Phytoplankton Carbon Solutions

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

OCEAN VISIONS

Front Matter

Project Team

The Phytoplankton Carbon Solutions Prioritized Research Framework (hereinafter the Phytoplankton Carbon Solutions Research Framework or PCS Research Framework) is a product of Ocean Visions in collaboration with CEA Consulting, 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 many experts whose time, perspectives, and constructive feedback informed the recommendations presented in this report. This includes insights gained from 67 participants in a workshop held during the 2025 Ocean Visions Biennial Summit in Vancouver, Canada, dozens of experts interviewed by the project team, and 56 individuals who provided comments on the draft report (Appendix A: Acknowledgements).

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Abbreviations

ASMASYS	Unified Assessment Framework for marine Carbon Dioxide Removal
BCP	Biological carbon pump
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
ExOIS	Exploring Ocean Iron Solutions
$GtCO_2$	Gigaton
HNLC	High nutrient, low chlorophyll
LC/LP	London Convention and London Protocol
LNLC	Low nutrient, low chlorophyll
mCDR	Marine carbon dioxide removal
MRV	Measurement, reporting, and verification
NASEM	National Academy of Sciences, Engineering, and Medicine
ORCA	Ocean Resilience and Climate Alliance
PCS	Phytoplankton carbon solutions
POC	Particulate organic carbon
RD&D	Research, development, and demonstration
TEA	Techno-economic assessment
USD	United States Dollar

Executive Summary

About this report

This report was commissioned to (1) assess the current state of knowledge and activities for open ocean phytoplankton[i]-based carbon removal approaches (including ocean iron fertilization), (2) identify remaining critical uncertainties and knowledge gaps about their efficacy and safety, and (3) suggest key actions and research priorities to close knowledge gaps to facilitate future decision making.

The findings and recommendations are based on a combination of literature and white paper reviews, workshops, and numerous expert consultations. The work was guided by an international Advisory Board. A draft report was made available for open public comment in October 2025, and public feedback was integrated into this final report.

Background

In addition to dramatic emissions reductions, carbon dioxide removal (CDR) is a critical element of the toolkit needed to achieve the Paris Agreement goal of net zero carbon dioxide (CO_2) emissions. To date, investment in CDR has largely focused on terrestrial approaches, such as afforestation and soil carbon management, as well technologies such as direct air capture. Until very recently, far less attention has been directed to ocean-based pathways. Yet ocean-based pathways, commonly referred to as marine CDR (mCDR), hold great promise for efficient and durable carbon sequestration due to the size of the ocean and its natural carbon sequestering capacity. Increasing research investments into promising mCDR pathways is critical to prepare for science-informed societal decisions on a global CDR portfolio.

Marine CDR pathways include approaches that change ocean chemistry to enhance carbon sequestration, and approaches that enhance biological productivity to enhance carbon uptake. The latter include a range of strategies that would leverage the ocean's biological carbon pump (BCP), whereby phytoplankton remove CO_2 dissolved in surface waters – thereby enhancing CO_2 transfer from the atmosphere into the surface ocean – and a portion of the organic matter sinks and is sequestered in the deep ocean. Marine CDR pathways that leverage the BCP are here defined as **Phytoplankton Carbon Solutions** (PCS), which include, most notably, iron fertilization, but also other pathways by which phytoplankton could play a greater role in CDR.

PCS are a priority for further investigation due to the theoretical scalability and, in the case of iron fertilization, the potential cost effectiveness associated with low input requirements. Iron fertilization is currently the most advanced PCS pathway given the knowledge base developed through over a dozen field trials and decades of research. Other PCS approaches appear to have potential but have had few or no field trials to determine efficacy or scalability.

For all PCS approaches, many unanswered questions remain about both the full CDR benefit and associated environmental and social risks and benefits. These knowledge gaps must be

i Phytoplankton are microscopic, mostly single-celled photosynthetic organisms that float or drift in the sunlit surface layers of oceans. They use sunlight, carbon dioxide, and nutrients to produce their structure - organic matter.

filled before society can make informed decisions about future implementation. This PCS Research Framework presents a strategic prioritization of needed research, development, and demonstration (RD&D) activities.

Based on current scientific understanding of risks and uncertainties associated with any activities that alter the BCP, this PCS Research Framework recommends that research be prioritized for those specific PCS pathways that have the potential to achieve climate-relevant scales, often thought of as at least a gigaton of CDR per year. This threshold could be reduced as research identifies ways to better assess or reduce risks associated with PCS.

Report Structure

The report is organized into four sections. The first section provides a project overview and explains the basis for continued exploration of PCS. The second section discusses the scope of PCS pathways to be investigated and relevant research methods and potential RD&D activities. The third section introduces the **PCS Research Framework** components. These include priority research topics, a stage-gate approach to guide and evaluate RD&D in support of funding decisions, cost considerations, and key assumptions. The final section presents a prioritized set of recommendations in the form of an **RD&D Action Plan**, which outlines research priorities and activities and includes a recommendation for a dedicated **PCS RD&D Program** to advance the RD&D Action Plan and to ensure further progress on recommended actions.

An overview of these recommendations follows here. Greater detail on each of these recommendations can be found in the full report.

PCS RD&D Action Plan

PCS RD&D Action Plan recommendations are grouped into three themes: (1) Overarching Priorities, (2) PCS Pathway-specific Priorities, and (3) Implementation Priorities. There are a number of linkages, overlaps, and potential synergies among the recommendations. The final recommendation to create a PCS RD&D Program is to ensure coordinated progression of all the research recommendations within the PCS Research Framework.

I. Overarching Priorities

Overarching priorities address questions and issues applicable to all PCS pathways. Progress in these areas will efficiently address shared PCS questions and create framing and context for pathway-specific investigations.

There are four overarching priorities:

1. Reduce Uncertainty on Net Carbon Dioxide Removal

- **Findings:** There is substantial uncertainty related to the additionality and durability of CDR, and the ultimate scalability, across all PCS pathways. Quantifying and classifying the sources of uncertainty is a critical first step to then take the actions needed to reduce uncertainties to levels that support decision making. Failure to prove and measure the additionality and durability of CDR associated with a PCS pathway will render the pathway non-viable. There is also a lack of consensus on the most appropriate sequencing of model-based and field-based research approaches to address critical uncertainties.
- **Recommendations:** Identify the most important sources of uncertainty for each priority PCS pathway and the effects of this uncertainty on estimates of CDR. Establish clear targets for reducing uncertainty and initiate the research activities needed to reduce these uncertainties to their targets.

2. Improve Utility of Ocean Biogeochemical Models

- **Findings:** The long-term environmental impacts and additionality effects associated with gigaton-scale CDR by PCS will be challenging to identify and measure through field observations alone. Yet these effects are critical to informing risk-benefit decisions and confirming CDR additionality. Models, in conjunction with field observations, are essential to help resolve critical uncertainties about local and far-reaching environmental effects over different time horizons, and to determine CDR additionality. Current models lack consensus on PCS potential, and improved representation of biological processes is necessary. Advances in modeling may offer new opportunities to help address these critical needs.
- **Recommendations:** Initiate a model improvement program with model intercomparisons and scenario development, identification and prioritization of data input improvements (including biological inputs), and assessments of potential for model innovations, including the use of artificial intelligence.

3. Improve Understanding of the Ocean's Biological Carbon Pump

- **Findings:** PCS assessments must be grounded in an accurate understanding of the current and future state of the BCP, including mesopelagic processes, and other key indicators of ocean health. Ocean warming and acidification will continue to affect the BCP and overall ocean health, and a better understanding of these dynamic conditions will be needed to define the shifting baseline against which to measure impacts of PCS.
- **Recommendations:** Incorporate learnings from ongoing studies of the BCP, including research of natural phytoplankton conditions, targeted study of regional productivity shifts, studies of multi-trophic dynamics, and natural analogs of PCS pathways to increase PCS-relevant knowledge. Ensure knowledge integration to better characterize BCP baseline conditions and predictions to evaluate PCS interventions against 'business as usual' ocean health conditions.

4. Identify and Advance High Impact Field Trials

- **Findings:** There is a strong consensus among experts in the field that large-scale field trials are an essential step in assessing PCS viability. Field trials, however, are expensive to execute and require substantial regulatory compliance and community engagement work.
  Identification of high-impact field trials should be a top priority for the proposed RD&D program. Objectives to consider when selecting trials include whether they: substantially reduce or resolve critical uncertainties around PCS pathways; improve systems of monitoring and reporting of PCS benefits; assess the widest range of environmental impacts and socio-economic concerns; leverage additional funding; and build and sustain necessary community support and regulatory approvals.
- **Recommendations:** Use competitive processes to identify field trial designs and proposals that maximize learning and reduce key uncertainties by addressing as many of the objectives (above) as possible for a given PCS pathway. Prioritize and support field trials that are designed to generate widely applicable findings in a timely and cost-effective manner; contribute to specific stage-gate criteria (see full report); can navigate regulatory processes effectively; and incorporate social engagement in field trial planning and execution.

