Answering Critical Questions About

Phytoplankton Carbon Solutions

A PRIORITIZED RESEARCH FRAMEWORK TO INVESTIGATE CARBON DIOXIDE REMOVAL POTENTIAL AND INFORM DECISION-MAKING

OCEAN VISIONS

Front Matter

Project Team

This report is a collaboration between Ocean Visions and CEA Consulting. This report is a product of Ocean Visions, and outcomes and findings herein are at the discretion of Ocean Visions.

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Experts Consulted

The project team is grateful for the experts whose time, perspectives, and constructive feedback informed the recommendations presented in this report. This includes insights gained from participants in a workshop held during the 2025 Ocean Visions Biennial Summit in Vancouver, Canada, and dozens of experts interviewed by the project team (see Appendix A).

Public Review

The draft report is now open for a 30-day public review. The project team will review all feedback to inform the revision of the report and recommendations therein.

Acknowledgements

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Table of Contents

Abbreviations

ASMASYS	ASsessment framework for proposed methods of MArine CDR and interim knowledge SYnthesiS
BCP	Biological carbon pump
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
ExOIS	Exploring Ocean Iron Solutions
$GtCO_2e$	Gigatonne of carbon dioxide equivalent
HNLC	High nutrient, low chlorophyll
LNLC	Low nutrient, low chlorophyll
mCDR	Marine carbon dioxide removal
MRV	Measurement, reporting, and verification
NASEM	National Academy of Sciences, Engineering, and Medicine
OIF	Ocean iron fertilization
ONF	Ocean nutrient fertilization
ORCA	Ocean Resilience and Climate Alliance
PCS	Phytoplankton carbon solutions
POC	Particulate organic carbon
RD&D	Research, development, and demonstration
TEA	Technoeconomic assessment


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Executive Summary

Based on current scientific knowledge, the most scalable marine carbon dioxide removal (mCDR) pathways include ocean alkalinity enhancement and ocean nutrient fertilization (ONF). This report was commissioned to provide a current state of the landscape of knowledge on all open ocean phytoplankton-based carbon removal approaches, including ONF, identify remaining critical uncertainties and gaps, and suggest a strategy for closing these knowledge gaps to facilitate future decision-making. This investigation is focused on evaluating the potential to achieve gigatonne scale carbon dioxide removal (CDR) benefits and recommendations are prioritized in that context. Carbon dioxide removal from the atmosphere is now recognized as an imperative alongside elimination of carbon emissions (decarbonization) to stabilize, and ultimately reverse, climate change. Ocean-based pathways for carbon dioxide removal hold promise due to the size of the ocean, its natural carbon sequestering capacity, and the potential for highly durable pathways of ocean carbon sequestration.

These findings and recommendations were developed through a combination of literature and white paper reviews, workshops, and numerous expert consultations. The work has been guided by an international Advisory Board. The report is being offered now for public comment. Through this public comment period, the project team will further test areas designated as initial priorities and core questions that remain before issuing its final report.

The term "Phytoplankton Carbon Solutions," or PCS, represents a range of interventions that aim to leverage the natural biological carbon pump (BCP), whereby phytoplankton blooms stimulate the uptake of atmospheric carbon dioxide (CO_2) and contribute to export of organic carbon into the deep ocean. PCS categorization is intentionally inclusive, most notably, of ocean iron fertilization (OIF), and also other pathways by which open-ocean phytoplankton could play a role in CDR.

CDR is a critical element of the toolkit needed to get to the international goal of net zero CO_2 emissions by 2050. CDR is a complement to critical work to dramatically reduce CO_2 emissions. Increasing research investments into promising CDR solutions now, including PCS, is critical to prepare for effective evidence-based societal decisions on CDR options in the future.

PCS, and specifically OIF, hold promise due to the theoretical scalability and potential cost effectiveness. OIF is currently the most advanced PCS pathway given the knowledge base from over a dozen field trials and decades of research. Other PCS approaches may hold promise, but have had few or no field trials to determine scalability or efficacy. For all PCS approaches known to date, many unanswered questions remain and knowledge gaps must be filled before decision makers can make informed decisions about future application.

The report is organized into four sections. The first section explains the basis for continued interest in and potential future utility of PCS. The second section discusses the current landscape of research and other activities. The third section identifies priority research questions, proposes relevant research methods, and outlines a stage-gating framework to guide research, development, and demonstration (RD&D) and funding decisions. Finally, the report recommends priority research topics and approaches.

The recommendations in this report address both overarching needs applicable to a wide range of PCS approaches as well as pathway-specific priorities. The PCS activities proposed in this report further must proceed in accordance with recognized standards of ethical research and in full partnership where applicable with local communities and other interested parties.

The report's recommendations are grouped into eight priority areas for future work. Each area has supporting findings and recommendations. These are summarized below and addressed in much greater detail in section four.

Reduce Uncertainty on Net Carbon Dioxide Removal

- **Finding:** There is still significant uncertainty related to CDR additionality, scalability, and durability of PCS pathways. Reducing CDR uncertainty levels is critical. The field still lacks consensus on best approaches to address critical uncertainties.
- **Recommendation:** Perform a sensitivity analysis to identify the most critical sources of uncertainty around additionality and durability for priority PCS pathways, and design targeted research initiatives to reduce those key uncertainties.

During this comment period, the authors are particularly soliciting comments to advance consensus on proposed priority research topics and approaches.

Improve Utility of Biogeochemical Models for PCS Evaluation

- **Finding:** Models are essential to address critical uncertainties about local and far-reaching environmental effects. They are also necessary to determine CDR additionality. Current models lack consensus on PCS potential and lack representation of biological processes and inputs to sufficiently assess PCS.
- **Recommendation:** Initiate a model improvement program to perform model intercomparisons, prioritize targeted additions of field observations, particularly biological inputs, and assess and integrate potential innovations.

Improve Understanding of the Ocean's Natural BCP

- **Finding:** PCS assessments must be grounded in an accurate understanding of the current and future state of the ocean's natural BCP and other key indicators of ocean health. A better understanding of how ocean warming and acidification result in changes in the BCP and ocean health is needed as a baseline against which to measure the impact of PCS interventions.
- **Recommendation:** Work with a range of ongoing ocean health investigations to increase knowledge and characterization of BCP baseline conditions and trends to build a better foundation as a basis to measure the effect of PCS interventions against 'business as usual' ocean health conditions.

Improve Understanding of Southern Ocean OIF Potential

- **Finding:** Numerous models and studies identify Southern Ocean OIF as the most scalable PCS opportunity based on available macronutrients and idealized model scenarios. These idealized scenarios are not necessarily reflective of real-world implementation strategies or CDR potential.
- **Recommendation:** Develop realistic scaling scenarios to better characterize and quantify CDR potential, operational requirements, and consequences of Southern Ocean OIF. Use these findings to further assess PCS scalability, costs, and impacts to inform future PCS decisions.

Improve Understanding of Subtropical Nitrogen Fixation–Based OIF

- **Finding:** OIF in subtropical, low nutrient, low chlorophyll (LNLC) waters has received limited research attention compared to OIF in high nutrient, low chlorophyll (HNLC) waters, such as the Southern Ocean. This approach merits further research due to its potential to stimulate nitrogen fixation, thereby boosting naturally available nitrogen and stimulating growth of non-nitrogen fixing phytoplankton.
- **Recommendation:** Support assessments of viability and effects of subtropical nitrogen fixation-based OIF. Assess other macronutrient and site-based limitations to inform future CDR potential.

Support Preparatory Activities of the Northeast Pacific OIF Field Trial

- **Finding:** There is consensus amongst experts that large scale field trials are an essential step in testing PCS viability. Field trials are also the most expensive step and will require significant regulatory and public processes. The international consortium Exploring Ocean Iron Solutions (ExOIS) is planning a comprehensive, large-scale OIF field trial in the northeast Pacific Ocean. The availability of the resources needed for this trial is currently uncertain, and there is not complete expert consensus on timing and location of the next generation of field trials.
- **Recommendation:** Continue to support preparatory activities of the ExOIS field trial within the context the other recommendations in this report, to ensure that PCS field trials are executed at the right moment in time, in the most effective place, with public support, and with adequate funds to maximize the scientific knowledge gains. Preparatory activities include social engagement and navigating the trial's regulatory framework.

During this comment period, the authors are particularly seeking further expert opinion on the role, timing, location, knowledge transferability and cost efficiency of large-scale field trials and other field-based research to inform final program recommendations.

Catalyze Innovations that Enhance "Export" of Phytoplankton Carbon

- **Finding:** Innovations that enhance the export of carbon captured by phytoplankton into the deep ocean could improve the overall additionality and measurability of PCS pathways and therefore their techno-economic viability. These innovations, which could be essential components of future PCS effectiveness, have received little attention to date.
- **Recommendation:** Fund early-stage development, innovation, and testing of mechanisms to enhance export to prioritize approaches for further development.

Continue to Monitor and Assess Emerging PCS Pathways

- **Finding:** Several PCS ideas, such as artificial upwelling and light-based stimulation are at low levels of technology readiness and lack strong foundational knowledge needed to estimate CDR viability or identify and characterize their socio-economic and environmental risks.
- **Recommendation:** Monitor emerging PCS ideas and pathways and use the stage-gate framework to evaluate their progress for future funding consideration.

These recommendations will be most effective if they leverage and build on existing scientific programs and advance in close coordination with one another.

Enable Coastal Communities and Fisheries Engagement

- **Finding:** Coastal communities and fisheries industry leaders are often at the front lines of both risk and potential benefit from mCDR. Successful initiatives must specifically build fisheries and coastal community capacity to engage early and effectively on PCS proposals and enable co-design of PCS research.
- **Recommendation:** Build international fisheries and coastal community capacity to engage early and effectively on PCS proposals and enable co-design of PCS research and development. Enhance fishing industry and community understanding of risks and co-benefits of PCS and develop mechanisms and best practices for the community to engage with and co-design place-based research.

Ensure Consideration of PCS Impacts Against Alternative Actions

- **Finding:** Environmental and socio-economic risks and co-benefits of any CDR, including PCS, must be understood in the context of alternative scenarios, such as "no-action" alternatives and other CDR pathways.
- **Recommendation:** Collaborate actively with other CDR and mCDR entities to increase efficiencies across shared investigations and maximize future comparative capacities.

In addition to the eight major findings and recommendations, the report provides additional recommendations on future implementation of the proposed activities, covering socio-economic considerations, decision-making, and operational management.

Co-design Research to Inform Decision Making

- **Finding:** Co-designing PCS research with non-academic partners is essential to generate knowledge relevant for decision-making. Identifying relevant partners and affected communities for PCS can be challenging due the remote nature and potential far reaching impact areas of high seas interventions. Transparent engagement, clear framing of potential impacts and probabilities of impacts, and upfront consideration of containability, reversibility, and risk–benefit trade-offs are critical aspects of co-designed research.
- **Recommendation:** Ensure collaboration with local and potentially affected communities and other interested actors in PCS investigations, particularly that involve field components. Adopt existing research codes of conducts and best practices for mCDR RD&D to effectively engage relevant non-academic and local communities early to improve the utility of research outcomes to inform decisions. Develop and be guided by an international advisory board with diverse geographic and scientific perspectives.

The findings and recommendations contained in this report will directly inform early-stage philanthropic funding to set the course for generating societally relevant scientific evidence to inform PCS risk-benefit evaluations and deployment decisions. Currently, insufficient funding is available to answer all priority questions identified in this report. An important aim of this program is to develop a stronger base of scientific evidence to engage more societal, academic, and government support for PCS RD&D.

At any stage of the R&D program, findings may lead to conclusions that certain, or all PCS approaches, should not continue to be pursued due to diminishing scalability, durability, measurability, or desirability. Conclusions against future viability of PCS or any of its pathways will be guided by the stage gate framework and remain an option throughout the proposed R&D program.

Introduction

Why Phytoplankton?

Climate change is dramatically affecting the ocean, its productivity, and its biodiversity. Humanity depends on a healthy ocean ecosystem for our survival, and some of the world's most vulnerable coastal communities are at greatest risk from the effects of climate change.

While immediate and drastic emissions reduction is the most important and necessary approach to mitigate climate change, the Intergovernmental Panel on Climate Change reports that 100 to 1000 gigatonnes of carbon dioxide must be removed from the atmosphere to limit warming below 2 degrees Celsius by the end of the century.[i]

The knowledge and technological capacity required to achieve this scale of carbon dioxide removal (CDR) does not currently exist; achieving them will require thoughtful expansion of responsible research, development, and demonstration (RD&D).

Ocean-based CDR approaches, commonly referred to as marine CDR (mCDR), have the potential to remove carbon at the gigatonne scale and could play a substantial role in meeting global CDR needs.[2] Based on current scientific knowledge, the most scalable mCDR pathways include ocean alkalinity enhancement and ocean nutrient fertilization (ONF).[2,3] This report focuses on ONF and other open ocean phytoplankton-based approaches.

