration strategies,, i.e. restoring wetlands, eelgrass, and other coastal habitats that can sequester carbon and/or release alkalinity. This group excluded habitat restoration from discussions for a myriad of reasons including but not limited to: an existing body of evidence on the low carbon sequestration potential and high scalability challenges of using blue carbon for CDR, and the low environmental risks of restoration.*

Discussion Summary of Environmental Effects (primarily cultivation):
- Shifts in community structure and biodiversity: fisheries; phytoplankton and microbes, via nutrient changes; recruitment (larval fish, invertebrates); harmful algal blooms; benthic species
- Seaweed cultivation structures and biomass bundles as attractive nuisances: pollution, including microplastics; marine debris; mammals and birds, including entanglement and sublethal effects; invasive species; as well as hazards to navigation or other potential use conflicts
- Surface ocean habitat alteration: hypoxia, OA; sediment structure; shading (in the water column and on the seafloor); changes in O2 and $CO_2$; carbon inputs to the seafloor; changes to surface currents and mixing energy

Measuring Environmental Effects

*Approaches and considerations discussed:*

- Baseline surveys to understand biodiversity and environmental conditions before the biomass was sunk (applies to all mCDR pathways)
- Pre-deployment experiments to determine expected decomposition rate and determine appropriate timing and spacing for field sampling
- Before-After-Control-Impact (BACI) experimental design to understand the trajectory and recovery time
    - Particularly important for repeated mCDR activities at the same place
    - Periodic monitoring to keep track of changes in biodiversity and environmental conditions, including spatial extent of impact
- Use biogeochemical and food web models to understand scaled impacts (magnitude, extent)

*Measurements and methods needed to advance research on potential environmental effects:*

- Changes in water column chemistry: start with surface ocean $pCO_2$, pH and oxygen, but aim to include dissolved organic and inorganic carbon
- Changes in benthic community composition and function, including biodiversity, biomass, habitat use (methods: cameras, grab samples, eDNA, videos of biomass sinking and landing)
- Downstream effects or movement of water from location of cultivation (methods: ADCP arrays + hydrodynamic models)

**Box 2: The role of mCDR "pilot" projects for responsible, collaborative R&D**

What are pilot projects and who is conducting them?

In California and globally, most mCDR projects are operating in a research and development (R&D) phase and piloting under existing permitting regimes. For example, two California-based companies, Captura and Equatic, are operating small-scale (<100 T $CO_2$ removal/year) pilot projects under a Vessel General Permit at AltaSea at the Port of Los Angeles. These mCDR developers are working to improve technological readiness and conduct research on the efficacy and safety of their systems.

**Emphasized by workshop participants, small-scale 'pilot' studies are critical to advancing responsible R&D of promising mCDR approaches and, importantly, the environmental impacts are likely minimal at these 'pilot' scales. However, participants indicated that 'pilot' lacks a common definition and needs to be better articulated by both science and regulatory communities.** In California, all mCDR projects must ensure compliance with existing environmental regulations, such as the requirements of the California Environmental Quality Act (CEQA) and California Coastal Act. Development of mCDR-specific guidance for environmental compliance could benefit both project proponents and government regulatory agencies, ensuring that mCDR research and development is pursued in a responsible manner.

Optimizing mCDR pilot projects through public-private partnerships

To ensure compliance and minimize impacts at scale, mCDR pilot projects provide an opportunity for public-private partnerships between developers, academic researchers, and government. Currently, mCDR companies are developing and testing their measuring, reporting and verification (MRV) protocols at pilot sites to prove efficacy and ensure safety, with minimal guidance from regulators or managers. Designating research hubs to conduct pilot projects for responsible R&D, such as the activities at AltaSea at the Port of Los Angeles, could be an opportunity for regulators and managers to engage with mCDR developers. Involvement of academic researchers in these hubs could lead to trusted standards of MRV of mCDR that can be sustainable for the industry, protective of California's environment, and mitigate climate change.

## Recommendations to advance mCDR science in California

California is one of a handful of U.S. states going 'beyond net-zero,' with holistic climate plans and strategies aimed to reduce emissions, scale up removal efforts, integrate environmental justice, and protect and restore natural environments. The passage of SB905 in 2022 created a dedicated program for safely deploying CDR technologies, potentially including ocean-based methods.

The California Current System, with its intense upwelling and nutrient-rich coastal waters, is a well-studied oceanographic system, providing a unique opportunity to responsibly explore the safety, efficacy, and tradeoffs of mCDR pathways. **Due to the urgency of the climate crisis, workshop participants emphasized the need to consider not only the potential local costs and risks from a responsibly-scaled mCDR approach, but also the climate mitigation benefits accrued at a state (and global) level to avoid the worst of climate impacts on future generations.** With this in mind, participants produced the following recommendations to better understand the safety, efficacy, and tradeoffs associated with mCDR in California:

- **Incentivize cross-sectoral research partnerships or "innovation hubs" (e.g., AltaSea at the Port of LA, Port of San Diego, Humboldt Bay) that leverage the state's intellectual capital to support technological development and responsible field testing for mCDR R&D and data standards.**

- **Encourage public-private partnerships, including state and federal entities, to establish creative funding mechanisms that de-risk and streamline research investments to fill critical knowledge gaps on the safety and efficiency of mCDR in state waters. This could include incorporating existing federal research assets and programs (e.g., NOAA's decision support and ocean planning infrastructure).**

- **Coordinate the application of existing monitoring systems and long-term observational datasets for mCDR R&D, including data management standards and transparency (e.g., creating an mCDR network modeled after the National Science Foundation's Long-term Ecological Research (LTER) Networks).**

- **Research and evaluate the additional co-benefits to the state from a responsibly-scaled mCDR industry, including workforce development and 'green' job creation, economic growth, and environmental justice opportunities.**

- **Build strong community relationships early in the project design phase to inform risk mitigation research and risk management. Consider how to inform communities about mCDR and how to include community concerns into decision-making processes, with a focus on frontline EJ communities and Tribes.**