II. PCS Pathway-specific Priorities

Alongside the overarching priorities, direct investigation of individual PCS pathways [ii] is needed to better understand pathway-specific environmental and socio-economic risks and potential co-benefits. Additionally, movement of phytoplankton-derived organic carbon into deep ocean presents a source of great uncertainty, so targeted focus on export enhancement is also prioritized.

There are four PCS Pathway-specific Priorities:

5. Sharpen Understanding of Southern Ocean Iron Fertilization Scalability Potential

- **Findings:** Numerous models and studies identify iron fertilization in the Southern Ocean as the most scalable PCS opportunity, based on available macronutrients and idealized model scenarios. Idealized scenarios, however, often do not consider the complexity of real-world environmental conditions and implementation capabilities, and they still indicate significant uncertainty on estimated CDR potential. Better understanding the feasibility to achieve gigaton-scale CDR with Southern Ocean iron fertilization is a top priority.
- **Recommendations:** Develop realistic scaling analyses and scenarios to more accurately quantify CDR potential, identify operational requirements, and inform assessments of ecological consequences of iron fertilization in the Southern Ocean. Use these findings to inform model estimates of iron fertilization and further assess PCS scalability, costs, and impacts (including impacts of nutrient robbing, associated shifts in regional fisheries productivity, changes in deep sea oxygen levels).

6. Improve Understanding of Subtropical Nitrogen Fixation–based Iron Fertilization

- **Findings:** Iron fertilization in subtropical, low nutrient, low chlorophyll (LNLC) waters has received limited research attention compared to iron fertilization in high nutrient, low chlorophyll (HNLC) waters like the Southern Ocean. Iron fertilization in LNLC waters merits further research due to its potential to trigger nitrogen fixation by specific phytoplankton species, thereby creating a new pool of nitrogen that can support larger phytoplankton blooms. The production of additional nitrogen could extend the scalability of iron fertilization from the Southern Ocean into subtropical ocean gyres, though uncertainties on export dynamics and nutrient robbing impacts due to the consumption of residual phosphorus remain.
- **Recommendations:** Support assessments of the viability and effects of subtropical nitrogen fixation-based iron fertilization through lab, model, and field-based research. Assess other macronutrient and site-based limitations to improve CDR scalability estimates. Use the proposed stage-gate approach to evaluate knowledge progression and further scaling of RD&D activities, including field trials.

7. Advance Work on Innovations that Enhance Export of Phytoplankton Carbon

- **Findings:** Innovations that enhance the export of carbon captured by phytoplankton into the deep ocean could improve overall additionality and measurability of PCS pathways and techno-economic viability. Export innovations include a range of techniques, such as enhanced sinking through flocculation by clay or reduced degradation of organic carbon by adding aluminum. Cost-effective innovations could be essential components of future PCS effectiveness but have received insufficient attention to date.
- **Recommendations:** Identify and fund early-stage development, innovation, and testing of a range of approaches to enhance export. Based on early findings, prioritize approaches for further development.

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ii Based on the current state of scientific knowledge, iron fertilization is the PCS pathway with the greatest CDR potential due potentially low material input requirements and broad geographic applicability. There are two approaches for iron fertilization, one in high nutrient waters (e.g., Southern Ocean) and a second in low nutrient waters (e.g., subtropical gyres).

8. Continue to Monitor and Assess Other Emerging PCS Pathways

- **Findings:** Several additional PCS ideas, such as macro-nutrient fertilization, artificial upwelling, and light-based stimulation of blooms are at low levels of technological readiness, lack clear theories of CDR impact, or otherwise lack strong foundational knowledge needed to estimate CDR viability or fully characterize socio-economic and environmental risks.
- **Recommendations:** Monitor emerging PCS ideas and pathways and regularly evaluate their progress for future funding consideration in accordance with the PCS Research Framework, including use of the stage-gate approach to assess pathway merit and readiness for investment.

III. Implementation Priorities

Given the potential scale, benefits, and risks of PCS, advancing the RD&D actions recommended above requires thoughtful and ethical implementation processes. This includes considerations of who should be involved in research design, execution, and decisions, and how PCS research is communicated in broader discussions of climate change and solutions. Several mCDR RD&D best practices and codes of conduct are already available to support PCS research strategies.

Implementation priorities presented here are specifically applicable to the execution of a dedicated PCS RD&D Program and may also be helpful to others pursuing work in the field.

There are four implementation priorities:

9. Prioritize Community Participation in Research Consideration and Design

- **Findings:** PCS RD&D has potentially significant implications for coastal communities and other affected groups. Research initiatives often involve those communities too late in the process. Engaging affected communities early in the research design process can generate constructive partnerships, foster inclusion of local knowledge in experimental design, build needed safeguards that satisfy local communities, and enable more effective permitting processes. While identifying relevant partners and affected communities for PCS can be challenging due to the remote nature and potential far-reaching impact areas of activities conducted on the high seas, these steps are critical to long-term success of PCS RD&D.
  Transparent engagement, clear framing of potential impacts and probabilities of impacts, and upfront consideration of containability, reversibility, and risk–benefit trade-offs are critical for productive engagement with community partners and other affected groups.
- **Recommendations:** Ensure PCS projects identify and collaborate with local and other potentially affected communities and interested parties, in line with best practices and the stage-gate approach. This recommendation is particularly important for projects that involve field-based research and, more specifically, field trials.

10. Build Targeted Capacity in Affected Coastal Communities and Fisheries

- **Findings:** Coastal communities and fisheries are at the frontlines of both risk impacts and potential benefits from ocean-based climate solutions. Yet they often lack the time and resources to effectively build capacity and engage in decision-making processes. The PCS RD&D field must be aware of the need to build capacity within fisheries and coastal communities to enable early and effectively engagement on PCS proposals and co-design of PCS research, and to inform funding and regulatory decisions.
- **Recommendations:** Ensure PCS projects invest in and support partnerships and other relevant efforts to build the capacity of adjacent fisheries and coastal communities for them to be able to engage early and effectively on PCS RD&D proposals. Seek high-leverage partnerships with fishing industry organizations and other ocean interests to enhance understanding of PCS research risks and benefits and enable sufficient participation by and potential co-design of PCS RD&D with fully capable partners. Concurrently, support development of tools and mechanisms to enhance fishing industry and community understanding of risks and co-benefits of PCS and develop model mechanisms and best practices for the community to engage with and co-design place-based research.

11. Ensure PCS Impacts Are Contextualized Relative to Alternative and No-Action Scenarios

- **Findings:** Environmental and socio-economic risks and co-benefits of any mCDR pathway, including PCS, must be understood in the context of alternative scenarios, such as "no-action" alternatives and comparatively with other CDR pathways. Further, they must be addressed in the context of climate mitigation progress. Failure to execute comparative risk analyses will undermine future societal capacity to make risk-based PCS decisions.
- **Recommendations:** Support efforts to develop, adopt, and communicate a comparative risk assessment framework for mCDR, CDR, and other climate solutions. This work is needed to effectively and objectively understand and contextualize PCS findings to establish a foundation for future decisions. Collaborate actively with other CDR and mCDR entities to increase the efficacy of this work across fields and to maximize future comparative capacities. Prioritize communication of these efforts throughout the RD&D process to build an understanding of PCS pathway potential.

12. Establish a Dedicated PCS RD&D Program

- **Findings:** Numerous PCS-relevant research efforts are underway and can contribute to the PCS RD&D Action Plan described above. Ongoing and future research would benefit from enhanced coordination across activities, greater alignment and prioritization of needed RD&D, and a concerted effort to raise additional funds to execute that work. Scaling efforts to close the key knowledge gaps will require substantial, international, multi-year research efforts with strategic coordination among academic, government, private, and philanthropic interest and resources. Additionally, given ongoing challenges in securing sufficient research funds, the field would benefit from efforts to prioritize and sequence research activities to maximize the value of funds allocated.
- **Recommendations:** The final recommendation of this report is to establish a dedicated PCS RD&D Program to coordinate and catalyze progress on the recommended actions in the PCS RD&D Action Plan. While there will be many individual actors engaged in delivering elements of this work, a central body could help to ensure coordination, synthesis, and inclusive decision-making processes.

A PCS RD&D Program would need research and implementation funds to be able to identify and support the best options to deliver against the Action Plan, apply the stage-gate approach, and adhere to other elements of PCS Research Framework. A PCS RD&D Program should also advocate for adoption of existing research codes of conducts and best practices for RD&D to effectively advance credible and responsible project implementation. Finally, PCS RD&D will require engagement across diverse regions globally. This report recommends that the PCS RD&D Program be developed and guided by an international advisory board with diverse geographic and scientific perspectives.

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Introduction

Why Phytoplankton?

Climate change is dramatically affecting the ocean, its productivity, and its biodiversity (Box 1). 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.

Immediate and drastic emissions reduction is the most important and necessary approach to mitigate climate change. Additionally, the Intergovernmental Panel on Climate Change reports that hundreds of gigatons of carbon dioxide ($GtCO_2$) must be removed from the atmosphere to limit warming below 2 degrees Celsius by the end of the century. This means removal of 6 to 10 $GtCO_2$ per year by 2050 and increasing thereafter1. Achieving this scale of carbon dioxide removal (CDR) will require immediate expansion of responsible research, development, and demonstration (RD&D) to prepare for future CDR needs. Multiple CDR pathways will be needed, and CDR pathways must be technologically scalable, economically feasible, socially desirable, and governable, with benefit and risk profiles that justify implementation over decades and can be sustained over diverse political landscapes.