ONF leverages the ocean's natural biological carbon pump (BCP) (Box 2) via addition of growth-limiting micronutrients (e.g., iron) and/or macronutrients (e.g., phosphorus, nitrogen, silica) to the surface ocean. ONF represents a deliberate intent to increase photosynthesis by marine phytoplankton to enhance uptake of carbon dioxide (CO_2) in surface waters. To achieve net CDR, the increase in production would have to be in excess of any increase in remineralization of the additional organic carbon. The theoretical CDR potential of ONF is on the order of 1+ gigatonne CO_2 equivalent ($GtCO_2e$) removal per year.[2,3]

Box 1. The ocean as a climate solution

The ocean plays a critical role in the global carbon cycle. Covering 70 percent of global atmospheric-surface contact, the ocean is in a state of constant gas exchange with the atmosphere and serves as an enormous carbon sink. Once atmospheric CO_2 dissolves into surface waters, various natural processes sequester a portion of that dissolved CO_2 for hundreds to thousands of years.

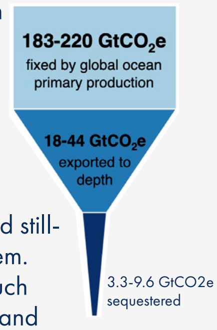
The ocean has absorbed approximately 25 to 30 percent of anthropogenic CO_2 emissions, changing ocean chemistry and causing a decline in pH generally termed 'acidification'. Combined with ocean warming and stratification, the ocean's capacity to absorb CO_2 is declining. These changes are disrupting aquatic habitats and altering the productivity and distribution of organisms ranging from plankton to fish species of both recreational and commercial importance.

Scientists have identified CDR pathways which aim to safely enhance the impact of the ocean as a carbon sink through controlled interventions meant to avoid impacts of unmanaged CO_2 exchange from atmospheric emissions. Some pathways aim to boost carbon capture via photosynthesis (e.g., blue carbon habitat restoration, seaweed cultivation, ocean nutrient fertilization) while others leverage seawater chemistry (e.g., direct ocean capture, ocean alkalinity enhancement). Collectively, ocean-based CDR pathways could theoretically yield gigatonne-scale CDR.[2]

i The ASMASYS framework (Baatz et al., 2025) is a comprehensive, transdisciplinary assessment framework for assessing the feasibility and desirability of mCDR options. The framework organizes a variety of criteria and indicators into seven dimensions: techno-environmental feasibility, political feasibility, legal feasibility, effectiveness, efficiency, equity and environmental ethics.

Box 2. CDR efficiency of the Biological Carbon Pump

The ocean's BCP is the process by which a portion of the organic carbon that is produced by phytoplankton through photosynthesis is transported from the surface ocean to the deep sea, where it is sequestered for centuries to millennia.



The BCP is an important but complex and still-unresolved component of the Earth system. Large uncertainties remain as to how much carbon flows through the BCP annually and its sensitivity to climate change. The figure (right) depicts the currently understood magnitude of annual global ocean primary production, carbon export, and sequestration in the deep sea.[4,5]

A gigatonne CDR intervention requires increasing global ocean primary production by 10-30 percent or enhancing export of primary production by 10-30 percent.

Global ocean primary production is expected to decline due to climate change,[6] but model representation of the BCP is far from complete.[5] Moreover, climate change could increase or decrease the effect of any one of the underlying biological and physical processes that drive the model-estimated CDR efficiency of the BCP.[5,7]

The leading ONF strategy is ocean iron fertilization (OIF) and is consistently reported to be able to exceed one $GtCO_2e$ per year.[8] Due to the limited material and energy required to boost primary production (one tonne of iron could potentially capture thousands of tonnes of carbon),[3] OIF has a high potential to be cost-effective. However, estimated cost ranges are still wide, ranging from <25 to 53,000 USD per tonne of CO_2.[9,10]

During the 1990s and 2000s, 17 ONF field trials were conducted (Box 3), including 13 OIF trials. These field trials successfully demonstrated the capacity to generate phytoplankton blooms through nutrient fertilization. Hundreds of academic research papers emerged from this early work. While the trials were not designed to test CDR efficacy or durability of ONF, they did lead to significant insights on the potential for ONF to lead to CDR. However, lack of follow-on funding and concerns about safety and environmental risk led to curtailment of research.

As such, the outstanding knowledge gaps on CDR efficacy, durability, and long-term environmental and socioeconomic risks identified over ten years ago remain today.[11] These uncertainties reflect the complexity of designing scalable biological interventions and present an opportunity for scientific research to inform future CDR decisions.

Box 3. History of ONF field trials

Between the 1990s and early 2000s, 17 ONF field experiments were performed: 13 academic iron fertilization experiments, two commercial trials using iron, and two academic phosphate addition studies.[12] The experiments were relatively small in scale (25-300 km^2) and duration (10-40 days) but confirmed that the addition of limiting nutrients, specifically iron, stimulates phytoplankton blooms and CO^2 uptake from seawater.[3] The trials were not intended to evaluate the CDR potential of ONF. The experiments were not long- nor large-enough to properly evaluate whether fertilization led to enhanced export and durable sequestration.

Based on these field experiments, numerous potential undesirable, unpredictable, and unverifiable environmental impacts of ONF were identified.[13] Leading environmental concerns include nutrient robbing, a potential for reductions in fisheries, and a decline in ocean oxygen levels.

The field faced a significant setback in 2012 when one set of private sector field trials triggered significant concern about improperly regulated open ocean trials. At the same time, research funding waned.

Why Now?

In the last five years, the need to find scalable CDR solutions increased significantly and brought renewed attention to ONF due to its theoretical scalability, vast scientific knowledge base, and potential cost-effectiveness. Following the publication of the 2022 National Academy of Sciences, Engineering, and Medicine (NASEM) *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, a handful of both academic and private sector ONF research activities emerged through support from new philanthropic, public, and private sector funding. In addition, since the last academic OIF field trial in 2009, significant advancements in ocean observations and technology, biogeochemical models, and understanding of the BCP have been made, which provides new scientific capabilities and capacities to address outstanding questions on phytoplankton-based CDR interventions.

From 2021 to 2023, numerous organizations published mCDR road maps, collectively calling for RD&D attention to both abiotic and biotic approaches. Ocean Visions published a series of mCDR road maps, synthesizing the state of the science, knowledge gaps, and priority research needs for a variety of CDR pathways, including microalgae-based approaches.

In 2023, a consortium of funders launched the Ocean Resilience and Climate Alliance (ORCA) to catalyze new work across seven ocean-climate priorities over a three-to-five-year period. One of the seven ORCA pillars is focused on mCDR and led by the Grantham Environmental Trust. This initiative provides a new opportunity to rigorously assess the efficacy, measurability, and risks of and inform decisions on open-ocean, phytoplankton-based CDR approaches.

Project Overview

Contents of the Report

This report is a product of an RD&D strategy design project. It summarizes the current state of knowledge and efforts related to open ocean phytoplankton-based CDR approaches. The report describes the breadth of phytoplankton-based CDR pathways and the current landscape of activities. The report describes priority research topics, questions, and recommendations to advance near-term scientific research to inform decisions on these mCDR pathways in the next five to ten years.

Project Methods

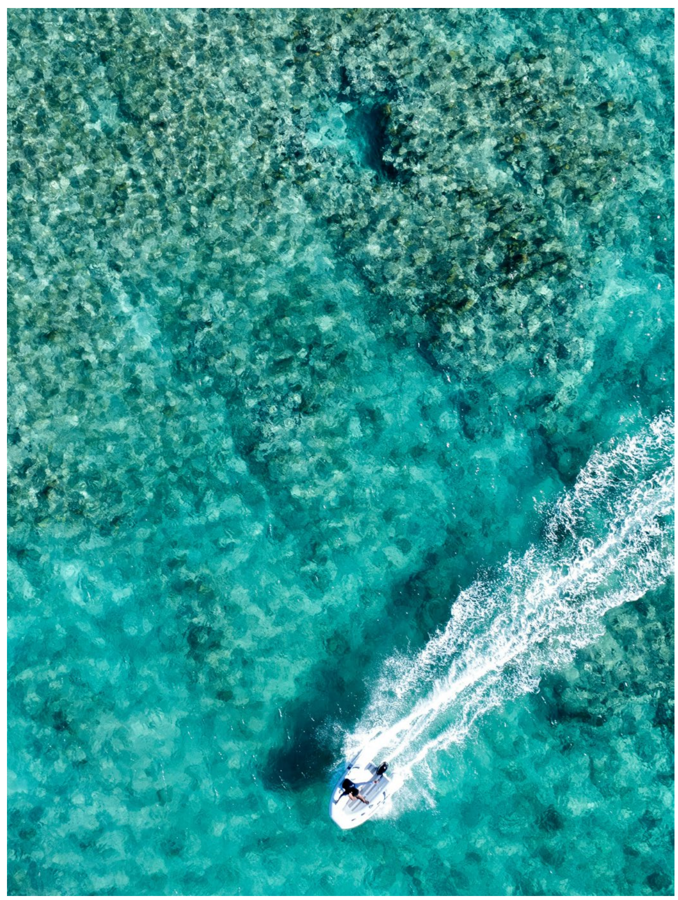
The project team developed this report through four-phases. Each of the first three phases concluded with an Advisory Board workshop to refine recommendations and next steps.

- **Phase 1: Define Project Focus** (October 2024–December 2025) The project team established the Advisory Board, project scope, logic framework to guide the project focus and public communications, and research plan.
- **Phase 2: Research and Design** (December 2024–March 2025) The project team initiated a landscape scan of relevant programs, projects, and initiatives and conducted a comprehensive review of relevant scientific literature and reports. The team used the ASsessment framework for proposed methods of MArine CDR and interim knowledge SYnthesiS (ASMASYS) to guide and characterize the research, which resulted in four focus areas for the RD&D recommendations:
    - CDR accounting
    - Socio-economic and environmental impacts
    - Specific phytoplankton pathways and innovations
    - Inclusive decision-making
- **Phase 3: Development, Feedback, and Revision** (March–August 2025) The project team tested prioritized themes and initial recommendations via a workshop at the Ocean Visions Biennial Summit. RD&D recommendations were further developed through numerous topic-specific expert interviews.
- ***[NOW]* Phase 4: Public Comment & Final Recommendations** (September–October 2025) The project team will integrate public feedback via dissemination of the draft report and a webinar before producing final recommendations into a report for the Phytoplankton Carbon Solutions (PCS) RD&D program.

Audience and Outcomes

This report is designed to inform the deployment of philanthropic funding to pursue the key scientific questions underlying the evaluation of the viability and impacts of open-ocean, phytoplankton-based CDR pathways. Many aspects of the required work leverage larger scale institutional investments already underway or planned. Philanthropic funding can sometimes be deployed to jump start or otherwise catalyze large government and research efforts. As such, the framing and priorities described in this report can also be used to help guide such institutional investments.

The recommended funding areas, while not exhaustive, highlight key priorities to advance research to inform real world decisions. The report includes a stage gate framework to evaluate the merit, safety, and efficacy of individual phytoplankton-based approaches. The framework is intended as a tool to inform decisions that would result in supporting only the approaches that can pass through each stage gate. The intended outcome of this report is thus a funder-ready RD&D strategy that sets the course for responsible research and development, with a framework to enable science-based decisions for either scaling or ceasing research.



Hugh Whyte © Ocean Image Bank

Landscape of Phytoplankton Carbon Solutions

Definition and Scope

The landscape assessment phase of the project began with defining the scope of phytoplankton-based CDR pathways to be investigated. For the purpose of this project, **Phytoplankton Carbon Solutions**, PCS from hereon, are defined as CDR pathways that seek to leverage open ocean phytoplankton communities to capture and sequester atmospheric CO_2. By using this term and definition, the subject matter of the PCS RD&D Program includes OIF and other ONF pathways and enables pathway innovations in the future (Figure 1).

Within a taxonomic representation of mCDR pathways (Figure 1), PCS pathways proposed to date can be divided in two categories: (1) production-based pathways, which include all ONF techniques, and (2) export-based pathways, which include additional interventions that aim to improve export efficiency. Overlap between these categories is possible. Appendix B lists all known potential PCS pathways and the current state of knowledge on their scalability, technological readiness, efficiency and durability, cost, environmental and social risks, and geographic applicability.

