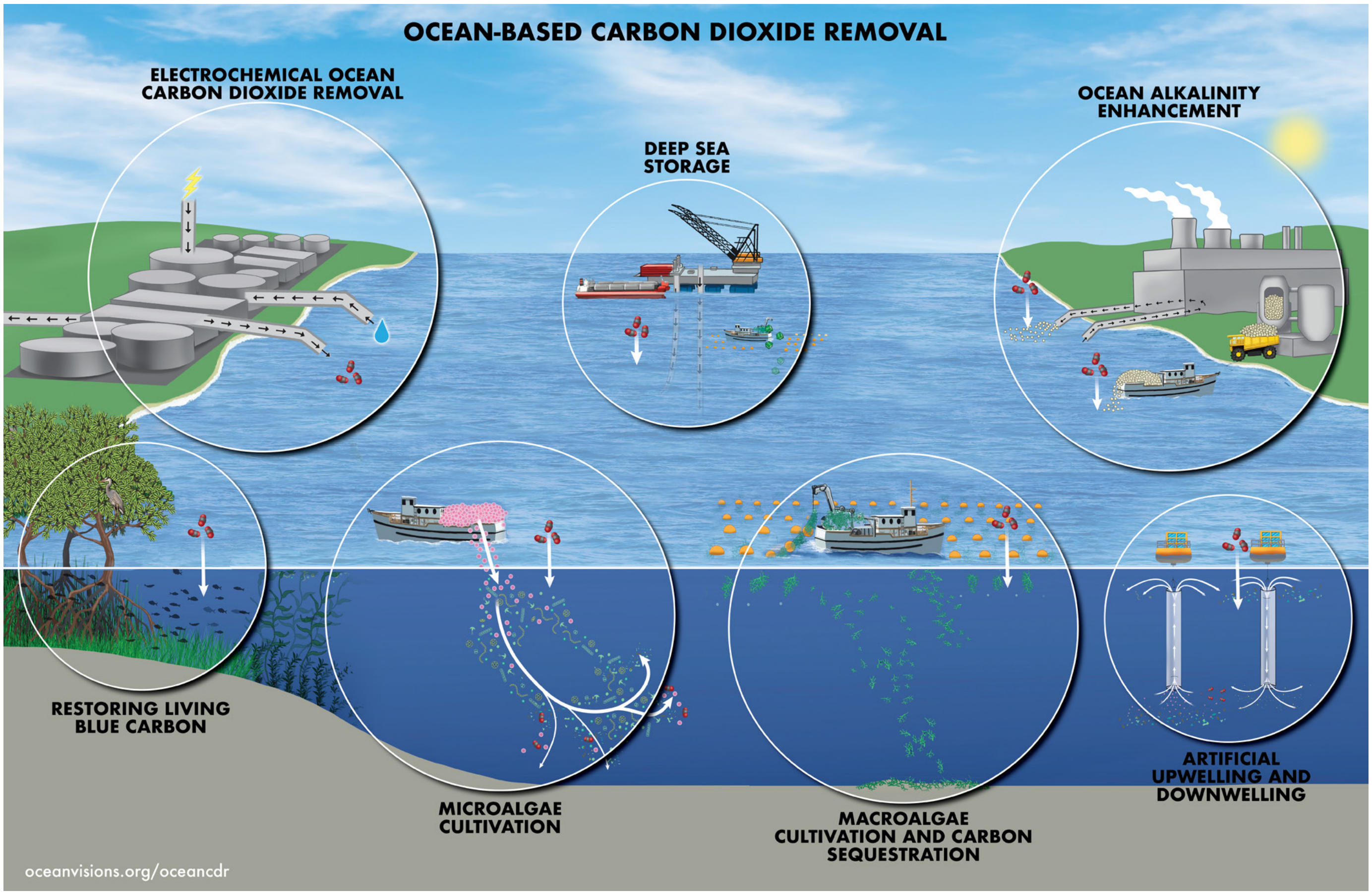
OCEAN VISIONS

A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030



Introduction[1]

The last three years have seen a tremendous growth in the level of awareness, interest, and engagement with carbon dioxide removal (CDR) broadly and especially with marine carbon dioxide removal (mCDR, sometimes also called ocean-based carbon dioxide removal). This interest stems from the increasing recognition that CDR is now an essential part of the path to achieving a safe climate. Hundreds of billions to a trillion tons of CDR by 2100 is necessary to achieve the goals set out in the Paris agreement, and far more CDR will be needed for future generations to have any chance to reverse temperature increases that are already pushing many human and natural populations and systems to the limits of their viability.