Ocean-based CDR approaches, commonly referred to as marine CDR (mCDR), have the potential to remove carbon dioxide (CO_2) at the gigaton 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.[2,3]

The Phytoplankton Carbon Solutions Research Framework focuses on ocean fertilization and other related approaches, collectively referred to here as **Phytoplankton Carbon Solutions** (PCS; see Definition and Scope). PCS leverage the ocean's biological carbon pump (BCP; Box 2), via various interventions that intend to increase the ocean carbon sink by enhancing phytoplankton growth and/or export of organic carbon into the deep ocean where it remains isolated from the atmosphere for 100 to more than 1,000 years. Ocean fertilization is the most well-developed PCS pathway and works as follows:

1. Growth-limiting nutrient(s), such as iron, phosphorus, nitrogen, and/or silica, are distributed over the ocean surface and stimulate phytoplankton blooms.
2. Phytoplankton photosynthesize to produce organic carbon, thereby removing CO_2 dissolved in seawater and inducing surface waters to absorb additional CO_2 from the atmosphere.
3. A portion of the produced organic carbon sinks into the deep ocean where that carbon remains isolated from the atmosphere for 100 years or more.

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, thereby buffering the rate of global warming. 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. These include processes involving the Biological Carbon Pump (BCP) and other marine carbon pumps (i.e., Microbial Carbon Pump, Carbonate Counter Pump, and Solubility Pump).

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 and circulate nutrients is declining. These changes are disrupting aquatic habitats and altering the productivity and distribution of organisms ranging from plankton to socio-economically important fish species.

Scientists have identified CDR pathways that aim to safely enhance the role of the ocean as a carbon sink through controlled interventions meant to increase uptake of atmospheric CO_2. Some pathways aim to boost carbon capture via photosynthesis (e.g., blue carbon habitat restoration, seaweed cultivation, ocean fertilization) while others leverage seawater chemistry (e.g., direct ocean capture, ocean alkalinity enhancement). Collectively, ocean-based CDR pathways could theoretically yield gigaton-scale CDR[2].

PCS modification to the BCP could, in theory, provide global CDR benefits, but significant uncertainties, risks, and co-benefits need to be addressed with scientific research.

Over the last 35 years, ocean fertilization, specifically with the micronutrient iron, garnered significant attention following the hypothesis that in vast regions of the ocean, phytoplankton blooms are limited by iron[4], a micronutrient. A series of early scientific field trials and observations of natural iron fertilization events demonstrated and confirmed this (Box 3)[3]. The CDR potential of ocean fertilization remains largely untested, but some idealized theoretical models suggest that iron fertilization has a CDR scalability potential of 2 to 4 $GtCO_2$ per year[5]. With the limited amount of iron and energy needed to fertilize blooms (e.g., one unit of iron could potentially remove 100s to 10,000s more units of carbon from the surface ocean[3,6]) iron fertilization has the potential to be highly cost-effective. Current cost estimates, however, are wide due to several factors (including uncertainty in carbon export efficiency) and range from less than 25 to up to 53,000 United States Dollar (USD) per ton CO_2[7,8].

Fertilization with macronutrients (e.g., nitrogen, phosphorus, silica) could also generate the desired phytoplankton blooms but would require orders of magnitude greater nutrient addition to achieve the same impact as iron, thereby significantly influencing implementation costs[3]. Other PCS pathways, such as those that enhance the sinking of organic carbon, are also being explored but are at much earlier stages of study (Appendix B: Assessment of PCS Pathways).

The **feasibility** of achieving scalable CDR via PCS depends on several important factors that require additional research. These include[3]:

- Efficiencies of biological processes
- Air-sea CO_2 gas equilibration efficiency
- Rates and depths of organic carbon export from the surface to the deep ocean and remineralization of organic carbon back into CO_2 and other greenhouse gases
- Ventilation rate of deep waters containing dissolved CO_2
- Potential reduction of net CDR due to large-scale perturbation of nutrient cycles, also referred to as nutrient robbing[iii]

The societal **desirability** for PCS is challenged by a wide range of known and unknown potential environmental and socio-economic impacts. PCS entail intentional modification of large-scale, regional, or even global biological processes. Such modifications can have impacts on ocean health, biodiversity, food security, and legal rights and authorities of nations, and sociocultural values.

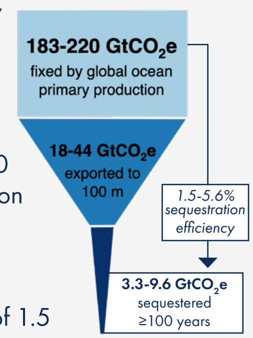
Natural ecosystem disruptions, including food web dynamics, and other environmental changes are expected to be challenging to identify, predict, and monitor[9]. Enhancing primary

Box 2. Efficiency of the ocean biological carbon pump (BCP)

The ocean BCP refers to the processes by which a portion of the organic carbon that is produced by phytoplankton through photosynthesis in the upper ocean is transported to the deep sea, where it is sequestered for centuries to millennia[14].

The BCP is an important, complex, and not yet fully constrained component of the global carbon cycle. Model representation of the BCP is far from complete, and large uncertainties remain about how much carbon flows through the BCP annually and its sensitivity to climate change[14–16]. While phytoplankton drive enormous, quantifiable, regional and seasonal variations in air-sea CO_2 flux[17], the fate of the organic carbon is more challenging to quantify as it is governed by numerous complex ecological and physical processes in deeper ocean layers[14].

The figure (right) depicts the currently understood magnitude of annual global ocean primary production[15], carbon export from the surface to 100-meter depth[15], and carbon sequestration in the deep sea for 100 years or more[18], converted into carbon units of CO_2 equivalent (CO_2e).



These data indicate a global CO_2 sequestration efficiency of the BCP of 1.5 to 5.2 percent and suggest that **achieving an additional gigaton of durable CDR annually would require a 10 to 30 percent increase in global sequestration efficiency of the BCP.** This would require a 10 to 30 percent increase in either global primary production or organic carbon that reaches durable sequestration depths, or a combination of both strategies. Given regional differences and uncertainties in ocean primary productivity, rates of carbon export, and sequestration depths[14,19], understanding where a modification to the BCP can achieve maximum and scalable climate impact is a priority.

Recent studies suggest climate change may be weakening the BCP. Trends of declining ocean primary production have emerged and linked to nutrient limitation, as warming increases stratification and reduces upwelling and the recycling of nutrients back to the surface ocean[20–22]. Consequently, global ocean carbon export is largely expected to decline over the coming decades, with some regions experiencing greater impacts than others[15].

iii Nutrient robbing occurs when artificially stimulated phytoplankton blooms (e.g., by iron fertilization) deplete other nutrients (e.g., nitrogen and phosphorus) that would otherwise be available to fuel primary production and BCP benefits in another region. Nutrient robbing can reduce the overall CDR additionality of ocean fertilization.

production could boost the bottom of the food chain, thereby supporting higher trophic levels in the near field[iv], including fish stocks[3]. Fisheries co-benefits are still unproven experimentally and the far-field impact of nutrient robbing could mean a decline in fish stocks elsewhere[10]. Other leading concerns include deep sea deoxygenation, production of greenhouse gases (nitrous oxide and methane), the potential for toxic blooms, and impacts on deep-sea benthic communities. These impacts, which can occur within, adjacent to, or far from perturbed sites, need to be better understood and considered to inform societal desirability of PCS.

It will also be critical to address governance of open ocean mCDR approaches, such as PCS, to fully account for and address mCDR risks and benefits. Notably, many concerns around PCS and governance challenges also apply to other CDR solutions[3,11–13].

Why Now?

In the last five years, the need to find scalable CDR solutions has increased significantly, bringing renewed attention to ocean-based biological pathways. Some of this attention has specifically been directed back to iron fertilization, due to its theoretical scalability, past scientific studies, and potential cost-effectiveness. Following the publication of the 2022 National Academy of Sciences, Engineering, and Medicine (NASEM) report "A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration"[3], a number of ocean fertilization research activities emerged through support from philanthropic, public, and private sector funding. Other PCS strategies have also received renewed attention.

In addition, since the last academic iron fertilization field trial in 2009, significant advances in ocean observation technology, biogeochemical models, and understanding of the BCP have been made, providing new scientific capabilities and capacities to address outstanding questions on the viability of PCS.

From 2021 to 2023, numerous organizations published mCDR roadmaps, collectively calling for RD&D attention to both abiotic and biotic mCDR. Ocean Visions published a series of mCDR roadmaps, synthesizing the state of the science, knowledge gaps, and priority research needs for a variety of CDR pathways. The Microalgae Cultivation and Carbon Sequestration roadmap includes both open-ocean approaches (i.e., PCS) and enclosed phytoplankton-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 five-year period. One of the seven ORCA pillars is focused on mCDR and is led by the Grantham Environmental Trust. These developments provide a new opportunity to rigorously assess the efficacy, measurability, and risks of and inform decisions on open-ocean, phytoplankton-based CDR approaches.