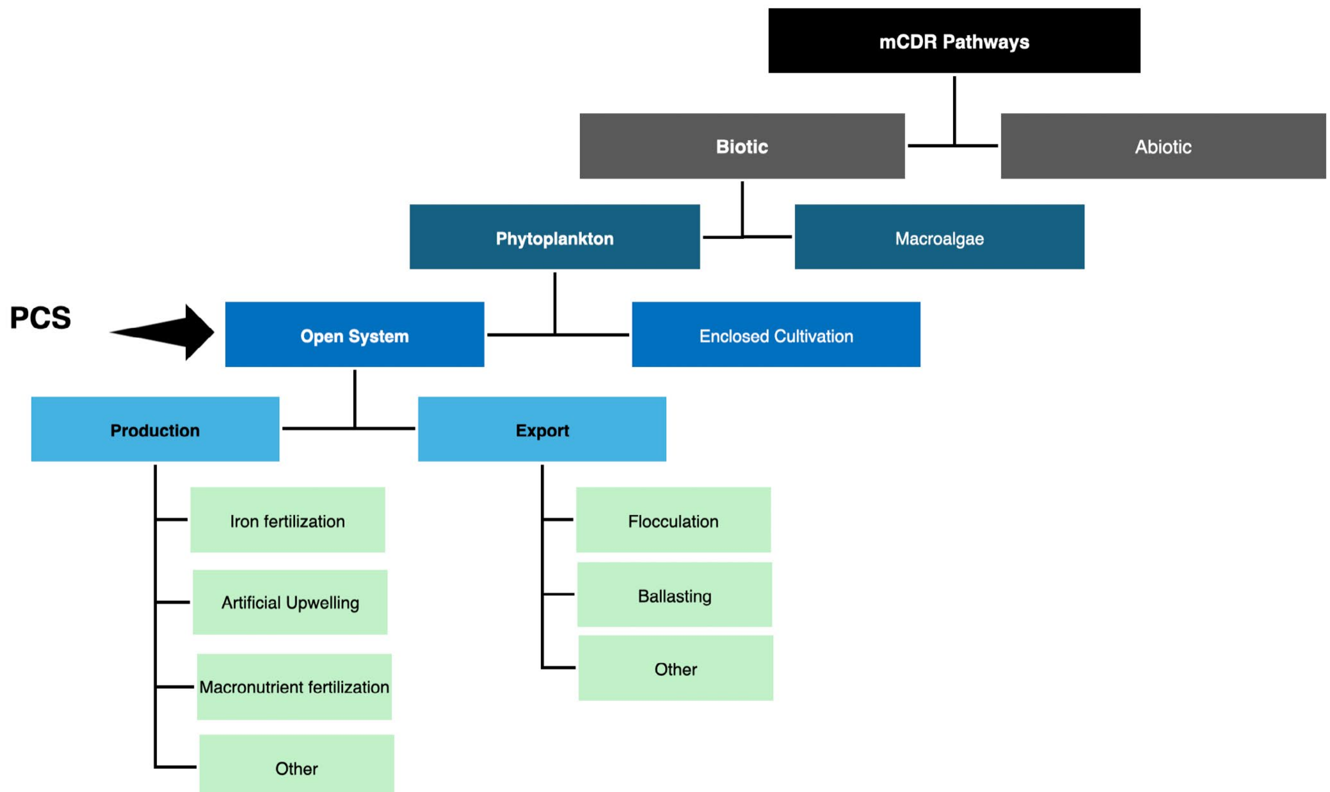


Figure 1. Placement of PCS within the mCDR pathway taxonomy

Production-based Approaches

PCS Pathways that aim to increase phytoplankton-driven primary production require a productivity stimulant and rely on gravitational sinking of the additional organic carbon to achieve durable CDR. Stimulants can be categorized as 'iron-based' and 'non–iron based'.

Iron-based pathways include OIF in ocean regions characterized by either high nutrient, low chlorophyll (HNLC) or low nutrient, low chlorophyll (LNLC) regions. In both scenarios, OIF alleviates the first order nutrient limitation, but the mechanism leading to durable CDR differs (Box 4).

Non-iron-based pathways include macronutrient fertilization—surface addition of nitrogen, phosphorus, and/or silica—and artificial upwelling—pumping deep nutrient-rich water to the surface (see Appendix B for detail).

Box 4. Difference between OIF in HNLC and LNLC regions

In HNLC regions, such as the Southern Ocean, phytoplankton growth is limited by iron. In these regions, the addition of iron triggers phytoplankton productivity (and thus the removal of dissolved CO_2 from surface waters) due to the abundance of unused macronutrients, nitrogen and phosphorus. To achieve CDR and durable sequestration, the additional biomass generated must be transported into the deep ocean to avoid remineralization, and surface waters must absorb additional CO_2 from the atmosphere.

In LNLC regions, such as subtropical gyres, and phytoplankton growth is co-limited by iron and macronutrients. In contrast to HNLC regions, the addition of iron to subtropical LNLC regions can stimulate growth of a class of phytoplankton called diazotrophs that fix nitrogen, thereby adding a new pool of bioavailable nitrogen to the ocean. Unlike HNLC OIF, nitrogen fixation–based OIF does not only require deep export to achieve durable CDR because, in addition to stimulating the BCP, the additional nitrogen remains active in the surface ocean, where it can be continuously recycled and consumed such that the carbon is also durably sequestered in a steady state of increased biomass. Scalability may still be limited by phosphorus.

Export-based Approaches

Export-based approaches intend to overcome the production-based pathway challenge of relying on the highly variable, hard to measure, passive export of organic carbon to achieve durable CDR. There have been limited early-stage investigations of processes that could enhance export. Examples include **flocculation** (adding clay particles to bind algal biomass and cause rapid sinking)[14], and **ballasting** (introducing silicates or minerals to increase diatom sinking rates;[15] using engineered nanoparticles to enhance export).[16]

Representation in mCDR Literature

Numerous mCDR strategy reports have been published in recent years and provide a strong foundation and starting point for developing PCS RD&D recommendations. The project team conducted a desktop review of these reports (Box 5), and extensively surveyed resources beyond those referenced directly in this report.

Box 5. PCS in mCDR literature

Most mCDR strategy reports seek to characterize the opportunities, challenges, and roadmaps for RD&D across mCDR approaches.[2,3,17–23] PCS pathways are represented via the slightly more narrow definition of ONF, inclusive of iron fertilization, macronutrient fertilization, and artificial upwelling approaches. These reports identify leading priorities and significantly informed PCS RD&D recommendations presented in this report.

In comparison to other mCDR pathways, mCDR strategy reports consistently highlight ONF's potential scalability. However, across reports, the ranking of ONF in comparison to other mCDR approaches is inconsistent, reflecting large uncertainty on the true scalability of ONF. For example, three reports list ONF's scalability as equal to or greater than ocean alkalinity enhancement and other electrochemical approaches,[2,3,23] and one publication lists it as lower than ocean alkalinity enhancement and direct ocean removal.[21]

Although the reports vary in their perspective of ONF scalability, all reports[2,3,17–23] identify the need to investigate environmental safety and potential ecosystem impacts associated with ONF interventions. Concerns include the production of nitrous oxide and methane, reduction in seawater pH, hypoxia and anoxia, toxic algal blooms, toxic material exposure, habitat alteration, nutrient robbing, and changes in supply of food and energy to benthic ecosystems.

All reports recommend further investigation to improve the knowledge base and de-risk mCDR approaches through a suite of research methods, including biogeochemical modelling, environmental impacts experiments, marine spatial planning, hardware development, and field trials. Most recommend controlled, iterative field trials as a next step to address fundamental questions on scalability and environmental impacts of ONF. However, there is little guidance on the scientific priorities to be addressed or the steps necessary to build the social and financial support for field trials, particularly large-scale trials (over 1,000 km^2). Further, they lack guidance on other research approaches that could identify the scientific, technological, or socio-political factors that might indicate modification or cessation of PCS RD&D.

The scientific literature and discussions with experts identified that, although large-scale field trials are a key component of assessing PCS viability and often recommended as a next step (Box 5), there remain significant differences of opinion regarding location and timing of large-scale trials. Field trials are costly and, depending on location and other factors, can be limited in their ability to comprehensively reduce some important uncertainties (see Field Trials). Field trial costs vary widely based on size, duration, and location. Smaller scale field trials could range from 3 to 25 million USD, while demonstration-scale research programs range from 30 to 200 million USD and last over five to ten years.[3,20] Numerous field trials would eventually be needed to provide sufficient evidence to deploy a PCS pathway at scale and build governance capacities needed to ensure that happens through community-based processes, thus multiplying the cost of field trials.

Research Methods

Multiple research methods and approaches can contribute to PCS and must be effectively integrated into a comprehensive RD&D program.[3,19–22] Each research method has its own opportunities and limitations for evaluating PCS. Priority research methods described here were informed by numerous expert consultations.

Observations

Opportunity: Observing systems are a critical component of both field trials and efforts to better understand natural processes. Observing capacity is rapidly improving, significantly enhancing the power to assess near field events, including export dynamics. This includes the speed and extent of particle movement below the mixing layer and early stage understanding of fate of particles in the deep ocean. Observing system improvements will improve model inputs and thus model accuracy and precision.

Understanding, incorporating, and enhancing advances in observing system capacities will help reduce uncertainty. These improvements will also be critical in a developmental role as they form the foundation of any measurement, reporting, and verification (MRV) capacity.

Multiple institutional research cruises are testing emerging observation technologies. Investments in observing systems are the backbone of government and university research on oceanography and biogeochemistry. Multiple expert interviewees shared that Argo and Argo-like systems have advanced to provide extensive observational capacity across the world's ocean. Recent Argo systems advances can deliver more biogeochemical data, including nitrate, pH, oxygen, chlorophyll fluorescence, suspended particles (backscatter), and downwelling irradiance. Emerging camera technologies are contributing new information on particle size and movement in ways that can better inform particulate organic carbon (POC) export.

Limitations: These systems are expensive to build and operate. While they present a significant opportunity to address key questions, it is unclear how philanthropic funding could best leverage improvements in observing capacities. Current system improvements still lack the ability to directly measure carbon export. And systems must be designed to answer a wide range of additional environmental questions. Addressing these shortcomings are a high priority to reduce uncertainty related to carbon benefits and address other critical social and environmental questions, including impacts on higher trophic levels to eventually be able to inform impacts on fisheries.

Natural Analogs

Opportunity: Natural analogs—such as seasonal phytoplankton blooms, volcanic ash deposition events, and shallow hydrothermal vents—offer ways to study bloom and export dynamics without a deliberate intervention. Using the same observational technologies as field trials, natural blooms can be tracked over space and time, allowing researchers to observe biomass export below the mixed layer and into the deep ocean. Natural analogs avoid permitting challenges and potential public opposition, making them a low-risk entry point for PCS research. Natural analog studies can also be paired with ongoing, institutionally funded research. Past observational datasets of natural analogs for ONF could be leveraged for additional analysis, and new field campaigns could address uncertainties and model limitations in baseline conditions, bloom and senescence dynamics, POC generation and export, and smaller scale physical drivers such as storm, currents, and eddies.

Limitations: Natural analogs are location-specific, and their findings may not apply to areas with different oceanographic, biological, or chemical conditions. These analog events are also, of course, unpredictable by nature. They share limitations in resolving far-field questions of export, durability, and socio-environmental impacts. Critically, they cannot test or demonstrate specific primary production stimulants or intervention strategies, limiting their role to an intermediate step in PCS RD&D. While they provide valuable insights, they cannot substitute for controlled trials needed to validate interventions or scale PCS. Finally, locating natural events and timing investigations to their occurrence can present a range of logistical and cost challenges.

Models

Opportunity: Models are a critical component of PCS investigations and can be used to efficiently represent many key aspects of the PCS process. Many effective oceanographic modeling efforts are already well developed, and companion earth systems models illustrate further opportunities. Building on those models presents cost efficiencies as they can effectively estimate both near-field and far-field biological, chemical, and physical dynamics. Models can be employed to predict and parameterize carbon sequestration potential, estimate environmental risks, and design and manage trials. Model comparisons can be used to assess and prioritize new model inputs and approaches. Advanced computing capacities and artificial intelligence present significant innovation potential.

Limitations: Complex oceanographic, biological, and chemical conditions can be difficult to effectively represent. Scaling challenges magnify model limitations. Inputs are often limited as more complete model inputs would render them overly complex. Most current oceanographic models lack sufficient ecosystem inputs to effectively assess biological effects. Prioritizing and incorporating the right set of additional inputs can require a range of trade-offs.

Field Trials

Opportunity: Field trials provide controlled, location-specific experiments that, when appropriately designed and rigorously executed, can answer priority questions about PCS while managing risks. They offer concrete opportunities for research engagement and co-design with interested and potentially affected communities. Field trials can generate essential information on baseline conditions, additionality, and environmental impacts. They also provide proof of concept for planning, execution, MRV protocols and models, and measurement approaches to inform standard protocols for scaled interventions. Field trials can be employed to test specific input approaches and deployment methodologies.

Limitations: Field trials are location-specific, with findings constrained by local oceanographic, biological, or chemical conditions. They offer limited insight into far-field questions of durability and socio-economic and environmental impacts. Field trials are also costly, requiring substantial resources for scientific rigor, and involve complex permitting and public engagement that may heighten opposition before fundamental efficacy questions are resolved.