Marine-based pathways for CDR offer some significant potential advantages, given the scale of the ocean and the existing biological and chemical processes it already contains that cycle carbon over long periods of time. However, while there has been a rapid growth in understanding of some of these pathways, and in small-scale testing and development, it is necessary to significantly ramp up the scale and pace of research, development, and demonstration (RD&D) to answer fundamental questions about both the additionality and durability of carbon sequestered using mCDR approaches, and their environmental and social impacts.

1 This document was written in October 2023. It is intended to be a living document that evolves as more members of a global community contribute to the activities and initiatives described here. Think this document is missing something? We'd love to hear from you at info@oceanvisions.org.

Fundamental questions that must be answered using a series of controlled field trials include:

- Does the mCDR activity generate a *measurable* reduction in seawater carbon dioxide concentration?
- Can *net additional* ocean uptake of atmospheric carbon dioxide be tracked in response to the mCDR activity using a combination of sensors, platforms, and models?
- What are the impacts to marine ecosystems of mCDR activities and are they acceptable when compared with the impacts of the no-action alternative or of other feasible mitigation measures?
- What are the range of impacts to human populations and are they acceptable when compared with the impacts of the no-action alternative or of other feasible mitigation measures?

Questions that are equally fundamental to the scalability of mCDR approaches, but which do not require field trials to be answered include:

- What are the necessary materials for scaling an mCDR approach and can they be sourced, transported, and delivered to key regions with acceptable cost and environmental impact (from a lifecycle perspective)?
- What is the required suite of technical, economic, social, and political enabling conditions required to permit growth of a given mCDR technology to the scale of gigatons of annual CDR and what is needed to establish them?

These questions are not meant to be sequential, nor will all questions be relevant to all mCDR pathways. This set of questions can help to establish the needed checkpoints (also commonly called "stage gates") that any mCDR pathway will need to pass through to justify transition from RD&D to scaled deployment as an ocean-climate solution.

This document lays out a high-level overview of needed actions to answer the fundamental questions that remain about different mCDR pathways by 2030, along with estimated cost ranges. It is assumed that various elements of the needed work outlined here would be distributed widely across the globe with many different governments and institutions involved. The value of having a generally agreed upon, high-level "road map" is to help coordinate and integrate diverse actors and actions, ensure advance of all the necessary pieces, and hopefully create synergies among and coordination between various efforts.

This high-level road map centers around three interconnected pillars of needed investment and work:

1. Doing the **science and engineering** at the appropriate scales to answer important outstanding questions about mCDR technologies.
2. Development of **enabling environments** that allow for accelerated research and development.
3. **Improvement and optimization of mCDR technologies** to increase their potential to achieve climate-relevant scale and impact.

Scaling and accelerating mCDR RD&D is unlikely to happen without significant amounts of public investment, along with regulatory changes that facilitate this large-scale research and development. Governance structures that allow for all relevant interests to participate in the RD&D process and interpretation of the results also are needed.

All of these elements are important and can be worked on by different entities in different settings, synchronously and asynchronously. Overviews of the key components in each of these areas of need are described in greater detail below, and further levels of detail, including more specific estimates of costs and time, are a next step.

Moving forward and completing the core elements outlined here will yield rigorous and actionable information regarding the efficacy and impacts of the different mCDR approaches. This then allows society to make well-informed decisions about any deployments of mCDR as part of the portfolio of approaches needed to provide the gigaton-scale CDR that is now required.

1. Doing the Science and Engineering

A. Conducting Controlled Field Trials

It is not possible to answer the most critical outstanding questions about the efficacy and impacts of mCDR pathways without testing them in the ocean at multiple scales. Modeling and lab tests are important, but insufficient alone to answer the most fundamental questions about efficacy and impacts. Controlled field trials are needed across every pathway and with multiple replicates in different conditions and appropriate monitoring and verification.