Box 3. History of ocean fertilization field experiments

Between the 1990s and early 2000s, scientists performed 15 open-ocean fertilization field experiments (13 using iron and two using phosphate) and commercial entities conducted two iron fertilization trials[23]. The scientific field experiments were relatively small in scale (0.3-4 tons of iron at a time over 25-300 km^2) and duration (10-40 days) and confirmed that the addition of limiting nutrients, specifically iron, stimulates phytoplankton blooms and CO_2 uptake from seawater[3,24].

The experiments were neither long nor large enough to comprehensively evaluate the fate of the produced organic carbon (i.e., how deep it sank, rate of remineralization back into CO_2, ventilation back to the atmosphere) and whether fertilization led to removal of atmospheric CO_2. Only one experiment focused on and detected additional carbon export into the deep sea[25]. Several studies of natural iron fertilization events provide evidence for highly effective bloom stimulation and export of carbon out of the surface ocean[6,26].

Based on these early experiments and field studies, hundreds of academic research papers were published and provide insights on potential CDR benefits and environmental impacts of ocean fertilization[3,9,27,28]. Desirability for ocean fertilization was harmed in 2012 when a commercial field trial triggered significant concerns about ineffective governance of open-ocean iron fertilization[29]. No scientific field trials have been conducted since. Consequently, uncertainties about CDR efficacy and potential environmental risks and benefits discussed over a decade ago remain today.

iv The near field is the area close to where the activity takes place and where direct effects are expected to occur. The far field refers to regions that are distant from the activity, where indirect or delayed effects could occur.

Project Overview

Contents of the Report

The PCS Research Framework is a product of an RD&D strategy design project. Building on the current state of knowledge and PCS-relevant activities, the PCS Research Framework identifies priority research topics, questions, and actionable recommendations to advance scientific research and enable science-informed decision-making on PCS pathways in the next five to ten years.

Project Methods

The project team developed the PCS Research Framework through four phases. Each phase included 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 "Unified assessment framework for proposed methods of marine CDR and interim knowledge synthesis", or ASMASYS project[v], to guide and characterize the research, which resulted in four focus areas for PCS RD&D recommendations:
    - CDR accounting and uncertainties
    - Socio-economic and environmental impacts
    - Specific PCS pathways and innovations
    - Inclusive decision making
- **Phase 3: Development, Feedback, and Revision** (March–August 2025). The project team tested focus areas and initial recommendations via a workshop at the Ocean Visions Biennial Summit wherein 67 ocean science, conservation, and industry experts participated. RD&D recommendations were further developed through numerous topic-specific expert interviews.
- **Phase 4: Public Comment & Final Recommendations** (September 2025 - January 2026).The draft report underwent a 30-day public comment period during which 56 individuals submitted feedback. The project team synthesized feedback and used the feedback to inform final revisions to PCS Research Framework.

Audience and Outcomes

The potential audience for the PCS Research Framework is broad, including national governments sponsoring RD&D, philanthropic efforts to support science and climate solutions, oceanographers, ecologists, life cycle assessment experts, engineers, and others interested in advancing PCS RD&D.

In the near-term, the PCS Research Framework recommends the establishment of a dedicated PCS RD&D program that strategically and cost-effectively coordinates and advances PCS research activities. Central to the PCS Research Framework is a stage-gate approach to, in a consistent and structured way, iteratively support evaluation of merit, efficacy, and desirability of specific PCS pathways. This approach is designed to aid funding decisions both within and beyond a dedicated PCS RD&D program.

In the long-term, the PCS Research Framework aims to strengthen the scientific basis for PCS research and funding, close critical knowledge gaps, and support inclusive, science-informed, societal decisions on whether (and under what conditions) PCS can contribute to a global CDR portfolio.

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v The ASMASYS framework is a comprehensive, transdisciplinary assessment framework for assessing the feasibility and desirability of mCDR options[30]. 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.

Landscape of Phytoplankton Carbon Solutions

Definition and Scope

The landscape assessment phase of the project began by defining the scope of **Phytoplankton Carbon Solutions (PCS)**, here defined as CDR pathways that seek to leverage open-ocean phytoplankton communities to capture and durably sequester additional atmospheric CO_2. This scope directs attention to both currently prominent ocean fertilization pathways while also enabling attention to future PCS innovations (Figure 1).

Within the mCDR pathway taxonomy (Figure 1), PCS pathways proposed to date can be divided in two categories: (1) production-based pathways, which include all ocean fertilization techniques, and (2) export-based pathways, which include additional interventions that aim to improve export efficiency. Overlap between these categories is possible. Appendix B (Assessment of PCS Pathways) lists proposed PCS pathways and the current state of knowledge on their scalability, technological readiness, efficiency and durability, cost, environmental and social risks (many of which are shared across multiple pathways), and geographic applicability.

Production-based Approaches

PCS pathways that intend to increase phytoplankton-driven primary production require either natural or enhanced gravitational sinking of the additional organic carbon to achieve durable CDR (Figure 1; Appendix B: Assessment of PCS Pathways).

Iron fertilization is applicable in ocean regions characterized by high-nutrient, low-chlorophyll (HNLC) waters and low-nutrient, low-chlorophyll (LNLC) waters, where the mention of chlorophyll refers to the photosynthesizing organisms in the region, i.e., phytoplankton. In both regions, iron fertilization alleviates the first order nutrient limitation on phytoplankton but the pathway mechanics to stimulate production differ[28]:

- **HNLC iron fertilization:** As demonstrated through past field trials and observations of natural fertilization (Box 3), the addition of iron in HNLC regions alleviates the iron limitation on phytoplankton, unlocking phytoplankton capacity to consume the available macronutrients (e.g., nitrogen and phosphorus) and bloom.

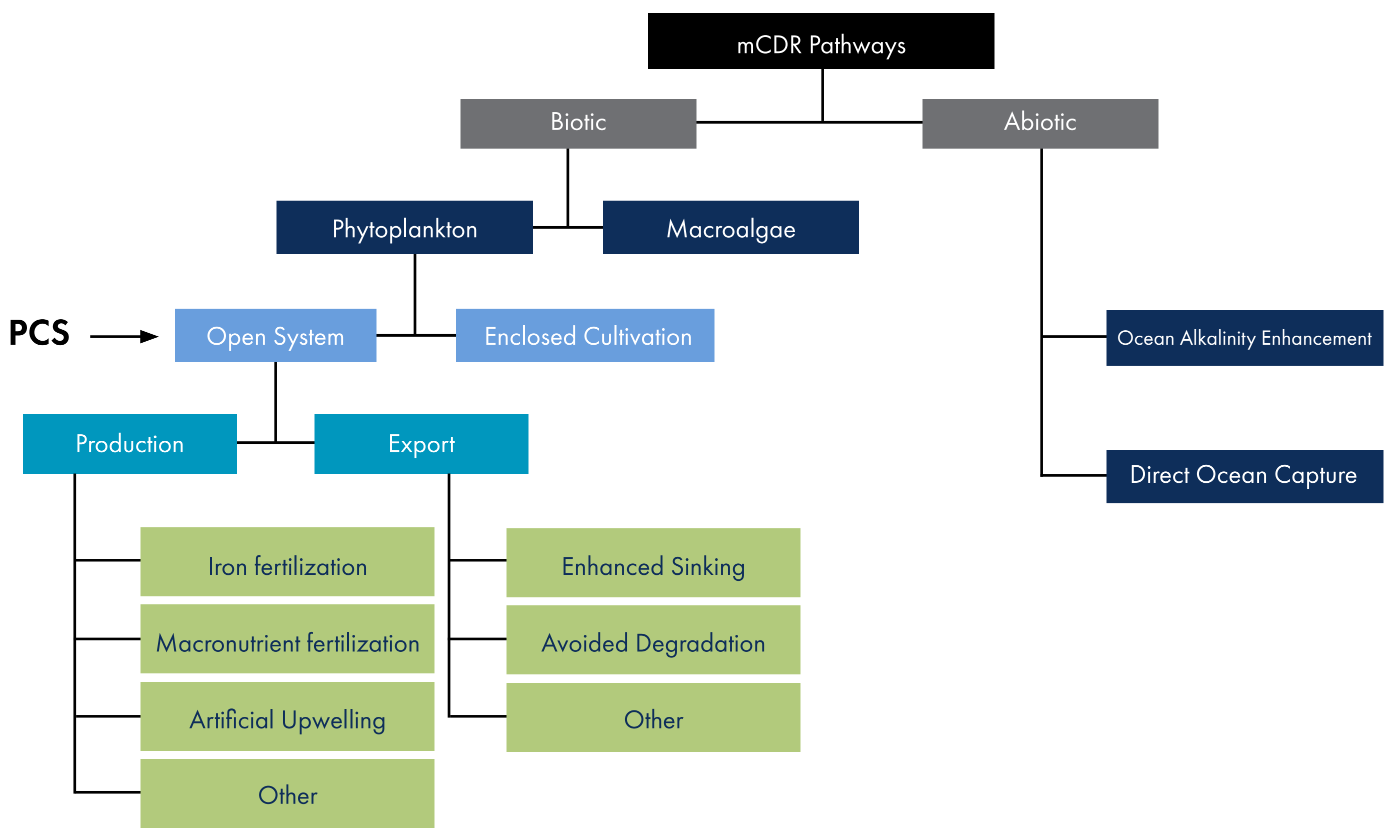

Figure 1. Placement of PCS within the mCDR pathway taxonomy

- **LNLC iron fertilization:** Based on observations of natural fertilization, iron fertilization in LNLC regions targets the proliferation of a class of phytoplankton called diazotrophs, which convert nitrogen gas (N_2) into ammonia (NH_3), thereby creating a new pool of bioavailable nitrogen that can stimulate broader phytoplankton blooms in regions with residual phosphorus.