Box 6. Field trial case study: Exploring Ocean Iron Solutions

Exploring Ocean Iron Solutions (ExOIS) is an academic research consortium housed at Woods Hole Oceanographic Institution that aims to evaluate the efficiency, safety, and scalability of OIF. As described in their 2023 *Paths Forward for Exploring Ocean Iron Fertilization* report, ExOIS represents one of the most advanced OIF field trial concepts to date.[24] The first recommended study site is in the northeast Pacific Ocean, an HNLC region. This trial site has been selected for its access to support infrastructure and to maximize control of the bloom and field observations and minimize downstream effects. The goal is to address key questions on bloom generation and export and assess local environmental impacts using advanced measurement and modeling tools. The proposed scientific field trial seeks to raise public awareness and provide proof of concept to further advance OIF experimentation in other locations. The trial would also generate insights to inform future governance.

The ExOIS program currently predicts a total field trial cost of 40 to 45 million USD to fully fund two field trials over a three-year period in the northeast Pacific Ocean. While the proposed field trial strategy would address many critical OIF questions, additional trials will ultimately be required to resolve site specific conditions in other locations where OIF could be scalable, such as the Southern Ocean. A comprehensive field trial approach is estimated at 25 million USD per year for ten years.[3]

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Current Activities

In addition to extensive scientific literature, numerous programs, initiatives, and projects are underway that either directly or indirectly contribute to a better understanding of the potential and viability of PCS. These efforts can be classified as academic and non-academic and are summarized here, representing a non-exhaustive landscape of activities (see Appendix C for detail).

Academic Initiatives

Most of the current PCS-relevant activities are academic, covering studies of the global carbon cycle and BCP, biogeochemical modeling, and a few pathways-specific investigations.

Several long-standing international ocean observing initiatives contribute to the advancement of global and ocean carbon cycle and climate models. Horizon Europe's OceanICU and projects like Biogeochemical-Argo, SOCCOM, GEOTRACES, SOCAT, and GLODAP provide large-scale datasets and frameworks to standardize and harmonize biogeochemical measurements and carbon cycle analyses.[25] Several ship-based long-term, open-ocean reference stations measuring dozens of variables and monitoring the full depth of the ocean from air-sea interactions down to the seafloor also contribute to understanding carbon dynamics, for example the Hawaii Ocean Time-series and Bermuda Atlantic Time-series Study.[25] These time-series and others contribute to the OceanSITES program, a worldwide system of time-series whose mission is to collect, deliver, and promote the use of high-quality data from long-term, high frequency observations at fixed locations in the open ocean. These programs are critical to understanding the natural and changing carbon sink capacity of the ocean.

Numerous BCP research programs aim to better understand processes that drive primary production and carbon export. These include APERO (France), BIOPOLE (UK), BIO-Carbon (UK), EXPORTS (USA), and PICCOLO (UK). These are multi-year programs that combine ship-based fieldwork, novel sensors, genetic tools, and data-model integration to understand and model phytoplankton productivity, particular organic carbon flux, mesopelagic processes, and export of organic carbon into deeper ocean layers. Synthesis activities to integrate BCP process learnings into oceanographic and climate models are underway and facilitated by the JETZON consortium (UK).

Among PCS pathways, OIF remains the dominant focus of academic studies internationally. New technoeconomic assessments (TEA) of Southern Ocean OIF were published in recent years[9,10,26] and modeling studies continue.[27–30] Southern Ocean field trials were previously proposed by the Korea Polar Research Institute.[31] In 2022, scientists from Alfred Wegener Institute in Germany led an expedition to study OIF through natural analogs in the Southern Ocean.[32] In 2023, the international Exploring Ocean Iron Solutions (ExOIS) consortium published a comprehensive OIF RD&D strategy, focused on the design and execution of a large-scale OIF field trial in the northeast Pacific, with the aim of achieving a better insight on export dynamics.[24,33]

Several academic research projects on subtropical OIF to stimulate nitrogen fixation are underway.

Non-Academic Initiatives

Following the renewed prioritization of OIF by the 2022 NASEM *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, several non-academic efforts were developed. These include commercial initiatives such as GigaBlue, a company working to boost phytoplankton growth and enhance export through the addition of iron-infused particles in surface waters. In support of GigaBlue, Puro.earth, a carbon removal crediting platform, is developing an MRV methodology.[34] At this point, neither effort is accompanied by peer-reviewed scientific studies, and some aspects of the process have not been disclosed. Other topic-related organizations exist, but their role in advancing RD&D is unclear (see Appendix C for details).

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PCS Strategy Foundation

A Risk-Benefits Approach

Understanding PCS viability comes down to two fundamental questions on feasibility and desirability.[35,36]

1. **Can PCS lead to quantifiable CDR?**
   This is a scientific question. Viable CDR approaches must be shown to be **additional, scalable, durable, and measurable**. Most PCS pathways are in the early stages of development, but even for OIF, significant measurement uncertainties and efficacy risks remain.

2. **Should we deploy PCS?**
   If PCS is found to be effective for CDR, the decision to implement PCS is a socio-political, legal, and ethical decision and requires a deep understanding of the **socio-economic and environmental risks and co-benefits** that could impact different natural and human communities. Unlike other CDR options, PCS entails intentional modification of global biological processes and ecosystems. These interventions can impact metrics of ocean health, biodiversity, food security, and legal rights and authorities of nations, and other sociocultural values.

   PCS impacts must be understood from the perspectives of containability, reversibility, probability, and accountability to effectively inform societal risk-benefit assessments and decisions on PCS field trials and deployments.

   Risks and benefits must also be considered and compared to other CDR options and in the context of both current and future ocean conditions to assess whether the potential deployment of a PCS solution in a particular place is desirable.

   Although research cannot resolve these societal decisions, an effective RD&D program can provide the evidence base required to inform such a risk-benefits evaluation.

Program Goal

The goal of a PCS RD&D program is to fund activities to inform a risk-benefit assessment to support decision-making on whether, or which, and under what conditions PCS pathways should be part of a global CDR portfolio.

The Program is designed to be outcome agnostic. The Program must generate the scientific evidence to overcome current scientific concerns, social license concerns, and uncertainties associated with PCS. At any stage of this RD&D Program, emerging findings around CDR benefits, socio-economic risks, or environmental risks may suggest curtailment or discontinuation of these investigations. Those are acceptable Program outcomes.

Research Priorities

1. **Ability to Achieve CDR Accounting**
   PCS pathways must demonstrate high confidence CDR measurability to understand their true scalability and durability. Research will need to objectively answer whether, where, and how PCS might contribute to global CDR.

   The Program must guide prioritization of MRV RD&D to identify, define, and reduce uncertainty in variables with the greatest influence on durability. Along the way, the Program will identify unsolvable impacts and/or insurmountable levels of uncertainty as potential off-ramps.

   The Program must also ensure MRV approaches are consistent with other CDR pathways and cost considerations are well understood and comparable in a lifecycle context.

   It is unrealistic to assume any PCS operations can or would be sustained in perpetuity. Thus, research must address realistic deployment scales and durations, including minimum commitment periods and termination effects.

2. **Identifying, Prioritizing, and Addressing Socio-Economic and Environmental Impacts**
   PCS poses a wide range of environmental and socio-economic risks, but co-benefits could also emerge and need to be investigated.

   Viable PCS approaches will need to be able to define expected and acceptable environmental impacts, their durations, and a range for key environmental health measures. These include near-field concerns immediately within and adjacent to intervention sites and far-field and longer term impacts that might not materialize until decades later, far from the intervention site. Priority concerns include dissolved oxygen changes, risks of nutrient depletion and redistribution, changes in phytoplankton species diversity, overall ecosystem productivity, and fisheries impacts.

Understanding baseline ecosystem conditions, including natural interannual and geographic variations, across key indicators of environmental and socioeconomic health is critical to any meaningful evaluation of PCS impacts.

A critical dimension of this work will focus on engaging interested and affected communities to inform scientific priorities, enhance research design, and build public trust and understanding of impacts on ocean ecosystems and impacted communities. Early discussion and prioritization of risks, co-design of investigations, and transparent two-way communication will be required to ensure program work addresses the right challenges in acceptable ways.

Through consultations, the project team identified fisheries and other coastal community concerns as in need of special attention. Historically underrepresented communities in ocean resource decision-making must be placed at the center of planning, research, and development work. The Program will rigorously incorporate practices such as Free and Prior Informed Consent, co-design of research and inclusive decision-making, benefit-sharing, and equitable access to data.[37–39] Fisheries risks are uniquely prominent and socio-economically important, and it is thus critical that researchers can understand, predict, and monitor fisheries impacts at local, regional, and global scales.

3. Understanding and Prioritizing PCS Pathways and Innovations

There are multiple PCS pathways under investigation (Appendix B). The program must continuously scope, evaluate, and prioritize PCS pathways and ocean regions that have the potential for scalable, durable, and cost-effective PCS, with socio-economic and environmental impacts that could be managed or accepted in a representative, participatory, and risk-based decision process.

The RD&D program should prioritize pathways and innovations with the best opportunities to demonstrate CDR benefit, scalability, lower environmental and socio-economic risk, and techno-economic feasibility. Based on the current options, ongoing activities, and expert opinions, the project team identified the following PCS pathway prioritization:

- **Southern Ocean OIF** represents the most scalable approach based on relatively well-developed, foundational scientific knowledge and theory. Scalability of OIF in HNLC regions, like the Southern Ocean, is estimated to be 2–4 $GtCO_2e$ per year[29,40–42] at a price point of <25 to 53,000 USD per tonne of CO_2.[9,10] While many reports advocate for longer and larger-scale field trials to determine the viability of Southern Ocean OIF, this is extraordinarily expensive and challenging. The program must address several critical knowledge gaps before large-scale field trials can be justified, including the realistic scaling of OIF operations, OIF's ability to achieve durable CDR with high confidence MRV, and environmental risks of nutrient robbing, harmful algal blooms, fisheries impacts, among others.

Box 7. Priority research questions

1. CDR Accounting

- Which PCS pathways and regions have the potential to achieve measurable, scalable CDR of ≥1 $GtCO_2e$ per year for multiple decades?
- How scalable is sequestration across durability time horizons of 100 to 1000+ years?
- Can advances in observations and modeling enable MRV systems that are robust, trusted, and within the acceptable bounds of remaining uncertainty?
- Can PCS be cost-competitive with other CDR pathways?

2. Socio-economic and Environmental Impacts

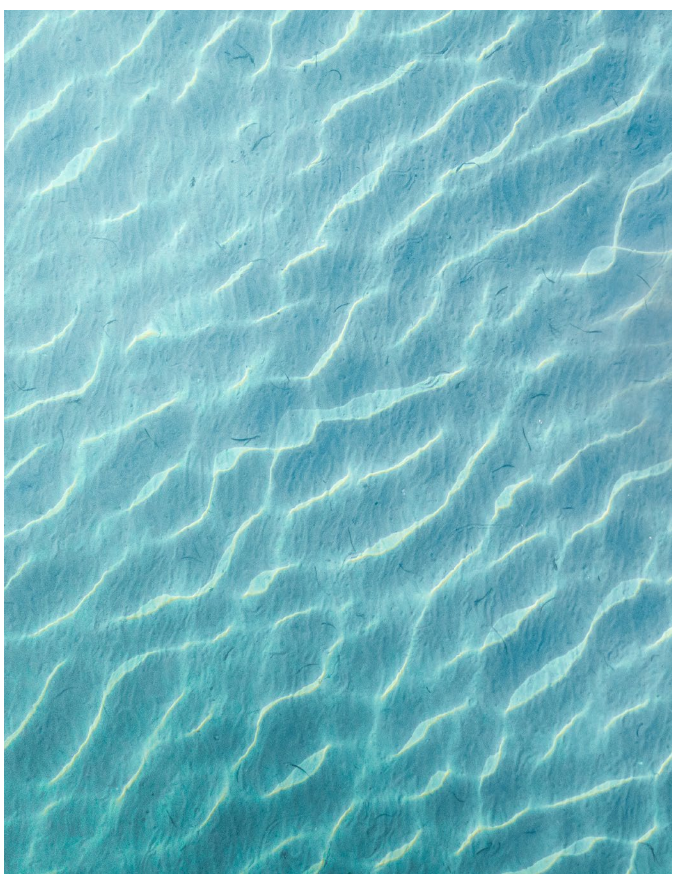
- What are the key local and far-field socio-economic and environmental risks, concerns, and potential benefits?
- How do risks align with principles of containability, reversibility, probability, and accountability?
- To what degree can these impacts be quantified with sufficient certainty and probability to inform decision-making?
- How do expected PCS risks and benefits compare to expected climate change impacts?
- What thresholds of negative impacts, if any, would be considered acceptable, and under what decision process(es) and by what audience?

3. Pathways and Innovations

- What criteria and decision-making processes should guide the prioritization of PCS pathways for investment within the RD&D program?
- What technological or governance innovations are required to improve the safety, scalability, and efficacy of PCS?

Some of the logistical challenges of Southern Ocean OIF could potentially be addressed through work in other HNLC regions such as the northeast Pacific.