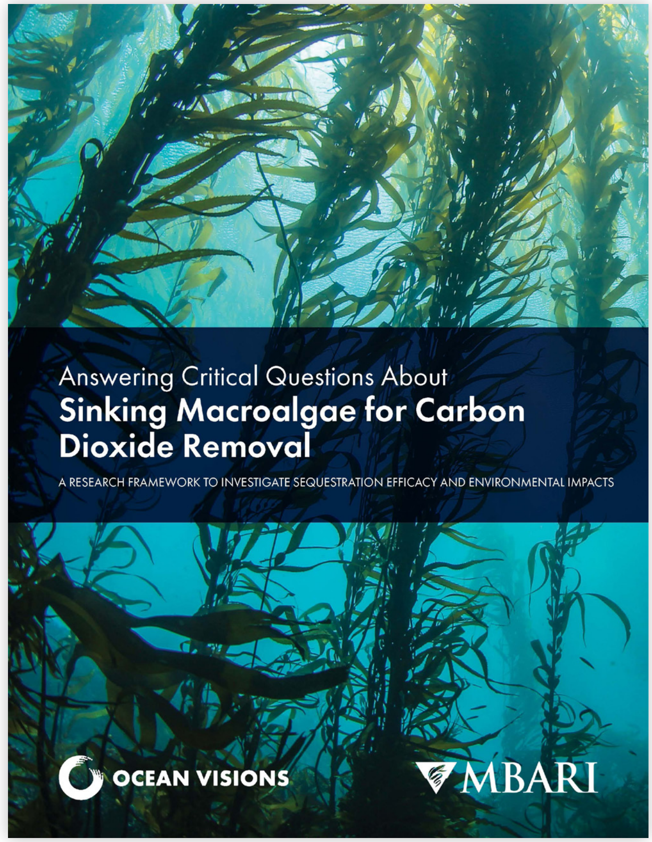
The scale of the investment needed to support controlled field trials across all mCDR pathways is going to be in the billions of dollars. The United States National Academy of Science Engineering and Medicine report on mCDR called for a budget of approximately $2 billion for RD&D for the US alone. The estimate of $2 billion dollars may actually be an underestimate for the resources required to support sufficient field trials based on the initial assessment that Ocean Visions led with the Monterey Bay Aquarium Research Institute to outline the trials needed to understand the efficacy and effects of sinking seaweed—just one of the mCDR pathways.

It is also important to consider who does the field trials. Field trials must involve the breadth of organizations involved in oceanographic research and technology development, including national laboratories, oceanographic institutions, academic institutions, and private science corporations. While much of the current testing is being done by private companies, which is helping advance science and understanding, these companies do not have the required resources to do trials at the scale necessary and with the number of replications needed to provide actionable data for public policy. A full set of field trials must involve partnerships that cross traditional stakeholder boundaries.

I. Designing Controlled Field Trials: A Critical First Step

The first step towards controlled trials is to do rigorous designs that can then be executed. Funding and experts are needed to develop field trial research designs that can answer fundamental remaining questions about each major mCDR technology's efficacy and impact. These designs need to be built by multidisciplinary teams with expertise in a range of fields related to the technologies themselves, key science questions, and tools to employ. The process of creating these designs must allow for other interested parties to review and provide comments.

Effective research designs must determine the minimum sufficient number of trials to produce robust findings; ensure evaluation of all key hypotheses and performance questions; and ensure that risks are mitigated to the maximum extent possible. Designs must specify the ranges of environmental conditions (e.g., size, location, etc.) in which trials need to be conducted, as well as well-grounded cost estimates. Determining the number of replicates and confidence in the results will require engaging with decision makers during field trial design exercises to understand what they would need to see to have confidence to take action based on the results of such field trials.



Examples of this type of rigorous detailed design work exist. Ocean Visions and the Monterey Bay Aquarium Research Institute published a *Framework to Guide Research on Seaweed Cultivation and Sinking for Carbon Dioxide Removal* in 2022. This work was guided by an international advisory body of scientists and practitioners. The report details a comprehensive set of fundamental science questions that must be answered to generate actionable information on the efficacy and impacts of cultivating and sinking seaweed for carbon sequestration, design of field trials intended to produce answers to this information, a budget tool to support resource allocation for field experiments, and a table of existing oceanographic assets, infrastructure, and pilot projects.