Other production-based approaches include **macronutrient fertilization**, which involves surface addition of nitrogen, phosphorus, and/or silica; **artificial upwelling**, which involves pumping nutrient-rich water from the deep ocean to the ocean surface[3]; and **Other** approaches including potential future or untested hypotheses, such as artificial illumination in the ocean's interior (see Appendix C: Landscape of PCS projects).

For all production-based pathways, significant uncertainty remains as to the fate and durability of the carbon captured by phytoplankton in upper ocean waters and exported to the deep ocean and the environmental and societal impacts of nutrient robbing.[2] In the case of artificial illumination in the ocean's interior, additional questions remain about whether this pathway leads to additional ocean uptake of atmospheric CO_2.

Export-based Approaches

Export-based PCS 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. Enhancing export could theoretically include approaches that enhance physical sinking of organic carbon or help to avoid degradation of the organic carbon back into CO_2 (Figure 1).

Export-based approaches have been subject to limited scientific research. Examples include the use of clay particles to bind algal biomass and cause rapid sinking[31], silicates or minerals to increase diatom sinking rates[32], engineered nanoparticles to enhance export[33], and aluminum to reduce organic carbon decomposition[34]. Export-based approaches could potentially be paired with production-based approaches.

PCS in mCDR Literature

The numerous existing mCDR strategy reports collectively provided a strong foundation and starting point for designing the PCS Research Framework. These reports generally recommend further study of PCS pathways given their CDR potential, prioritize research on both the CDR potential and environmental risks, and suggest a number of research methods to be pursued (Box 4).

Most mCDR strategy reports include large-scale PCS field trials as a priority to address fundamental questions about scalability and environmental impacts. Proposed large-scale field trials are on the order of 100 to 1,000 tons of iron and on par with the scale of a fertilization event via a volcanic eruption[3]. For context, the largest scientific iron fertilization field trial conducted to date added only four tons of iron to the surface ocean. These larger scale trials are proposed to more fully test the range of export, long-term storage, and environmental impact questions not previously addressed.

Generally, high-level mCDR strategy reports to date provide limited specificity on where, when, and at what scale trials should occur to answer critical questions on CDR potential and environmental impacts and offer limited direction on how to achieve the social, financial, and governance support required for such trials. The reports also do not address scientific, technological, or socio-political factors and indicators that might signal the need to curtail or discontinue PCS RD&D.

The PCS Research Framework presented in this report builds on previous high-level recommendations with a more detailed roadmap of specific research recommendations that together will more fully answer critical PCS questions and build support for sustained research, including a path towards large-scale field trials and additional research priorities that will inform and complement field trial initiatives.

Box 4. PCS in mCDR literature

Since 2021, nine mCDR strategy reports have been published by non-governmental organizations, federal agencies, and independent scientific bodies[2,3,12,35–40]. Most reports characterize the opportunities, challenges, and potential roadmaps for RD&D across mCDR approaches. PCS pathways are often represented via the slightly narrower definition of 'ocean nutrient fertilization', including iron fertilization, macronutrient fertilization, and artificial upwelling.

The reports consistently highlight the potential scalability of ocean fertilization and collectively present a broad scalability range of 0.1 to 3 $GtCO_2$ per year[2,3,38]. The ranking of the scalability of ocean fertilization in comparison to other mCDR approaches, however, is inconsistent, reflecting large uncertainties for the true scalability of ocean fertilization and other mCDR pathways. For example, three reports list the CDR scalability as equal to or greater than that of ocean alkalinity enhancement and other electrochemical approaches[2,3,12], and one publication lists it as lower than ocean alkalinity enhancement and direct ocean removal[39].

All reports prioritize further investigation into the CDR potential and environmental safety and potential ecosystem impacts of ocean fertilization. Priority research methods identified include biogeochemical modeling, environmental impact experiments, hardware development, and field trials. In addition to these research methods, marine spatial planning was identified as a possible focus.

Research Methods

Multiple research methods can contribute to PCS and must be effectively integrated into a comprehensive PCS Research Framework[3,37–40]. Four important research methods, each with its own opportunities and limitations, are described below.

During consultations and interviews, experts rarely mentioned laboratory studies as a critical roadblock for PCS research, as they are more readily achievable than field trials. Nevertheless, laboratory studies are important for testing hypotheses, pathway mechanics, and environmental impacts, either alone or paired with other investigative methods.

Observations

Opportunity: Observing systems are a critical component of both field trials and efforts to better understand natural processes. Observing technologies are rapidly improving, significantly enhancing the power to assess near-field events, including export of particulate organic carbon (POC) into deeper ocean layers. These technological advances can be incorporated into observing system improvements and can improve model inputs and thus model accuracy and precision.

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

Multiple institutional research cruises are testing emerging observation technologies and system improvements. Investments in observing systems are the backbone of government and university research on oceanography and biogeochemistry. Several experts shared that Argo and Argo-like systems have advanced to provide extensive observational capacity across the world's ocean. Recent Argo system 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 POC export.

Limitations: Global ocean observing systems are expensive to build and operate. While they present a significant opportunity to address uncertainties in the BCP and PCS field trials and models, it is important that existing ocean observation efforts be coordinated with PCS specific research to strategically leverage targeted work intended to answer critical PCS questions. For example, current systems still lack the ability to effectively measure carbon export in ways that would inform critical PCS questions. Addressing these shortcomings is a high priority to reduce uncertainty related to PCS carbon benefits and other critical social and environmental questions, including impacts on higher trophic levels and fishing economies.

Natural Analogs

Opportunity: Natural analogs—such as seasonal phytoplankton blooms, volcanic ash deposition events, and shallow hydrothermal vents that fertilize surface waters—offer ways to study blooms, export dynamics, and potential environmental impacts without PCS interventions. 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 ocean fertilization could be leveraged for additional analyses, and government-funded 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. They share limitations in resolving far-field questions of export, durability, nutrient robbing, and socio-environmental impacts.

Critically, natural analogs cannot test specific materials that stimulate primary production, limiting their role to an intermediate step in PCS RD&D. While they provide valuable insights, they cannot substitute for controlled PCS field trials needed to validate PCS pathways and scalability. In addition, natural ecosystems may be specially adapted to natural fertilization events and sources, in which case natural analog data may not accurately reflect what would occur during an artificially triggered bloom.

Finally, some natural analog events are unpredictable by nature. Locating useful natural events and timing investigations to coincide with their occurrence can present a range of logistical and cost challenges.

Models

Opportunity: Ocean and Earth system models are critical components of PCS investigations and MRV. Models are needed to predict and parameterize CDR potential, estimate environmental risks, and design and analyze field trials. Model comparisons can be used to assess and prioritize new model inputs, parameters, and approaches to reconcile divergent CDR estimates that exist today. Advanced computing capacities and artificial intelligence present significant innovation potential. Opportunities exist to enhance oceanographic modeling efforts to better integrate the biosphere and other complex physical, chemical, and biological feedback. Building on those opportunities, model improvements, coupled with other research initiatives, potentially present cost-efficient ways to effectively estimate both near-field and far-field biological, chemical, and physical dynamics.

Limitations: While the assessment of PCS risks and benefits at climate-relevant scales will largely rely on models, significant limitations exist. Current model capabilities lack sufficient ability to assess aspects of PCS due to spatial and temporal complexity of physical, biological, and chemical conditions. Most current oceanographic models specifically lack sufficient ecosystem inputs to effectively assess biological effects in both near- and far-field conditions.

Field Trials

Opportunity: Field trials are consistently identified as an essential component of any effective mCDR RD&D Program (Box 4). Field trials provide semi-controlled, location-specific experiments that, when appropriately designed and rigorously executed, can answer priority questions about PCS baseline conditions, additionality, and environmental impacts in real-world, complex conditions that cannot be mimicked using other research methods.

They also provide proof-of-concept for planning, execution, MRV protocols, modeling, and measurement approaches to inform standard protocols for potential future PCS activities at scale. Field trials can be employed to test specific input approaches and deployment methodologies. Field trials also offer concrete opportunities for research engagement and co-design with interested and potentially affected communities.

Limitations: Field trials are location-specific, with findings constrained by contemporary local oceanographic, biological, and chemical conditions. They offer limited insight into long-term and far-field questions of durability and socio-economic and environmental impacts, unless they are part of a comprehensive RD&D plan. Field trials are costly, requiring substantial resources for scientific rigor, and involve complex permitting (Box 5) and public engagement that may heighten opposition before fundamental CDR feasibility questions are resolved.