- **Subtropical nitrogen-fixation-based OIF** expands the cost-effective OIF-scalability into LNLC regions but has seen limited investment and empirical field testing to date. Nitrogen-fixation-based OIF in the South Pacific could potentially sequester 1.5 $GtCO_2e$ per year,[43] with the benefit of reducing the risk of nutrient robbing by generating bio-available nitrogen. Given the lack of investment and testing of the OIF LNLC hypothesis, the knowledge gaps on efficacy, risks, and costs are larger than that of Southern Ocean OIF.
- **Improved control of carbon export** below the ocean's mixed layer may be an opportunity to address both the MRV challenge on export and the challenge of ensuring the durability of OIF for PCS pathways reliant on deep sea storage. A few academic research projects have explored the potential to enhance export via clay flocculation, or weighted nutrient addition and the creation of marine snow. Export-based pathways could theoretically be applied in tandem with Southern Ocean OIF.
- **Other PCS pathways** are considered lower priority and warrant monitoring. These include pathways that are in early stages of development or face significant environmental impact or scaling challenges. For example, macronutrient fertilization has cost and material scaling challenges,[3] and upwelling enhancement has lower CDR efficacy due to the high CO_2 content of deep water (Appendix B).



Lewis Burnett © Ocean Image Bank

Cost Considerations

To ultimately determine whether large-scale deployment of PCS is effective and desired, overall RD&D is estimated to cost on the order of 500 million to billions USD over the next 15 to 20 years.[3,20] Currently, there is no clear line of sight for PCS RD&D funding at the scale needed. While effective CDR solutions that can scale safely and cost-effectively may ultimately justify those expenditures, strategic execution of priority PCS work will be needed to build the scientific foundation and social trust and desirability for PCS research investments.

The PCS RD&D program thus requires:

- A clear, strategic, and appropriately sequenced set of recommendations such that early investments inform future budget priorities.
- A stage gate approach to evaluate progress and investment or curtailment of priorities for specific PCS pathways (see Stage Gate Approach).
- Leverage of other funding sources and related research programs (e.g., mCDR, BCP, global carbon budget studies).
- Independence of any commercial PCS activities (although it will be important that the Program monitor such activities and leverage opportunities for independent academic research and data transparency)

Stage Gate Approach

A key process to ensure the best use of limited resources is to complement strategic priorities with objective criteria to measure progress. The program will implement a four-stage, decision-driven, stage gate framework to guide and evaluate progress on the viability of individual PCS pathways (Figure 2).

Each stage includes clear objectives, evaluation criteria, and go/no-go or prioritization decision points that a PCS pathway must pass through to merit further investment. The framework incorporates technical, environmental, and socio-political considerations. and will be used by the program to inform funding decisions.

Key criteria that will be iteratively assessed across stages include:

- Scalability of 1 $GtCO_2e$ per year or more for multiple decades
- Durability that is quantifiable on time horizons ranging from 100 to 1000+ years
- Measurability and remaining uncertainties on par with other CDR pathways
- Cost trajectory towards 100 USD per tonne CO_2 or less
- Socio-economic and environmental impacts, risks and environmental justice dimensions are understood sufficiently to inform risk-benefits assessments
- Social and regulatory support for field research, particularly from affected communities and regions

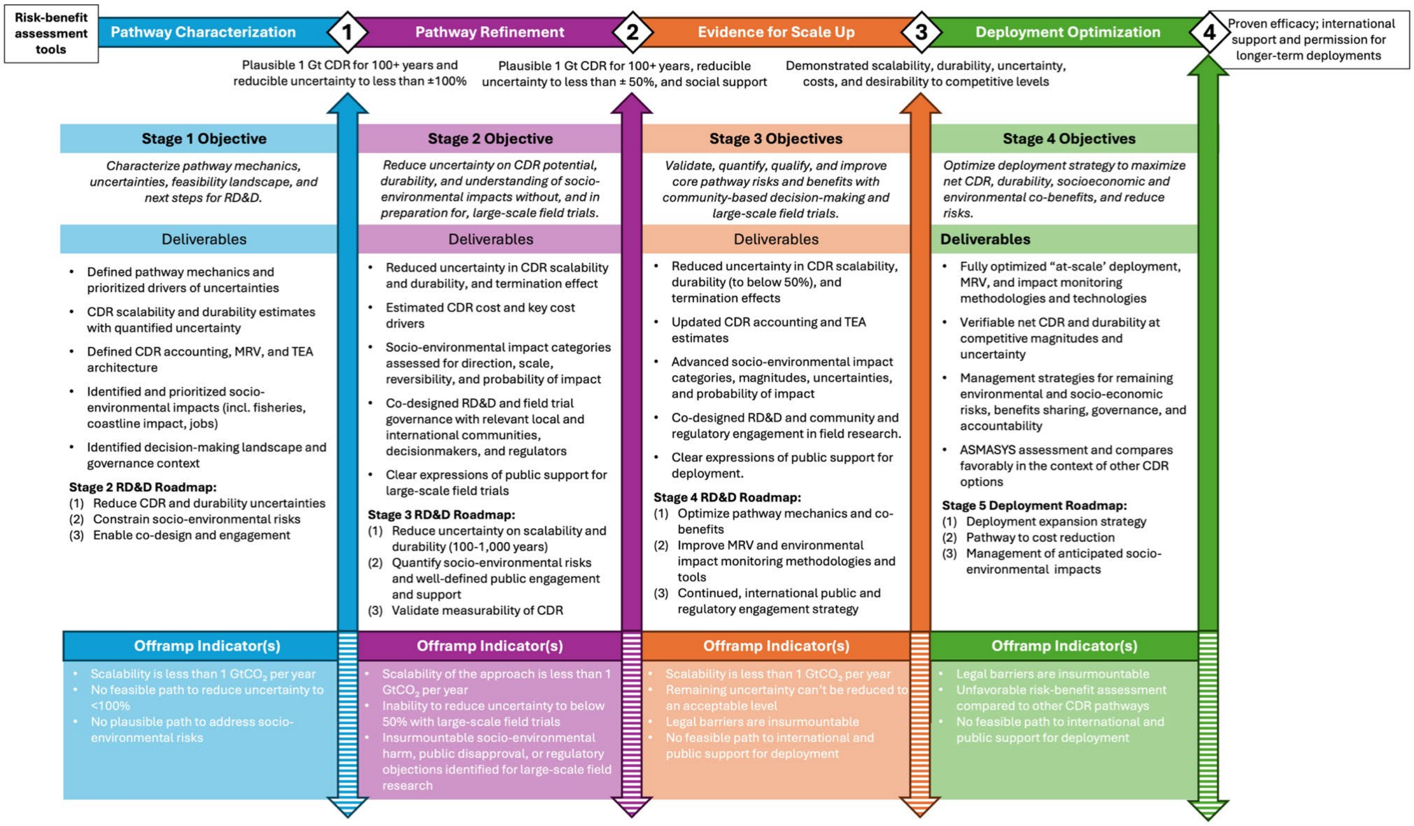


Figure 2. Stage gate framework for PCS pathways in a specified deployment region.

Key Assumptions

The strategic recommendations described above involve several important assumptions:

PCS desirability requires, at minimum, gigatonne-scale CDR benefits. PCS are complex CDR solutions with significant implications for natural ocean ecosystem function. Gigatonne-scale CDR benefits are needed to achieve desirability for research and overcome both real and perceived environmental risks of PCS. Additionally, the presumed risks, even when reduced or better characterized, will only be acceptable when the risk of no action is also perceived to be great.

Academic scientific inquiry must lead and advance PCS feasibility and desirability understanding before PCS operations could be deployed, at any scale, on the high seas.

Large-scale field trials will require public funding and broad societal and regulatory support. Early-stage RD&D will help build the scientific and socio-political foundation needed to justify and enable large scale field trial funding and permitting.

Legal viability and public desirability of PCS is subject to change with the emergence of scientific findings (as achieved through the execution of this RD&D strategy and other work), changing global environmental conditions, and shifting political priorities over the next five to ten years. The strategy prioritizes scientific knowledge gaps and development activities to form a strong foundation for the potential scaling of follow-on research.

Recommended RD&D Action Plan

The proposed RD&D Program is designed to iteratively identify and prioritize learning opportunities via an integrated and cost-effective strategy. The RD&D Action Plan outlines the execution of that strategy:

- **The RD&D Activities** describe the primary activities required to address critical PCS questions. The plan also proposes activity sequencing to best utilize available RD&D resources and avoid unnecessary socio-economic and environmental risks.
- **Engagement and Decision-making** will dictate the ways the program will ensure collaboration, transparency, and engagement throughout the R&D process. While decisions of this importance are informed by science, they ultimately require risk-based societal choices. Ensuring full engagement and ongoing expert advice will be essential.
- **Operational Requirements** detail resources required to run the program and operation responsibilities.

RD&D Activities

Recommended RD&D activities fall into three categories: Comprehensive Priorities, PCS Pathway Priorities, and Engagement and Decision-making. Comprehensive Priorities include activities that are critical to the advancement of any PCS pathway, while PCS Pathway Priorities advance pathway-specific and place-based evaluations. Engagement and Decision-making recommendations describe how research and development should proceed. This last group of recommendations ensures opportunities for co-design, participation and evaluation across all PCS R&D activities.

The plan proposes specific areas and sequences of investment. At the same time, there are inherent relationships and learning opportunities across PCS pathways and in the context of program comprehensive priorities.

Further, it is understood that changing conditions, new innovations, and ongoing learnings will dictate adjustments in the RD&D activities and priorities.

Table 1. RD&D Activities Plan

	Topic	Activities	Output	Outcome	Impact
Comprehensive Priorities	**Reduce Uncertainty on Net CDR**	Perform a sensitivity analysis to identify the most critical sources of uncertainty around additionality and durability for priority PCS pathways and design targeted research initiatives to reduce those key uncertainties.	CDR accounting and TEA framework for PCS and identification of uncertainties that can be reduced.	Mechanism to evaluate PCS pathway scalability, durability, uncertainty, and costs.	Viable PCS Pathways can be prioritized via a robust risk-benefits assessment informed by reduced uncertainty in: • CDR scalability, durability, measurability • Socioeconomic and environmental risks and co-benefits • Economic viability
	Improve Utility of Biogeochemical Models for PCS Evaluation	Initiate a model improvement program to perform model intercomparisons, prioritize targeted additions of field observations, particularly biological inputs, and assess and integrate potential innovations.	Identification of model input and process improvement priorities; Multiple model improvement projects.	Improved biogeochemical modeling tools for PCS impact evaluation and uncertainty reduction.	
	Improve Understanding of the Ocean's Natural (BCP)	Work with a range of ongoing ocean health investigations to increase knowledge and characterization of BCP baseline conditions and trends to build a better foundation as a basis to measure the effect of PCS interventions against 'business as usual' ocean health conditions.	Improved representation of BCP in assessments; and better characterization of risks under business-as-usual climate or alternative action scenarios, and with PCS implementation	Enhanced contextualization of PCS and climate-change driven socioeconomic and environmental impacts.	

Continued on next page

	Topic	Activities	Output	Outcome	Impact
PCS Pathways	**Improve Understanding of Southern Ocean OIF Potential**	Develop realistic scaling scenarios to better characterize and quantify CDR potential, operational requirements, and consequences of Southern Ocean OIF. Use these findings to further assess PCS scalability, costs, and impacts to inform future PCS decisions.	Realistic deployment scenarios and identification of development gaps (e.g., MRV); Updated characterization of socioeconomic and environmental risks.	Improved realism of Southern Ocean OIF that enables comparison to business-as-usual scenarios and other CDR approaches.	Stage Gate 2 and 3 evaluations enabled for PCS pathways, as warranted
	Improve Understanding of Subtropical Nitrogen Fixation–Based OIF	Support assessments of viability and effects of subtropical nitrogen fixation-based OIF. Assess other macronutrient and site-based limitations to inform future CDR potential.	Scientific knowledge aligned with stage-gate metrics via place-based, locally co-designed research.	Advanced understanding of the viability of this pathway.	
	Support Preparatory Activities of the Northeast Pacific OIF Field Trial	Continue to support preparatory activities of the ExOIS field trial within the context the other recommendations in this report, to ensure that PCS field trials are executed at the right moment in time, in the most effective place, with public support, and with adequate funds to maximize the scientific knowledge gains. Preparatory activities include social engagement and navigating the trial's regulatory framework.	Assessment of the socio-environmental risks, co-benefits, and regional desirability of a field trial; build needed funding support.	Stage-gate-based evaluation, and potential initiation, of the northeast Pacific Ocean OIF field trial.	
	Catalyze Innovations that Enhance "Export" of Phytoplankton Carbon	Fund early-stage development, innovation, and testing of mechanisms to enhance export to prioritize approaches for further development.	Identification, development, and viability evaluation of one or more export-focused innovations.	Potential improved export performance for PCS pathways.	
	Continue to Monitor and Assess Emerging PCS Pathways	Monitor emerging PCS ideas and pathways and use the stage-gate framework to evaluate their progress for future funding consideration.	Opportunity to incorporate new PCS pathways into the R&D portfolio.	Full awareness, development and evaluation of emerging PCS pathways.	