There are other efforts to advance design and execution of field trials moving forward now. Exploring Ocean Iron Solutions (ExOIS) is working to design the next set of field trials for ocean iron fertilization. The Carbon to Sea initiative is funding a handful of controlled field trials for mineral-based ocean alkalinity enhancements, which provides an excellent foundation for a more comprehensive design at the larger scale that is needed.

On a related note, the National Oceanographic Partnership Program brought together several US government agencies alongside private philanthropy to announce $24 million in awards for efforts to advance mCDR research, including through conducting field trials. Again, these individual efforts can provide needed information towards comprehensive field trial designs.

II. Securing Needed Funding for Field Trials

Well-conceived research designs will be critical in seeking to secure the funding needed to conduct the trials from public, philanthropic, and even private sources. The amounts required are likely substantial. Design efforts to date suggest that well-designed individual field trials may span a range in costs from several million US dollars for smaller-scale nearshore experiments, all the way to one hundred million dollars for large-scale trials (hundreds of square kilometers in size). These cost estimates include the need to include rigorous monitoring across large sections of the ocean, including the deep sea, in which trials are conducted or where effects may be seen.

Given the necessity of multiple field trials, in suitable locations throughout the world, for every mCDR pathway, the estimated total cost of a global set of field trials is likely to range between one and five billion US dollars, expended over five-to-seven years. Securing these sorts of funds will require a concerted effort to significantly increase the political and social priority around CDR and mCDR. That work is described more fully in the following section.

III. Establishing Test Beds to Accelerate Field Trials

Pre-permitted test sites, or test beds, are a critical tool in doing big science fast. These are locations that have already undergone extensive consideration and evaluation, and which offer a streamlined permitting process for responsible research of mCDR technologies, especially field tests. This concept draws on an idea already in use by the US Navy and Department of Energy. The Carbon to Sea Initiative is trying to utilize this concept to support accelerated research and development of ocean alkalinity enhancement. More resources and effort are needed to develop a global network of these sites.

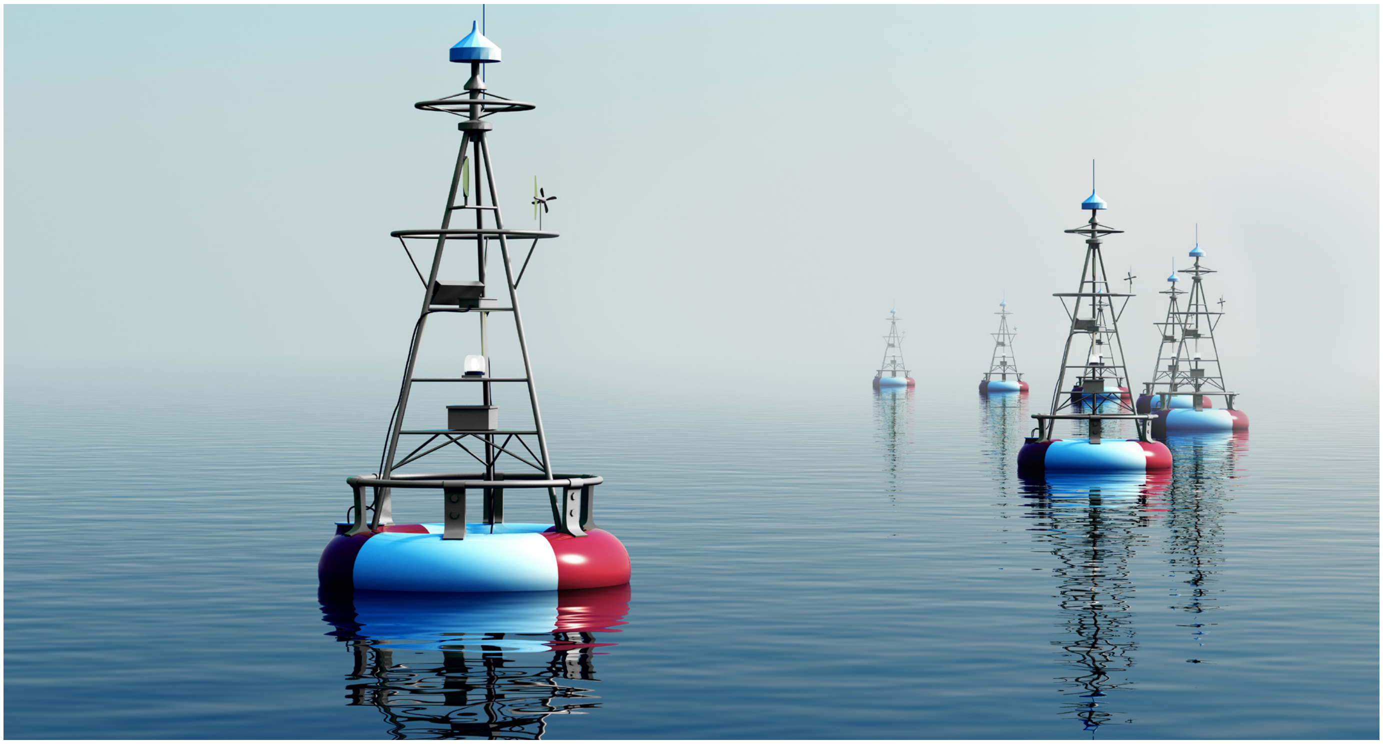
B. Developing Robust Monitoring, Reporting, and Verification (MRV) Technology