Field trial costs vary widely based on size, duration, and location. Costs for small-scale field trials, less than 100 km^2 with a two-month period of observations, could range from 3 to 25 million USD. A comprehensive field trial approach, with multiple trials greater than 100 to 10,000 km^2 in scale, over months to years, is estimated to cost 250 million USD over ten years[3].

A high priority is thus maximizing the impact of a field trial within a broader RD&D strategy for a specific PCS pathway to ensure the maximum benefit of the field trial investment and address inherent limitations. Location, costs, social support, and expected contribution to evaluating CDR benefits and environmental risks of a PCS pathway should be part of field trial design and funding priorities.

Box 5. Governance of PCS field trials

International governance of some mCDR pathways activities is under consideration by Parties to the London Convention and London Protocol (LC/LP). The LC/LP aim to prevent marine pollution by regulating the dumping of materials at sea and, since 2008, have declared ocean iron fertilization activities other than "legitimate scientific research" to be contrary to their objectives through a non-binding resolution[41]. In 2010, LC/LP Parties adopted an assessment framework to define "legitimate scientific research," outlining expectations for prior environmental assessment, transparency, monitoring, and reporting. In 2013, Parties to the London Protocol adopted an amendment to regulate ocean iron fertilization activities, though this amendment has not yet entered into force[42,43].

In parallel, the United Nations Convention on Biological Diversity placed a *de facto* moratorium on ocean fertilization in 2008, allowing only small-scale, controlled research in coastal or enclosed waters[43]. Because international instruments like the LC/LP are only legally binding for states that have ratified them, PCS field research may face uneven regulatory oversight, with some activities permitted or restricted differently depending on the jurisdiction responsible for authorizing the research.

For future implementation of mCDR pathways at scale, new governance frameworks will be needed. PCS research will be needed to support those discussions. Where the scientific evidence for the feasibility and desirability of a PCS pathway grows, the pathway may eventually merit a transition from research to deployment.

Prior to such a transition, research, including field trials, will contribute not only data towards evaluating the CDR viability and environmental impacts, but also knowledge needed to inform effective governance. This includes identifying key monitoring criteria and performance thresholds, clarifying responsibilities for long-term stewardship, informing rules on data transparency and verification, exploring liability and redress mechanisms, and defining how benefits, risks, and decision-making authority should be distributed among states, practitioners, and potentially affected communities.

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 viability of PCS. These efforts include a wide range of scientific initiatives with both direct and indirect contributions to PCS understanding. These are summarized here, representing a non-exhaustive landscape of PCS-relevant activities (see Appendix C: Landscape of PCS projects for more detail).

Scientific Initiatives

Most of the current PCS-relevant activities are scientific, 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. Numerous national and internationally funded programs and data coordination efforts, such as Biogeochemical-Argo, SOCCOM, GEOTRACES, SOCAT, and GLODAP, provide large-scale datasets and frameworks and help standardize and harmonize biogeochemical measurements and carbon cycle analyses. Several long-term, ship-based, open-ocean reference station programs measure dozens of variables and monitor the full depth of the ocean, from air-sea interactions down to the seafloor, and contribute to understanding carbon dynamics (e.g., Hawaii Ocean Time-series and Bermuda Atlantic Time-series Study)[44]. 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 long-term 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, POC 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, iron fertilization remains the dominant focus of scientific work internationally. New techno-economic assessments (TEA) of Southern Ocean iron fertilization were published in recent years[7,8,45], and modeling studies continue[10,46–48]. Southern Ocean field trials were previously proposed by the Korea Polar Research Institute[24]. In 2022, scientists from Alfred Wegener Institute in Germany led an expedition to study iron fertilization by natural analogs in the Southern Ocean[49]. In 2023, the international Exploring Ocean Iron Solutions (ExOIS) consortium published a comprehensive iron fertilization RD&D strategy, focused on the design and execution of a large-scale iron fertilization field trial in the northeast Pacific HNLC region, with the aim of achieving a better insight on export dynamics[50,51]. In 2025, another iron fertilization research initiative, Growing Oceans, was launched and is focused on studying nitrogen fixation-based iron fertilization in LNLC regions.

Research Support and Commercial Entities

With scientific prioritization of PCS research by NASEM in 2022[3], additional supportive efforts and commercial entities emerged. These include several PCS companies focused on a range of stimulants to enhance phytoplankton blooms (e.g., Gigablue, Ecopia, Ocean Nourishment Corporation) and export (e.g., MARINIX Ocean Tech), organizations promoting PCS-related research (e.g., Oceanry), and efforts to understand fertilization for the purpose of boosting food supply (e.g., Oceaneos).

One commercial effort that gained significant momentum in the last few years is the company GigaBlue, which aims 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, published an MRV methodology for the approach[52]. At the point, neither effort is accompanied by peer-reviewed scientific studies and some aspects of the process have not been disclosed.

A few organizations recently rebranded their work on iron fertilization with terms such as ocean 'nourishment' or 'restoration' of marine biomass and fisheries. Other PCS related organizations exist, but their role in advancing PCS RD&D is unclear (Appendix C: Landscape of PCS projects).

PCS Research Framework

Based on PCS literature, expert consultations, and other feedback summarized above, the project team identified the following key components for developing a PCS Research Framework:

- **Goal,** to define the endpoint from which to work backwards to build an RD&D roadmap
- **Priority Research Topics,** which set the stage for RD&D activities
- **Cost Considerations,** to ensure effective use and growth of resources
- **Stage-Gate Approach,** to guide outcome-agnostic research investment decisions
- **Key Assumptions,** which may change over time

Goal

The goal for a PCS Research Framework is to enable a comprehensive, science-based, risk-benefit approach to inform societal and community-based decisions on whether, or which, and under what conditions PCS pathways should be part of a global CDR portfolio. Understanding PCS viability will come down to fundamental questions of feasibility and desirability[30,53].

1. **Can PCS lead to quantifiable CDR?**
   his is a scientific question. To have climate-relevant impact, CDR approaches must be additional, scalable, durable, and measurable (Box 6). The ability to meet these criteria is still highly uncertain for all PCS pathways; even for iron fertilization, significant uncertainties remain.
2. **Should we deploy PCS?**
   If PCS are found to be effective for CDR, the decision to implement PCS is a socio-political, legal, and ethical decision and requires a deep, scientific understanding of the desirability for PCS, including socio-economic and environmental risks and co-benefits that could impact different natural and human communities.

Pursuing the PCS Research Framework goal requires (1) establishing merit for PCS research, (2) prioritizing and funding activities to inform feasibility and desirability criteria, and (3) maintaining an outcome-agnostic approach in closing knowledge gaps. At any stage of execution, emerging findings around CDR benefits, socio-economic risks, or environmental risks may suggest curtailment or discontinuation of specific PCS pathways. Those are acceptable outcomes.

Box 6. CDR feasibility criteria

Additional – CDR that occurs due to the CDR activity and would not have occurred otherwise, as measured against a clearly defined and credible counterfactual baseline, accounting for remaining uncertainty, displacement of natural or anthropogenic CDR processes, and greenhouse gas emissions associated with the CDR activity. Within the context of a carbon credit market, additionality may also involve financial and regulatory factors[54].

Scalable – The capacity for a CDR pathway to achieve climate-relevant impact, such as annual gigaton-scale CDR sustained over decades, within fundamental biophysical, operational, economic, and governance constraints.

Durable – The extent to which the additional CO_2 removed remains isolated from the atmosphere over climate-relevant timescales, such as centuries to millennia, with a clearly characterized risk of reversal.

Measurable – The ability to quantify net CDR, accounting for uncertainties, using transparent, reproducible methods, accounting for additionality and durability in accordance with accepted MRV practices and requirements.

Box 7. Priority research questions

CDR Accounting

- Which PCS pathways and regions have the potential to achieve measurable, scalable CDR of ≥1 $GtCO_2$ per year for multiple decades?
- How scalable is sequestration across durability time horizons of 100 to 1000+ years?
- What advances in observations and modeling enable MRV systems that are robust, trusted, and within the acceptable bounds of remaining uncertainty?
- How cost-competitive is PCS with other CDR pathways?

Socio-economic and Environmental Risks and Co-benefits

- What are the key near- and far-field socio-economic and environmental risks, concerns, and co-benefits, and on what scale and timeframes are impacts likely to occur?
- How do risks align with principles of containability, reversibility, probability, and accountability?
- To what degree can 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, and other feasible mitigation alternatives?
- What thresholds of negative impacts, if any, would be considered acceptable, and under what decision process(es) and by what audience?
- Which co-benefits increase desirability for research?

Pathways and Innovations

- Based on emerging research, which pathways are likely to succeed in achieving political acceptance over the scale and durability likely to be needed?
- What criteria and decision-making processes should guide the prioritization of PCS pathways for investment?
- What technological or governance innovations are required to improve the safety, scalability, and desirability of PCS?

Priority Research Topics

1. Ability to Achieve CDR Accounting

PCS pathways must demonstrate high-confidence CDR additionality, scalability, durability, and measurability to be considered for deployment. Research will need to objectively answer whether, where, and how PCS might contribute to a global CDR portfolio (Box 7). As such, MRV approaches and uncertainty thresholds must be consistent with other CDR pathways and cost considerations will need to be well-understood and comparable in a lifecycle context, which includes consideration of all input, execution, and measurement impacts.