Continued on next page

	Topic	Activities	Output	Outcome	Impact
Engagement and Decision-making	**Co-design Research to Inform Decision Making**	Support co-design activities, adopt codes of conduct and best practices for mCDR RD&D, and form an international advisory board for program guidance.	Inclusive RD&D design and decision-making on PCS grants	Trust in PCS research and decision-making processes	PCS program produces scientific research that addresses public interest and can inform international decision-making
	Enable Coastal Communities and Fisheries Engagement	Build international fisheries and coastal community capacity to engage early and effectively on PCS research. Enhance fishing industry and community understanding of risks and co-benefits of PCS.	Advanced understanding and integration of socio- cultural- and -economic priorities in the context of PCS; Proven principles and processes for successful consultation and co-design.	PCS research advances through social priorities and co-design processes leading to improved social license and project benefits.	
	Ensure Consideration of PCS Impacts Against Alternative Actions	Collaborate actively with other CDR and mCDR efforts to increase efficiencies across shared investigations and maximize future comparative capacities.	Consistent evaluation and aligned communications on mCDR and other CDR risks and benefits.	Improve public understanding of comparative CDR risks and benefits across all CDR pathways.	

Comprehensive Priorities

Reduce Levels of CDR Uncertainty

Finding: There remain significant levels of uncertainty around the additionality, scalability, and durability potential of PCS. Some are quantifiable and some are not. It is not clear which areas of uncertainty along the MRV path are most influential, modifiable, or reducible with additional scientific research, which complicates the prioritization of research approaches (e.g., near-field *in situ* studies vs. far-field biogeochemical modeling.) The field still lacks consensus on the best approaches to address critical uncertainties.

Recommendation: Perform a sensitivity analysis to identify the most critical sources of uncertainty around additionality and durability for priority PCS pathways (Southern Ocean OIF and sub-tropical OIF), and design targeted research initiatives to reduce those key uncertainties (e.g., models, field trials, enhanced observational capacity). Integrate TEA capabilities into the sensitivity analysis framework to generate CDR cost estimates. Throughout this process, seek to build greater consensus for priority topics and approaches.

Outcome:

- Identification of the most important uncertainties that can be reduced with RD&D within 2-3 years for Southern Ocean OIF and sub-tropical OIF.
- A combined sensitivity analysis and TEA framework that can be used to evaluate PCS scalability, durability, and costs iteratively over time.
- Increased evidence-based agreement within the scientific community in support of priorities and approaches.

Improve Utility of Biogeochemical Models for PCS Evaluation

Finding: Models are essential to address critical uncertainties about local and far-reaching environmental effects. They are also necessary to determine CDR additionality and durability. Current models used to predict PCS CDR benefits lack agreement on CDR benefits. Additionally, most models lack sufficient biological and ecosystem inputs to adequately address BCP dynamics. There is significant oceanographic modeling work underway and advances in computing and artificial intelligence capacities offer potential for significant model improvements.

Recommendation: Initiate a model improvement program specific to PCS to adequately assess and predict far-field environmental and CDR effects. Primary areas of focus will include model intercomparisons to build consensus around current conclusions and potential enhancements, improved ecosystem inputs to better characterize and assess biological trends under natural and perturbed conditions, prioritization of model input needs, and identification of opportunities for advanced computing and artificial intelligence innovations. Initial findings will inform future investments.

Outcomes:

- A model intercomparison project to better quantify and address uncertainty in biogeochemical impacts of PCS, including characterization of long-term, far-field impacts.
- Improved representation of biological processes in current oceanographic models.
- Identification of current model differences and feasible opportunities to reduce model uncertainty.
- Consensus in support of priority model innovations according to priority opportunities identified.

Improve Understanding of the Ocean's Natural Biological Pump Health Trends

Finding: PCS assessments must be grounded in an accurate understanding of the current and future state of the ocean's natural biological pump and other key indicators of ocean health, most notably fish stocks. A better understanding of how ocean warming and acidification result in changes in the BCP and ocean health is needed as a baseline against which to measure the impact of PCS interventions.

Fundamental questions remain about the ecological processes that drive productivity, bloom senescence, and export efficiency for CDR. Improved understanding of the role of everything from grazers to viruses is a critical, but less well incorporated, aspect of PCS investigations. Incorporating learnings from BCP studies and natural analogs can help address some aspects of CDR uncertainty.

Recommendation: Work with a range of ongoing BCP investigations and observing programs to increase knowledge and characterization of BCP baseline conditions and trends to help build a better foundation as a basis to measure the effect of PCS interventions against 'business as usual' or other intervention pathway impacts on ocean health. Support BCP research synthesis activities, advance characterization of the BCP in biogeochemical models, and enhance understanding of socio-environmental impacts of interventions in the BCP. Identify and prioritize efforts that can provide insight to baseline conditions and trends as a means to measure the effect of PCS interventions. Augment uncertainty analyses through assessment of natural analogs.

Outcomes:

- Targeted BCP synthesis activities to leverage and accelerate work necessary to improve the understanding of ocean ecosystem baseline conditions and 'business as usual' trends.
- Improved characterization of socio-economic and environmental impact of PCS interventions on BCP processes.
- Comparison of socio-economic and environmental risks of PCS interventions and no-action alternative scenarios.
- Use of natural analogs to improve understanding of BCP dynamics under perturbed conditions.
- Improved representation of BCP in models used to assess PCS interventions.

PCS Pathway Priorities

Improve Understanding of Southern Ocean OIF Potential

Finding: Numerous models and studies identify Southern Ocean OIF as the most scalable PCS opportunity with gigatonne scale potential based on available macronutrients and idealized model scenarios. These model scenarios are often not reflective of real world implementation strategies or CDR potential. Realistic deployments would likely achieve less CDR and have lower environmental risks. Despite a strong scientific knowledge foundation of Southern Ocean OIF, many uncertainties remain. Work should focus on better understanding the realistic CDR potential in the highest potential regions of the Southern Ocean.

Recommendation: Develop realistic deployment scaling scenarios to better characterize and quantify CDR potential, operational requirements, and consequences of Southern Ocean OIF. Incorporate work under the proposed sensitivity analysis and model improvement project to refine projected CDR potential and environmental risks. Concurrently, in lieu of additional in situ work, monitor ongoing Southern Ocean field campaigns and observation programs to identify any additional opportunistic research opportunities to better characterize near-field measurability of export and additionality.

Outcomes:

- Improved understanding of CDR potential and MRV capacity of Southern Ocean OIF, based on realistic deployment scenarios.
- Updated characterization of socio-environmental risks, based on realistic deployment scenarios.
- Informed decisions on future RD&D priorities to better inform PCS pathway consideration.

Improve Understanding of Subtropical Nitrogen-Fixation-Based OIF

Finding: OIF in subtropical, LNLC waters has received limited research attention compared to OIF in HNLC waters, such as the Southern Ocean. Based on observations of natural hydrothermal plumes in the Tonga-Kermadec Ridge and small-scale lab experiments, OIF in subtropical waters could potentially stimulate nitrogen fixation, thereby boosting phytoplankton growth more broadly. Preliminary work in select South Pacific Islands recently spurred interest in evaluating the potential for this PCS pathway. If determined to be viable, this pathway could avoid or reduce some, but not all, of the macronutrient allocation challenges that come with HNLC interventions.

Recommendation: Support assessments of the viability and effects of subtropical nitrogen-fixing based OIF (e.g., Stage Gate Phase 1). Assess other macronutrient and site-based limitations to further inform future CDR potential. Ensure that the research prioritizes local engagement and capacity building to enable co-design and lab-, mesocosm-, and field-based research.

Outcome:

- Viability testing and characterization of subtropical OIF, aligned with stage-gate metrics evaluation.
- Engagement of South Pacific nations on PCS research.
- Development of best practices for local community and regional engagement in early co-design of RD&D work.

Support Preparatory Activities of the Northeast Pacific Ocean OIF Field Trial

Finding: There is consensus among experts in the field that large-scale field trials are an essential step in testing PCS viability. They are also the most expensive step and will require significant regulatory and public processes.

The international consortium Exploring Ocean Iron Solutions (ExOIS) is planning a comprehensive, large-scale OIF field trial in the northeast Pacific Ocean. The availability of the resources needed for this trial is currently uncertain, and there is not complete expert consensus on timing and location of the next generation of field trials.

OIF field trials in this region could support proof-of-concept testing of MRV methodologies and environmental impact assessments, while informing technological considerations of bloom management and near-field dynamics associated with OIF. The extensive community of practice developed through this effort provides an important coordination mechanism for OIF-specific research and development. Aspects of this research are valuable in informing governance challenges and larger scale opportunities in the Southern Ocean.

Recommendation: Continue to support preparatory activities of the ExOIS field trial within the context the other recommendations in this report, to ensure that PCS field trials are executed at the right moment in time, in the most effective place, with public support, and with adequate funds to maximize the scientific knowledge gains. Preparatory activities include social engagement and navigating the trial's regulatory framework. Continue to seek further consensus on the role, timing, location, knowledge transferability and cost efficiency of large-scale field trials and other field-based research as a part of final program recommendations.

Outcome:

- Determination of the northeast Pacific as a viable OIF field trial site under cost-benefit considerations.
- Assessment of the socio-economic and environmental risks, co-benefits, and regional desirability of a field trial.
- A sustained community of practice to prioritize, coordinate, and evaluate PCS RD&D.

Catalyze Innovations that Enhance "Export" of Phytoplankton Carbon

Finding: The magnitude and depth of POC export generated by phytoplankton blooms is a key driver of the CDR efficacy and costs of PCS. While much funding has been devoted to characterizing natural export and generating blooms, only a few studies have explored the potential to better understand, control, and enhance export (e.g., clay flocculation, ballasting, marine snow enhancement).

Innovations that enhance the export of carbon captured by phytoplankton into the deep ocean could improve the overall additionality and measurability of PCS pathways and therefore their techno-economic viability. These innovations, which could be essentially components of future PCS effectiveness, have received little attention to date.

Recommendation: Fund early-stage development, innovation and testing of mechanisms to enhance the export of POC to prioritize approaches for further development.

Outcome:

- Identification, development, and viability evaluation of one or more export-focused innovations.
- Early stage scalability and TEA analysis and lab testing.
- Improved viability assessment of PCS.

Continue to Monitor and Assess Emerging PCS Pathways

Finding: Several PCS ideas, such as artificial upwelling and light-based stimulation, are at low levels of technology readiness and lack strong foundational knowledge needed to estimate CDR viability or identify and characterize their socio-economic and environmental risks.

Recommendation: Monitor emerging PCS ideas and pathways, and use the stage-gate framework to evaluate their progress for future funding consideration.

Outcome:

- Ongoing monitoring of emerging PCS innovations.
- Consideration of emerging PCS pathways and promotion of the stage-gate framework.
- Efficient use of limited RD&D funding.

Engagement and Decision-making

In addition to the eight major findings and recommendations, the report provides three specific recommendations for future implementation of the proposed activities (Table 1).

Co-design Research to Inform Decision Making

Finding: Co-designing PCS research with non-academic partners is essential to generate knowledge relevant for decision-making. Identifying relevant partners and affected communities for PCS can be challenging due the remote nature and potential far reaching impact areas of high seas interventions. Transparent engagement, clear framing of potential impacts and probabilities of impacts, and upfront consideration of containability, reversibility, and risk–benefit trade-offs are critical aspects of co-designed research.

Recommendation: Prioritize collaboration with local and potentially affected communities and other interested actors in PCS investigations, particularly that involve field components. Adopt existing research codes of conducts and best practices for mCDR RD&D to effectively engage relevant non-academic and local communities early to improve the utility of research outcomes to inform decisions (Box 8). Develop and be guided by an international advisory board with diverse geographic and scientific perspectives. The advisory board should be active in establishing grant-making priorities, ongoing progress evaluation, and future program direction.

Enable Coastal Communities and Fisheries Engagement

Finding: Coastal communities and fisheries industry leaders are often at the front lines of both risk and potential benefit from mCDR. Successful initiatives must specifically build fisheries and coastal community capacity to engage early and effectively on PCS proposals and enable co-design of PCS research.

Recommendation: Build international fisheries and coastal community capacity to engage early and effectively on PCS proposals and enable co-design of PCS research and development. Enhance fishing industry and community understanding of risks and co-benefits of PCS and develop mechanisms and best practices for the community to engage with and co-design place-based research. Further seek out and integrate scientific priorities and concerns raised by affected communities, including academia, fishing industries, high seas authorities, governments, coastal and Indigenous communities, and ocean conservation groups.

Ensure Consideration of PCS Impacts Against Alternative Actions

Finding: Environmental and socio-economic risks and co-benefits of any CDR, including PCS, must be understood in the context of alternative scenarios, such as "no-action" and other CDR pathways.

Recommendation: Collaborate actively with other CDR and mCDR entities to increase efficiencies across shared investigations and maximize future comparative capacities.