Among the biggest technical challenges associated with mCDR technologies are being able to monitor, report, and verify (MRV) the amount of additional carbon durably removed over time, and to measure the environmental effects of the mCDR technology. Both capabilities are essential to any future deployment at scale and, before that, to evaluate the efficacy and effects of technologies being tested in controlled field trials.

Being able to achieve these outcomes requires both development and integration of new generations of sensors, platforms, communications systems, and models. Scientists, engineers, experts in verification and accountability, and others need to work together to build MRV systems capable and robust enough to operate at the scales and in the conditions needed to deliver the information.

Current field trials and observational research by universities and oceanographic institutions, as well as pilot testing by mCDR start-up companies, provides an emerging opportunity for building, testing, and refining MRV systems. Development and testing of these new monitoring and verification tools must start now at smaller settings so that they are ready in time to accompany the deployment of larger controlled field trials. Subsequently, controlled field trials will be an excellent proving ground and field laboratory for the ongoing development and calibration of MRV systems, including the integration of observations and models.

Additional support to build MRV testing into all these efforts would be a valuable investment. There are efforts underway here: The SEA-CO2 program of the US Department of Energy's



Advanced Research Projects Agency—Energy office (ARPA-E) is a $45 million effort to advance sensors and models needed for mCDR MRV. The Carbon to Sea Initiative is also funding teams in the range of one million dollars to develop technologies for mCDR MRV. Woods Hole Oceanographic Institution is developing a large-scale, full-depth, high-resolution network of advanced technologies to track carbon as it moves between the atmosphere and the ocean called the Ocean Vital Signs Network. The Ocean Frontier Institute at Dalhousie University is actively developing the North Atlantic Carbon Observatory that will connect and enhance ocean observation and modelling efforts to allow for more accurate measurements of the ocean's ability to absorb and store carbon.

Together, these initial efforts suggest that full support for the suite of MRV development needs—sensors, platforms, communication systems, and models—is likely to run into the hundreds of millions of US dollars.

C. Supporting Laboratory and Mesocosm Science

Alongside the controlled field trials, there are other high-priority research questions that remain to be addressed through laboratory and/or mesocosm approaches. The controlled conditions of laboratory and mesocosm studies are important for research and development needs with high intercomparison needs across a range of inputs and expected responses. These include mineral dissolution studies, targeted environmental impact studies, and microbial responses to mCDR inputs. These studies need to be funded, with an eye towards accelerating production and dissemination (publishing) of knowledge.

Some of this work has begun through grants to individual investigators, as well as larger consortia efforts (e.g., OceanNETs and SeaO2-CDR in Europe). These grants have ranged in size from ~$100,000 US dollars to nearly 10 million euros. Time-bound research and development programs, such as the US National Science Foundation's Ocean Acidification Program ($67 million dollars in research support between 2010 and 2016), may provide a good example for expected costs of a coordinated research program.