A high priority for future work on PCS is to identify, define, and reduce uncertainty in variables with the greatest influence on additionality and durability (Table 1). Such research must also include identifying and quantifying irreducible uncertainties. Excessive remaining uncertainty in the CDR benefit would indicate that that particular PCS pathway is non-viable.

It is unrealistic to assume any PCS operations can or would be sustained in perpetuity. Thus, research on CDR potential 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 pose a wide range of environmental and socio-economic risks, but co-benefits could also emerge and must be investigated (Box 7). 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.

Table 1. MRV components for PCS

Topic	Key MRV Targets	Tools
Near-Field Carbon Capture	Baseline CDR	Observations and Models
	(the counterfactual)	
	Bloom size	
	Air-sea CO_2 flux	
	POC generated	
	POC export to depth	
Far-Field & Other Sequestration Efficiency Cuts	POC fate (durability)	
	Nutrient robbing	
	Biological emissions	
	Nitrous oxide and methane	
	Operational emissions	

PCS viability will depend on the ability to define expected and acceptable environmental impacts and their durations for a range of 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 environmental concerns include dissolved oxygen changes, risks of nutrient depletion and redistribution, changes in phytoplankton species diversity, overall ecosystem productivity, fisheries impacts, and potential risks to deep-sea communities.

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

A necessary 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 engagement with affected communities will require both commitment by researchers and capacity building among involved communities to enable discussion and prioritization of risks, co-design of investigations, and transparent two-way communication that ensure the PCS research addresses the right challenges in acceptable ways.

Executing the PCS Research Framework includes rigorously incorporating practices such as Free and Prior Informed Consent, co-design of research and inclusive decision-making, benefit-sharing, and equitable access to data[55–57]. Fisheries risks and potential opportunities are uniquely prominent and socio-economically important, and it is critical that researchers can understand, predict, and monitor fisheries impacts at local, regional, and global scales.

3. Prioritizing PCS Pathways and Innovations

The PCS Research Framework must include a process to continuously scope, evaluate, and prioritize PCS pathways and ocean regions that have the highest feasibility and prioritize understanding aspects of desirability. Based on the current scientific knowledge, the project team determined the following priorities:

- **HNLC iron fertilization** represents the most scalable PCS approach based on its applicability to large portions of the Southern Ocean and already has a well-developed scientific foundation. Future work can address several critical knowledge gaps on CDR scalability potential and robust MRV to enable broader support for large-scale field trials.
- **LNLC iron fertilization**, to enhance nitrogen fixation and the availability of nitrogen to stimulate blooms, could expand scalability of potentially cost-effective iron fertilization into subtropical ocean gyres when sufficient phosphorus is also available. This pathway has seen limited investment and empirical field testing to date. Given the lack of investment and testing of the enhanced nitrogen fixation hypothesis, the knowledge gaps on efficacy, risks, and costs are larger than those of HNLC iron fertilization.
- **Improved control of carbon export** below the ocean's mixed layer may be an opportunity to address a key MRV challenge on export and ensuring the durability of sequestered carbon in the deep sea. Export innovations may be paired with ocean fertilization approaches.

Other PCS pathways are considered lower priority but warrant monitoring for new opportunities or advances. Most prominently, this includes **macronutrient fertilization**, which has been shown to successfully fertilize blooms in field trials. Macronutrient fertilization, in comparison to micronutrient strategies, has significantly greater cost and scaling challenges due to the quantity of nutrients required[3]. For example, gigaton-scale CDR via macronutrient fertilization could require 40 percent of the current phosphorus market and mining efforts[3].

See Appendix B: Assessment of PCS Pathways for additional detail.

Cost Considerations

There is a wide range of potential PCS RD&D investments needed. The PCS Research Framework is intended to maximize RD&D benefits based on a variety of funding scenarios. As there is no clear line of sight for PCS RD&D funding at the scale needed to fund all potential activities, the PCS Research Framework is designed as an RD&D roadmap that iteratively strengthens the scientific foundation for continued PCS research investments while also building momentum for more costly experiments over time.

Executing the PCS Research Framework requires:

- A clear, strategic, and appropriately sequenced set of recommendations such that early investments inform future budget priorities.
- Prioritization of early, cost-effective activities that can contribute sooner to comprehensive understanding of PCS pathway potential and risks.
- 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., on mCDR, BCP, global carbon budget), including effective coordination with commercial PCS research activities and opportunities.

Stage-Gate Approach

The PCS Research Framework establishes a stage-gate approach where pre-defined sequential phases of RD&D activities called 'stages' are separated by 'gates' which function as key evaluation points for decisions on continued investment (Figure 2). The utility of a stage-gate approach for PCS is to channel efforts toward the most viable PCS pathways and optimize the use of available resources over time. For PCS, the four-stage, decision-driven, framework draws on the ASMASYS assessment framework for evaluating the *feasibility and desirability* of mCDR options[30] and functions as a roadmap to progress research on individual PCS pathways.

Recommended stage-gate targets for any given PCS pathway include:

- Potential to reach scalability of one $GtCO_2$ per year or more for multiple decades, with durability of at least 100 years
- Ability to achieve durability that is quantifiable on time horizons ranging from 100 to 1,000 or more years
- Measurability and remaining uncertainties is on par with other CDR pathways
- Cost trajectory towards 100 USD per ton CO_2 or less
- Understanding of socio-economic and environmental impacts, risks, and justice dimensions sufficiently to inform risk-benefits assessments
- Social and regulatory support for field research, particularly from affected communities and other impacted regions

Failure to achieve these criteria could lead to an offramp decision. The stages are designed to iteratively address these targets and decrease uncertainties over time.

To enter Stage 1, a PCS pathway should be evaluated against a clearly stated theory of impact that incorporates proposed methods, critical learnings and its own evaluation criteria. Each stage then includes clear objectives, key activities, evaluation criteria, and go/no-go or prioritization decision points that a PCS pathway must pass through to merit further investment.

Apart from HNLC iron fertilization, all PCS pathways currently under development would fit into Stage 1. HNLC iron fertilization would fit into Stage 2, due the extensive knowledge base on feasibility to achieve a gigaton CDR impact and field trials conducted so far (Box 3)[3]. Key MRV uncertainties and social license gaps need to be addressed before progression to Stage 3.

Progression of a particular PCS pathway through stage gates will depend not only on CDR benefits but also more complex socio-economic and environmental risk dimensions not readily amenable to quantitative thresholds (Box 7). As such, desirability indicators must be identified early, studied, and evaluated progressively to understand temporal evolution in opinions of a broadening landscape of relevant decisionmakers and communities, as research, regulatory, and funding needs scale across the four stages. Certain desirability dimensions may be more important for research at different stages of pathway development. For example, socio-economic and environmental impact research are high priority at all stages while legal feasibility research may be more relevant after early-stage confirmation of CDR feasibility.