Box 8. Program best practices to follow:

- American Geophysical Union's Ethical Framework for Climate Intervention
- Aspen Institute's Code of Conduct for mCDR Research
- Community engagement best practices (the United Nations' Free, Prior and Informed Consent Manual; University of Delaware's Developing Best Practices for Community Engagement in Marine Carbon Dioxide Removal Research; National Wildlife Federation's Informing mCDR Projects: Best Practices Guidance for Tribal and Indigenous Engagement; Sabin Center for Climate Change Law, Columbia Law School's Expert Insights on Best Practices for Community Benefits Agreements)
- Other best practice guidance for CDR research (Carbon Business Council's Carbon Dioxide Removal Responsible Deployment Trainings; Carbon180's Lessons from the Field: Conversations on Resident-Centered CDR Deployment

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Operational Recommendations

Essential program operation responsibilities should include:

- Program manager(s) who oversee and coordinate grantee progress and collaboration, lead inclusive decision-making processes on follow-up grants, and execute required monitoring activities.
- Communication leadership to represent the PCS program and coordinate communications with partner organizations.
- Participation in policy leadership to monitor and engage existing international decision-making efforts, scope governance priorities, and inform effective policy frameworks.
- Transparent and efficient financial administration to make grants, report to funders, and maintain ongoing grantee partnerships.
- Flexible and efficient grantmaking capacity (small and large grants).
- Flexibility to strategically pivot with emerging science and societal priorities.

Progress monitoring of PCS research and activities:

- Maintain an outcome-agnostic posture, and be prepared to end specific or overarching inquiries in response to findings and/or socio-economic conditions.
- Adopt practices that place primacy on scientific credibility and independence. Adhere to peer review processes and remain committed to collaborative, transparent, and open access to knowledge and data.
- Monitor for emergence of new PCS pathways, opportunistic field campaigns, and other CDR projects to leverage the advancement of PCS knowledge.
- Engage, track progress of, and coordinate with the broader CDR field and adapt to relevant changes in CDR markets, CDR policy landscape, and comparative advancements in other CDR pathways.
- Coordinate with a (growing) PCS funder and expert network community.

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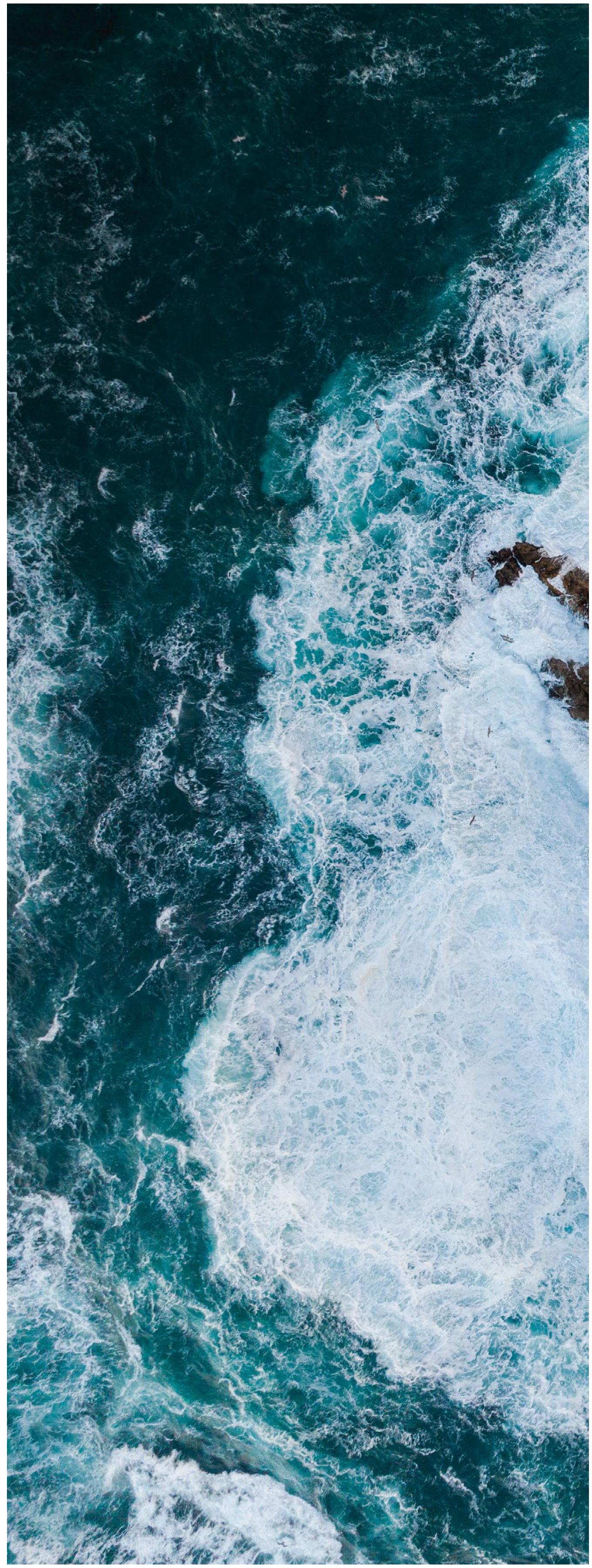

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Appendices

Appendix A: Acknowledgements

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Appendix B: Assessment of PCS Pathways

The two tables below describe PCS pathways. Built on the framework used in the 2022 NASEM Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration, the tables provide a qualitative overview of theoretical scalability (of CDR potential), technological readiness, durability, cost, environmental risks, and social risks of each pathway. Given the limited scientific knowledge and data gaps, the assessments provided for each criterion represent the project team's best current estimates based on available evidence.

Table A1. Production-based PCS pathways. This table summarizes the current state of knowledge approaches that aim to enhance primary production. These methods — including ocean iron fertilization in high nutrient, low chlorophyll (HNLC) regions, nitrogen-fixation-based iron fertilization in low nutrient, low chlorophyll (LNLC) regions, macronutrient fertilization, artificial upwelling, and light stimulation — represent a spectrum of interventions aimed at increasing primary productivity and phytoplankton growth. While some, such as OIF in HNLC regions, have undergone limited field trials1–4, others remain largely conceptual or untested at scale[5,6]. There are other proposed or developing approaches, such as light-based stimulation, that are still further away from scientific publication and have therefore not been included in this table.

Criteria	Ocean iron fertilization (HNLC)	Nitrogen-fixation-based iron fertilization (LNLC)	Macronutrient fertilization	Artificial Upwelling
Description	Adding iron to High Nutrient, Low Chlorophyll (HNLC) regions to stimulate phytoplankton growth.	Adding iron to stimulate nitrogen-fixing in Low Nutrient, Low Chlorophyll (LNLC) areas.	Adding nutrients like phosphorous [P], nitrogen [N], and silica [Si] to fertilize phytoplankton.	Mechanically bringing nutrient-rich deep water to the surface.
Theoretical scalability	**High** 2–4 $GtCO_2e$ per year[1–4]	**Medium** 1.5 $GtCO_2e$ per year[6]	**Medium** 0.9 $GtCO_2e$ per year sequestration[7]	**Low** 0.05 $GtCO_2e$ per year[5]
Durability	**Low** There is currently low certainty that a durability of 100+ years is achievable and quantifiable[8]. Export efficiency is highly variable.			
Technological readiness	**Medium** OIF has only been tested in field trials, but viability at commercial scales is yet to be tested[8].	**Low** OIF in LNLC regions is still in the early stages of conceptual design and experimentation[8].	**Low** There have only been a small number of field trials using nitrogen[9], and no documented open-ocean trials for phosphorus-based fertilization.	**Low** Various technologies have been demonstrated for artificial upwelling in coastal regimes for short durations, but none have remained functional or scalable due to high energy input and engineering constraints[10,11].

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Criteria	Ocean iron fertilization (HNLC)	Nitrogen-fixation-based iron fertilization (LNLC)	Macronutrient fertilization	Artificial Upwelling
Cost	**Low** Cost estimates are as low as 10 to 25 USD per tonne of CO_2, and as high as 53,000 USD[12,13]. Export efficiency is the biggest cost driver.	**Unknown** Costs may potentially be similar to OIF in HNLC regions.	**Medium** Estimated at 20 USD per tonne CO_2[14]. However, N and P are costly to source and distribute.	**High** High logistical and energy input costs of installing and operating upwelling pumps[15].
Environmental risks	**Medium** These approaches boost productivity by changing the surface ocean biology, but may cause deep-ocean changes with uncertain large-scale geochemical and ecological impacts[16].			**High** In addition to altering the surface ecosystem, upwelling also affects the ocean's density field and sea surface temperature due to the surfacing of deeper colder water[15].
Social risks	**High** There is a high potential for international legal and governance concerns, given the risk of negative environmental impacts and divisive history. These environmental impacts can also affect fisheries and other economic activities.			**High** There is a risk of marine debris and conflicts with other ocean uses (shipping, marine protected areas, fishing, recreation).
Applicable geographies	Southern Ocean Equatorial Pacific Ocean Subarctic North Pacific Ocean	Tropical oligotrophic gyres	Tropical and subtropical oligotropic gyres	Subtropical gyres Southern ocean

Table A2: Export-based PCS pathways. This table provides an overview of two emerging approaches — flocculation and ballasting — that focus on enhancing the export of organic matter to deeper ocean layers. While flocculation has seen some application in managing harmful algal blooms in freshwater systems, neither approach has been demonstrated for large-scale, long-term carbon removal in the open ocean. However, both approaches have been theorized to be applicable to mCDR and could be applied in combination with OIF and other production-oriented approaches to improve the efficiency of export17–21. Since enhancing export efficiency is an emerging area of focus, flocculation and ballasting are currently the only sufficiently documented approaches to be assessed using this framework.

Criteria	Flocculation	Ballasting
Description	Adding clay particles to bind algal biomass and cause rapid sinking[21].	Using nutrient-rich particles to enhance the aggregation and sinking of phytoplankton[17,19].
Technological readiness	**Low** While clay flocculation has been tested in applications for managing HABs in freshwater and mesocosm systems, it is yet to be tested for efficiency in facilitating export of phytoplankton in the open ocean[20].	**Low** The only testing has been conducted in lab settings[17].

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Criteria	Flocculation	Ballasting
Durability	**Medium** Carbon storage is likely temporary and shallow in coastal areas, where clay flocculation may be applicable[21].	**Unknown** Unknown durability of the resulting sequestration.
Cost	**Low-medium** Materials (clay) are somewhat inexpensive and widely available, potentially reducing transportation[22].	**Medium** May be costly to manufacture and distribute particles at scale.
Environmental risks	**Medium** Given the density of flocculated biomass, it can smother benthic communities or affect water chemistry[20,23].	**Unknown** Environmental risks (e.g., substrate degradation, unintended toxicity) are still unknown.
Social risks	**Unknown** Deployment in coastal regions could potentially affect fisheries, tourism, and local economies, but targeting harmful algal blooms could gain social support by mitigating these impacts[20,24].	**Unknown** The experiments are too early to know the potential implications on social risks. However, since it can be applied in combination with OIF, the corresponding social risks may apply.

Appendix C: Landscape of PCS projects

The following table provides an overview of (non-exhaustive) PCS-related projects and initiatives. It includes (31) academic research efforts, and (8) non-academic initiatives driven by both, non-governmental organizations (NGOs) and private companies. It summarizes each project's type, category, description, geographic focus, and timeline, highlighting efforts ranging from observational and modeling programs (e.g., SOCCOM, BIOPOLE, GEOTRACES) to targeted field campaigns (e.g., PICCOLO, SOLACE) and PCS pathway development (e.g., ExOIS, Oceanry).

Table A3. A summary of academic research efforts. This report surveys (30) academic research efforts, (16) of which focus on understanding the BCP, and (8) are efforts modeling ocean biogeochemical processes, and (5) study the early development of specific PCS pathways. A majority of these efforts are global in scope, although some target specific oceanographic regions.