D. Identifying and Executing Critical Social Science Research Priorities

Volumes of social science research have identified the social and political complexities of working in the ocean. These complexities vary across geographies, cultures, and industries. The very limited early research on mCDR suggests that mCDR pathways may face substantial social resistance and friction as communities struggle with risk assessments and perceptions of mCDR RD&D against those of a deteriorating background state of the ocean. In addition, there are crucial economic, political, ethical, and socio-cultural assessments that need to be completed to enhance the robustness of an international mCDR RD&D program.

A systematic and participatory social science research program is needed to create actionable knowledge about how a globally diverse and representative set of key stakeholders, communities, and audiences perceive and translate to their culturally specific context the benefits and risks of mCDR RD&D, with a particular focus on perspectives from Indigenous Peoples, Least Developed Countries (LDCs), and Small Island Developing States (SIDS). This step is critical to develop an evidence base from which to develop strategies to enhance public understanding and negotiate support for RD&D.

It is critical that social science research activities, whenever possible, are coordinated with field planning and testing so that results are grounded as much as possible in real experience with these technologies.

Estimating global costs for social science research priorities is difficult. But as a starting point for understanding costs, one can look to the 2022 US National Academies of Science, Engineering, and Medicine report on mCDR RD&D, which estimates that cross-cutting social science research priorities in the US would cost approximately $30 million. Social science research would likely need regional hubs to coordinate activities and results in different cultural contexts, as well as a centralized hub to share best practices, learning, and results. Ocean Visions estimates that total social science research costs could scale to approximately $100 million, which represents somewhere between 2% and 10% of the expected costs of controlled field trials.

2. Developing Enabling Policy for Advancing mCDR RD&D

While scientists and engineers advance work on design and execution of field trials and development of MRV technology, simultaneous efforts are needed to increase political and societal support for expanded action on CDR, including mCDR RD&D. Increased political and societal support is necessary because the world's governments have been slow to accept the Intergovernmental Panel on Climate Change's assessment that CDR must be part of climate mitigation.

It is essential to broaden and deepen knowledge and support for the imperative of CDR as a climate action tool, and the potential of mCDR within CDR, across all the key sectors, actors, and geographies engaged in shaping climate and ocean policy. This includes world climate and ocean opinion leaders, key national governments, major philanthropies, international financial institutions, and other audiences that can play a role in changing the narrative and trajectory on CDR action and mCDR RD&D.

Without elevating the priority level of CDR, and the potential of mCDR, on national agendas, and increasing social and political acceptance of these paths, it will be very difficult to achieve the scale of testing needed given the price tag for field trials, and the fact that they must happen in the open ocean—both currently significant political hurdles.

A. Increasing Social and Political Salience and Acceptance for CDR and mCDR RD&D

There is a need to develop and implement multi-dimensional, multi-year communications campaigns at various levels and in various places to reach critical actors in this space, with the objective to greatly expand support for accelerated research, development, and demonstration of mCDR pathways. Ocean Visions has laid substantial groundwork for such a campaign via its work to understand mindsets related to mCDR RD&D, but implementation of the recommendations from that work at a relevant scale requires a significant ramp-up in level of effort.

Expanded communications efforts should:

- Identify the target audiences that are essential to supporting an enabling environment for mCDR RD&D and the most effective ways to reach them.
- Develop appropriate informational content across a variety of media formats to reach these key audiences.
- Identify and engage diverse, credible spokespeople (scientists, business leaders, other opinion leaders) for particular target audiences and in relevant geographies (such as those where field testing may occur) to help carry the messages. Spokespeople should be diverse across a number of dimensions and balanced between the Global North and the Global South.
- Conduct continuing opinion and mindset research on current perceptions and understanding of CDR and mCDR (see social science research agenda above).

Effective global communications strategies will move CDR and mCDR RD&D more firmly in the mainstream of climate action, making sure the topics are on the table at all the major meetings and dialogues where climate action and ocean action are discussed and where decisions about actions are being made. These communication efforts will also help continue to build and expand a broad-based coalition of interests from diverse geographies, sectors, and points of view in support of advancing the field.

Some potential milestones of success would include:

- The United Nations Framework Convention on Climate Change (UNFCCC): 1) articulating clearly that carbon removal is a critical tool in the climate arsenal and that every national government should develop a carbon removal plan and, 2) further emphasizing the importance of quickly moving forward RD&D on novel approaches to CDR such as mCDR pathways.
- Key nations developing policy statements that indicate a clear national interest in CDR and why mCDR is part of the potential solution set, such as the US has recently done. These high-level policy statements then help to facilitate the allocation of effort and resources around CDR RD&D.
- Small Island Developing States on the front lines of ocean-climate change becoming key players in helping drive the needed political shifts by demanding a wider array of climate action from larger well-resourced nations as well as by driving research through running of controlled field trials.
- Increased support for mCDR RD&D among ocean and climate non-governmental organizations.

B. Creating Enabling Regulatory Frameworks

In addition to increasing social and political acceptance, advancing mCDR RD&D will require changes to existing governance structures to permit legitimate testing and development while ensuring that public interests are protected. Current impediments to progress include:

- An absence of global frameworks established specifically for the governance of mCDR, and the fact that existing global frameworks for ocean management are inadequate to the task.
- No specific country-level laws designed to govern mCDR RD&D (with the notable recent exception of Australia)
- Complex regulatory mazes to navigate in most jurisdictions to gain permits for field trials and RD&D, which can add years of time to get approval for RD&D.

So far, the experience of efforts to get permits for field research in various countries is that existing laws and regulations are poorly suited to regulating mCDR research. This creates confusion and complexity and adds significant time costs for individuals trying to obtain authorization to trial mCDR technologies.

Without bespoke enabling regulatory frameworks, the needed RD&D will continue to be regulated under a patchwork of laws developed for other activities. It is critical that key national governments and subnational governments create new regulatory frameworks, laws, and policies specifically designed to facilitate mCDR research and ensure that it occurs in a safe and responsible way. This requires action at various levels:

- Internationally, the key bodies that influence the course of action in the global ocean (International Maritime Organization, U.N Convention on the Law of the Sea, London Convention/London Protocol, UNESCO IOC, IUCN, and others).

- Internationally, the key bodies that influence the course of action on climate action: UNFCCC, Green Climate Fund, development banks, etc.
- At the national level for each country that intends to accelerate mCDR RD&D
- At relevant subnational levels where there is growing interest (e.g., key states in the US)

In the US, the Sabin Center for Climate Change Law at Columbia University developed a model federal law that outlines a proposal to redesign and streamline the process for permitting responsible research in US federal waters. If enacted, it would go a long way towards facilitating needed field trials. Similar efforts could be initiated at the state level. Other national governments will need similar analysis of existing regulatory regimes to best craft new frameworks that work in their legal system. Additionally, the London Convention and the London Protocol must be reviewed and updated to facilitate responsible scientific testing of all mCDR approaches.

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Developing Model Federal Legislation to Advance Safe and Responsible Ocean Carbon Dioxide Removal Research in the United States

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Understanding that new regulation takes time, intermediate steps towards regulatory clarity would include guidance on how existing laws apply to mCDR RD&D, as well as the establishment of learning committees within the various governing bodies to keep abreast of the rapid advances in mCDR science and technology.

C. Following a Code of Conduct for Responsible Research

Governance should also include adoption of and adherence to a code of conduct for responsible mCDR research. There are a number of efforts underway to develop such codes, notably the American Geophysical Union and the Aspen Institute. In addition, mCDR communities of practice have adopted their own codes of conduct, as have new mCDR startups.

While there is a high degree of complementarity between this set of efforts, there is an urgent need to unite the community around a single code of conduct that can be easily adhered to by researchers and entrepreneurs and easily tracked by local communities, government regulators, and other interested parties. This is critical to build collective transparency and accountability in mCDR RD&D.

3. Optimizing mCDR Technologies for Potential Scaling

The third pillar of this road map focuses on the need to continue developing mCDR technologies as well as looking ahead to how they can possibly scale. Most mCDR and associated MRV technologies lie at the beginning of the technology development curve. Supporting efforts to continue to develop the technologies and bring more people and disciplines into the arena should be prioritized now, along with critical analyses about the pathways to scale.