Project	Description	Timeline	Geography
Biological carbon pump (BCP) studies			
NORCE Reconstructing the biological carbon pump with ancient plankton DNA (BIOCAP) (Norway)	BIOCAP reconstructs past functioning of the BCP by analyzing ancient plankton DNA preserved in marine sediments. This approach enables the study of past plankton communities and their role in carbon export over millennia, providing insights into how climate variability influenced BCP efficiency. The project aims to inform future projections of ocean carbon sequestration by understanding historical responses to environmental changes.	2024 - current	North Atlantic; Nordic Seas
Global ONCE; ONCE (China)	Global ONCE is an international initiative led by Xiamen University, focusing on enhancing mCDR through the BCP. The program investigates microbial processes that convert dissolved organic carbon into recalcitrant forms, facilitating long-term carbon storage in the ocean. Research includes developing eco-engineering strategies, such as artificial upwelling and microbial-induced carbonate precipitation, to amplify carbon sequestration while mitigating environmental stressors	2023 - current	Global

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Project	Description	Timeline	Geography
APERO (France)	The APERO campaign aims to study the BCP with particular attention to the mesopelagic zone in the area of the Porcupine Abyssal Plain in the North Atlantic. The ultimate scientific objective of APERO is to reconcile estimates of the quantity of CO particulate matter produced by photosynthesis leaving the ocean surface (export) with the biological carbon demand in the mesopelagic zone.	2023 - current	North Atlantic
OceanICU, Horizon Europe	OceanICU is a five-year project that investigates the BCP and how activities like fishing, mining, and energy extraction influence it, particularly in terms of carbon export and ocean carbon storage. OceanICU conducted research cruises in 2023 and 2024 to measure key biological and industrial processes and embed them into models to improve predictions of the ocean carbon sink and resolve discrepancies between observed and modeled carbon uptake.	2022 - current	Eastern Atlantic; Southern Ocean; Arctic
Bio-Carbon (UK)	Bio-Carbon models key processes within the BCP to better predict how ocean carbon storage will change under future conditions. Their work focuses on three main components: calcium carbonate dynamics (coccolithophore-driven alkalinity changes), phytoplankton-driven primary production, and depth-dependent respiration and remineralization of organic carbon.	2022 - current	North Atlantic
BIOPOLE (UK)	BIOPOLE models how nutrient delivery and processing in polar ecosystems regulate primary productivity and carbon export. Their model is driven by inputs from sea ice, glaciers, and water-mass transport. It integrates observations, experiments, and computer simulations to improve the representation of how polar nutrient supply, ecosystem function, and carbon export may shift under climate change.	2022 - current	Arctic; Southern Ocean
Biological Pump and Carbon Exchange Processes (BICEP) (UK)	BICEP aims to enhance understanding of the BCP by developing a comprehensive, satellite-based characterization of its pools and fluxes. The project integrates remote sensing data, in-situ measurements, and Earth system models to quantify how carbon is transferred from the surface to the deep ocean, and how these processes vary spatially and temporally. Key outcomes of BICEP include the creation of high-resolution datasets that map particulate organic carbon (POC) concentrations globally from 1997 to 2020.	2020 - current	Global
Southern Ocean Large Areal Carbon Export (SOLACE) (Australia)	SOLACE is a multidisciplinary research initiative employing particle decomposition measurements, zooplankton sampling, bio-acoustics, and camera systems to investigate how the BCP functions in the Southern Ocean. Its primary goal is to quantify vertical carbon export processes and validate remote sensing proxies for biogeochemical fluxes.	2020 - current	Southern Ocean
Processes Influencing Carbon Cycling: Observations of the Lower limb of the Antarctic Overturning (PICCOLO) (UK)	PICCOLO aims to quantify how carbon in surface Southern Ocean waters is transformed and exported. Using tools such as autonomous gliders, floats, moorings (including year-round deployments), and animal-borne sensors (e.g., on seals), the project collected biogeochemical and physical data from the Weddell Sea to enhance model representation of carbon uptake, export, and overturning circulation in the Antarctic	2017 - current	Southern Ocean
Simons Collaboration on Ocean Processes and Ecology (SCOPE) (US)	SCOPE conducts in-depth research on the BCP at Station ALOHA in the North Pacific Subtropical Gyre. The collaboration focused on understanding microbial community dynamics, nutrient cycling, and carbon export processes, aiming to elucidate how microbial interactions and environmental factors influence the efficiency of the BCP.	2014 - current	Global
Ocean Carbon and Biogeochemistry (OCB) (US)	The Ocean Carbon and Biogeochemistry group is a consortium of scientists researching the BCP, which aims to develop a knowledge hub and organize workshops and other collaborative efforts to advance interdisciplinary research on the BCP.	2006 - current	Global

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Project	Description	Timeline	Geography
Center for Microbial Oceanography: Research and Education (C-MORE) (US)	C-MORE studies how marine microorganisms influence the BCP, particularly in the North Pacific Subtropical Gyre. Using long-term programs like the Hawaii Ocean Time-series, they investigate microbial community dynamics, nutrient cycling, and carbon export processes. C-MORE also develops innovative sensors and instruments to better measure microbial activity and its impact on ocean carbon sequestration.	2006 - current	Global
NASA's Ocean Biology Processing Group (OBPG) (US)	OBPG develops algorithms and processes satellite data to monitor ocean color,indicative of phytoplankton concentrations. The program provides data products for research and monitoring chlorophyll-a, sea surface temperature, particulate organic and inorganic carbon, and photosynthetically available radiation.	1996 - current	Global
EXport Processes in the Ocean from Remote Sensing (EXPORTS) (US)	EXPORTS aimed to develop a predictive understanding of the export and fate of primary production and its implications for the carbon cycle. Results demonstrated key relationships between ecological, biogeochemical, and physical processes that govern carbon export efficiency, providing improved satellite-based diagnostics and model parameterizations to better predict ocean carbon cycling.	2017 - 2022	Global
VAriability of vertical and tropHIc transfer of diazotroph derived N in the south wEst Pacific (VAHINE) (France)	VAHINE investigated how nitrogen fixed by diazotrophs in the South West Pacific is transferred vertically through the water column and horizontally through food webs, influencing carbon and nutrient cycling. The project combined in situ experiments, sediment traps, and biogeochemical measurements to quantify the efficiency of nitrogen transfer from microbes to higher trophic levels and into sinking organic matter. These insights improve models of nitrogen-driven primary production and carbon export in oligotrophic tropical ocean regions.	2012 - 2015	Southwest Pacific
Controls over Ocean Mesopelagic Interior Carbon Storage (COMICS) (UK)	COMICS was a five-year collaborative research project that aimed to quantify the flow of carbon in the mesopelagic zone, with a specific focus on the role of copepods and mesopelagic fish in biogeochemical models in carbon storage. The project conducted two research cruises in the tropical Atlantic and Southern Ocean, and key findings highlighted that the efficiency of carbon storage is influenced by factors like upper-ocean ecological interactions, dissolved oxygen concentrations, and temperature.	2010 - 2015	Global
Modeling systems and MRV efforts			
SEAO2-CDR (EU)	SEAO_2-CDR is a Horizon Europe-funded project that evaluates mCDR techniques, focusing on their environmental, social, and economic viability. The project aims to develop robust MRV strategies using Earth system models and autonomous sensors. SEAO_2-CDR also has a stated goal to establish governance frameworks and policy pathways to facilitate the responsible implementation of ocean CDR approaches at scale.	2023 - current	EU
[c]worthy (US)	[C]Worthy is a research organization working to focus on advancing mCDR quantification through open-source software and data integration tools. Their primary project, C-Star (Computational Systems for Tracking Ocean Carbon), develops models and analytics to quantify and verify the effectiveness of ocean-based carbon removal strategies.	2023 - current	Global
Coast Predict (Global)	CoastPredict is a collaborative initiative under the Global Ocean Observing System (GOOS) focused on observing and predicting conditions in coastal regions. CoastPredict can help monitor blooms, predict shifts in productivity, and support ecosystem management.	2021 - current	Global

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Project	Description	Timeline	Geography
GEOTRACES (France)	GEOTRACES is an international research program that maps the global distribution of trace elements and isotopes in the ocean to understand their sources, sinks, and role in marine biogeochemical cycles. The integration of GEOTRACES data into biogeochemical models has enhanced understanding of the sources, sinks, and internal cycling processes of trace elements and isotopes.	2003 - current	Global
Global Ocean Data Analysis Project (GLODAP) (Norway)	GLODAP compiles high-quality, global ocean biogeochemical data, including seawater inorganic carbon, nutrients, oxygen, and tracers, from over 1.4 million samples across 1,108 cruises. The dataset provides both raw and bias-adjusted merged products for consistent analysis.	2004 - current	Global
OceanSITES	OceanSITES is a global network of long-term open-ocean reference stations that collect sustained time series of physical, biogeochemical, and meteorological data. Coordinated under the Global Ocean Observing System (GOOS), it provides continuous observations across key regions to support climate research, forecasting, and satellite data validation.	2003 - current	Global
Surface Ocean CO_2 Atlas (SOCAT) (Germany)	SOCAT is a global compilation of quality-controlled surface ocean CO_2 measurements, spanning from 1957 to 2024 with over 50 million data points. The dataset provides gridded monthly and annual products at high spatial resolution.	2011 - current	Global
Biogeochemical Argo (BCG-Argo) (Global)	The BCG-Argo Program is an international effort that expands on the Argo array of autonomous profiling floats by equipping them with sensors that measure key biogeochemical variables in the ocean, such as oxygen, pH, nitrate, chlorophyll, suspended particles, and downwelling irradiance. These floats provide high-resolution, year-round observations from the surface to the deep ocean, filling critical gaps left by ship-based sampling and satellites.	2007 - current	Global
Surface Ocean - Lower Atmosphere Study (SOLAS) (China)	SOLAS is an international program investigating interactions and feedbacks between the ocean and atmosphere. It focuses on greenhouse gas exchange, air-sea fluxes, atmospheric deposition, aerosols, and oceanic influence on atmospheric chemistry.	2004 - current	Global
Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) (US)	The SOCCOM project employs a network of 260 biogeochemical Argo floats equipped with sensors for pH, oxygen, nitrate, chlorophyll, and others, to collect continuous data from surface to 2,000 meters depth across the Southern Ocean.	2014 - current	Southern Ocean
Studying and testing PCS pathways			
ExOIS, Woods Hole Oceanographic Institution (WHOI) (US)	The Exploring Ocean Iron Solutions (ExOIS) is an international consortium of scientists, housed at WHOI. The group investigates the feasibility, impacts, and governance of ocean iron fertilization.The group is planning a field trial to raise awareness, demonstrate OIF feasibility, study patch formation, and assess local impacts using advanced monitoring and modeling tools.	2022 - current	Northeast Pacific
Test ArtUp (GEOMAR) (Germany)	Test-ArtUp was a research initiative under the CDRmare program that evaluated artificial upwelling to enhance ocean carbon sequestration. The project conducted mesocosm experiments, field trials, and biogeochemical modeling to assess feasibility, ecological impacts, and CO_2 removal potential. It concluded that while artificial upwelling could stimulate primary production, its long-term effectiveness for carbon sequestration was limited, providing key insights for future mCDR strategies.	2021 - 2024	Subtropical North Atlantic

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Project	Description	Timeline	Geography
Air-lift (Zheijang University) (China)	Air-lift (Zhejiang University, China) focused on enhancing ocean carbon sequestration through artificial upwelling technology. This approach utilized air-lift pumps to transport nutrient-rich deep water to the euphotic zone, promoting phytoplankton growth and increasing biological carbon export. The research included optimizing energy efficiency using renewable sources and developing intelligent control systems to adjust operational parameters based on environmental conditions. The project conducted field trials in Qiandao Lake and the East China Sea.	2017- 2020	China
Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) (Korea)	KIFES was a proposed OIF field trial in the Southern Ocean. This field trial was, ultimately, not implemented.	2016	Southern Ocean

Table A4: A summary of non-academic efforts (including NGOs and private companies). This table summarizes the non-academic efforts to further PCS pathways and research. Many of these organizations focus primarily on awareness and coalition building to further collaboration on PCS and mCDR research more broadly. Some of the private companies included below are also testing the development of PCS technologies or applications.

Project	Description	Timeline	Geography
Ocience (Finland)	Ocience aims to stimulate phytoplankton blooms by strengthening their natural photosynthetic capabilities. Ocience's methodology is undisclosed, but claims to leverage the role of plankton in producing oxygen, generating cloud-nucleating aerosols, and contributing to long-term carbon sequestration through marine snow formation.	2024 - current	Finland
Oceanry (Finland)	Oceanry focuses on advancing research into the climate and biodiversity impacts of OIF. The project aims to increase awareness, promote research, and support the development of regulations and standards for OIF as a potential large-scale carbon sequestration method.	2024 - current	North Atlantic
Positive Polar (US)	Positive Polar intends to combine commercial polar expeditions and using their expedition vessels to conduct OIF research and spread awareness,although specific research objectives and activities conducted via the vessels is unclear.	2022 - current	Arctic
GigaBlue (New Zealand)	GigaBlue is an mCDR startup developing floating substrates intended to fertilize phytoplankton and provide structure for biomass aggregation for carbon export. They have conducted some field experiments in New Zealand's waters at mesocosm scales.	2023 - current	Southern Ocean
Puro Earth (Finland)	Puro.earth is a carbon removal crediting platform that certifies durable carbon removal and issues CO_2 Removal Certificates (CORCs) for each net tonne of CO_2 removed and stored for hundreds or thousands of years. Puro CORCs are issued and retired in the public Puro Registry, enhancing transparency in carbon markets.	2017 - current	Global
Ecopia (UK)	Ecopia Marine Limited (EML) is an mCDR startup that is developing a method called Tele-illumination to promote phytoplankton growth. Their light-emitting floating and submerged platforms, known as ECOPINs, stimulate the growth of phytoplankton by introducing light in aphotic regions of the ocean.	2015 - current	North Atlantic

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