A. Applying New Technologies to Improve mCDR

While there has been a rapid growth in understanding of mCDR pathways, accompanied by small-scale testing and development, many of the potential technologies are still at early stages of technology maturity and, as such, may be ripe for application of additional knowledge from the new frontiers of other disciplines, such as artificial intelligence, synthetic biology, green chemistry, nanotechnology, robotics, and others. Careful and intelligent application of cutting-edge tools from adjacent fields of science and technology may accelerate research and development of mCDR technologies by making them more effective, minimizing their environmental impacts, and/or enabling greater scaling.

Opportunities can be created to bring new disciplines into the mCDR RD&D arena in various ways. One would be prizes and competitions specifically targeting the application of new technology to mCDR approaches. Another would be to organize "big think" design studio convenings that engage diverse experts from different technology backgrounds with current inventors and innovators in different mCDR spaces (see example here) to explore how the tech that they know well might be integrated into mCDR.

B. Performing Scaling Analyses

While work on the foundational science and enabling policy moves forward, society must consider what it will take to bring any of these technologies to a meaningful scale to have detectable benefits for affecting climate change. Issues identified in such analyses might be significant enough to rule out certain approaches, or at least inform their continued development. Knowing as soon as possible the critical needs and obstacles to scaling can help to inform the continued development and testing of the mCDR technology.

Rigorous scaling analyses are needed for each of the leading mCDR technologies to assess their needs at scale, including energy, logistics, materials, workforce, etc. These analyses also need to assess the physical area required for achieving gigaton scales, and contrast that against the ideal conditions for the deployment of the technology. Analyses need to clearly identify conflicts and competing uses in the needed spaces. Scaling analyses should also be forward-looking and account for systematic differences in various technologies to assess which ones have a better chance of scaling and decreasing in cost over time.

Strategic partnerships between existing industries and actors, and mCDR companies, may provide expedited pathways to scale mCDR technologies and should be considered as part of scaling opportunities.

I. Spatial Suitability Analyses

Spatial analyses are an important part of scalability analyses because they identify the most (and least) promising locations for mCDR technologies. Such analyses can help to identify high-priority candidate sites where technical, economic, social, infrastructure, and political conditions—in addition to fundamental oceanographic and scientific conditions—are favorable for deployment of a particular mCDR technology. Identifying these sites now will help ensure that the next set of field trials are informed by real-world opportunities and constraints for potential deployment.

Ocean Visions is currently undertaking this work for ocean nutrient fertilization pathways and may be able to easily expand to other mCDR pathways based on learnings from this initial effort. NOAA and BOEM have already developed the OceanReports Tool that can also support many marine spatial planning analyses for mCDR

These spatial suitability analyses then provide a very strong foundation from which countries and regions could develop national action plans for any potential future deployments in their waters.

II. Co-Products Analyses

Costs of operating mCDR technologies are one of the biggest known impediments to scale. One way to potentially bring down costs of mCDR, and increase their value to society, is via development of co-products from the mCDR technologies. Many mCDR technologies have the potential to produce valuable co-products, such as high-value bioproducts from seaweeds or critical metals during alkalinity generation.

There is an immediate need to rigorously assess the potential co-products associated with different mCDR pathways, map existing market size for these co-products, and develop models and analyses that allow society to understand how bringing co-products to market may affect system cost and scale. These reports could identify pain points and cost drivers that could then help focus new initiatives and efforts by companies to overcome these obstacles.

C. Developing Innovation Hubs

The challenges facing continuing development and testing of mCDR pathways and their potential eventual scaling are enormous, and the ultimate solutions will likely be developed and distributed across many geographies and involve many sectors and disciplines. Active facilitation of continuing innovation in this space is critical.

One way that governments and non-governmental actors help advance the needed attention and innovation at regional levels is via development of innovation "hubs". Hubs can become critical focal points of mCDR RD&D by creating new partnerships, spaces, and opportunities for research, education, and outreach. Such hubs can take the form of public-private partnerships and can serve to convene all interested parties to work on development and testing of ocean-climate innovations.

Ocean Visions has been working with a distributed set of global partners to incubate regional innovation hubs designed and led by local actors. This model has significant potential for expanding opportunities and resources available for mCDR RD&D. Support for this idea is gaining traction in the US with the introduction of The Ocean Regional Opportunity and Innovation Act (Ocean ROI Act), which would mandate the creation of blue ocean clusters.