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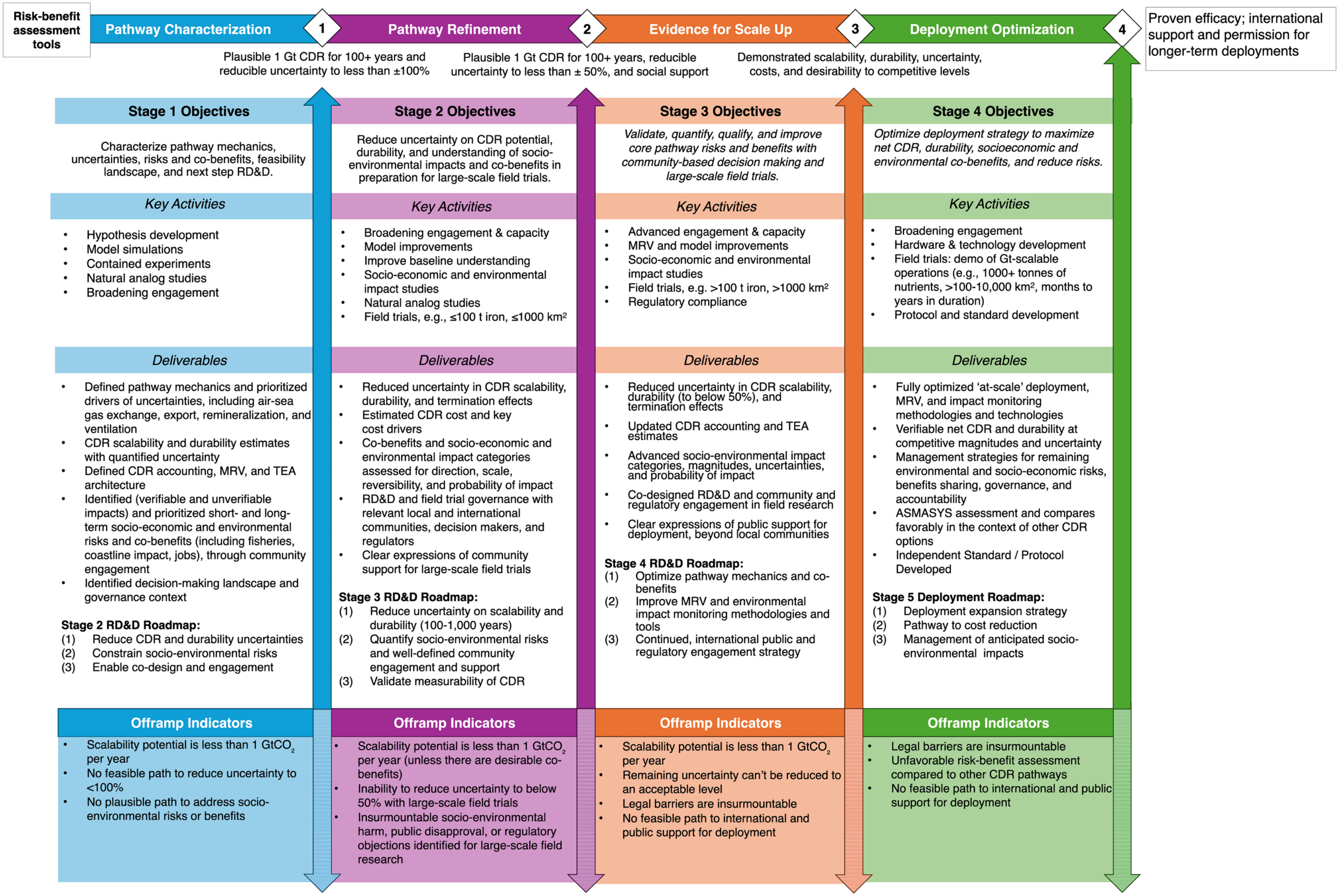
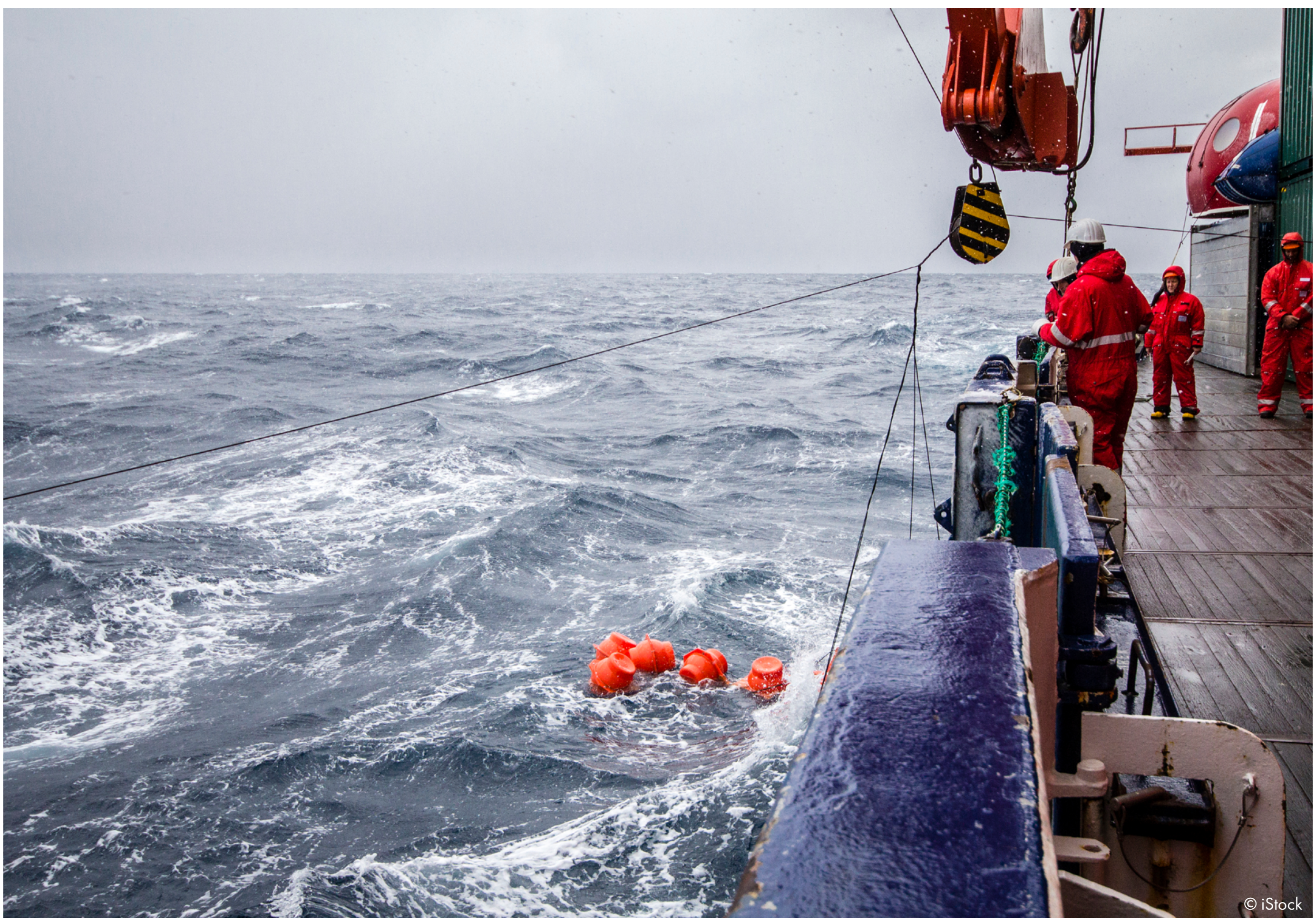


Figure 2. Proposed PCS Stage-Gate Approach. Field trial scales are based on iron fertilization experiments to date (Stage 2) and the scale proposed in mCDR roadmaps (Stage 3; Box 3).

Key Assumptions

Components for the PCS Research Framework described above involve several important assumptions, which must be monitored and may be subject to change over time. These include the following:

- **PCS desirability requires, at minimum, gigaton-scale CDR benefits.** Given the intentional modification of natural ocean ecosystem function and BCP, gigaton-scale CDR benefits are ultimately expected to justify research and overcome both real and perceived environmental risks of PCS. The 1 $GtCO_2$ per annum threshold standard is subject to change with emergence of desirable co-benefits and reduced uncertainty in CDR benefits and socio-economic and environmental impacts.
- **Cost trajectories can be improved over time and thus should not be viewed as an initial impediment to PCS RD&D.** CDR cost projections for PCS pathways must be tracked and aim for 100 USD per ton CO_2 or less, but costs are not a first-order offramp criterion due to the assumption that innovation can target cost-drivers if PCS pathways are demonstrated to be feasible and desirable.
- **Fisheries risk and benefits are uniquely critical to achieving desirability and political durability of PCS.** Work to adequately assess and address fisheries impacts of PCS will likely be a critical threshold activity in any PCS pathway or proposed project.
- **Transparent scientific inquiry and knowledge sharing is critical to advance PCS feasibility and desirability understanding before PCS operations could be deployed, at any scale, on the high seas.** Once a PCS pathway moves to Stage 4—nearing readiness for commercial-scale activities—the marketplace and regulatory environment, including independent standards and protocol organizations, are expected to assume further responsibility.
- **Governance, legal feasibility, and public desirability of PCS is subject to change over time.** The emergence of scientific findings (as achieved through the execution of the PCS Research Framework and other work), changing global environmental conditions, and shifting political priorities over the next five to ten years, could influence the mCDR regulatory environment and societal priorities.



PCS RD&D Action Plan

The PCS Research Framework described above is designed to iteratively identify and prioritize learning opportunities via an integrated and cost-effective strategy. The strategy is designed to sequentially inform decisions and grow resources as learnings progress. Within the PCS Research Framework, the PCS RD&D Action Plan describes target research projects and other activities that can commence as soon as PCS funding is available.

The PCS RD&D Action Plan consists of 12 Actions, grouped in three categories: (I) Overarching Priorities, (II) PCS Pathway-specific Priorities, and (III) Implementation Priorities, which includes a recommendation to establish a dedicated PCS RD&D Program (Table 2).

I. Overarching Priorities

1. Reduce Uncertainty on Net Carbon Dioxide Removal

- **Findings:** There remain significant levels of uncertainty around the additionality, scalability, and durability potential of PCS. Some stages of the CDR process are readily 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 and innovation, which complicates the prioritization of research approaches (e.g., near-field in situ studies, far-field biogeochemical modeling, export enhancements). The field still lacks consensus on the most critical uncertainties and therefore the best approaches to address knowledge gaps.
- **Recommendations:** Identify the most important sources of uncertainty for each priority PCS pathway and the effects of this uncertainty on estimates of CDR. Establish clear targets for reducing uncertainty and initiate the research activities needed to reduce these uncertainties to their targets.

  Design and implement targeted research initiatives to reduce those key uncertainties (e.g., models, field trials, enhanced observational capacity). These follow-on initiatives, whether it is modeling, field trials, or both, will also enable advanced research on environmental impacts.

  Integrate TEA capabilities into the sensitivity analysis framework, to generate CDR cost estimates as deployment scenarios are further refined (see II. PCS Pathway Priorities). Throughout this process, seek to build greater consensus for priority topics and approaches.

Outcomes:

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

2. Improve Utility of Ocean Biogeochemical Models

- **Findings:** Models are essential to many efforts to address critical uncertainties about near- and far-field environmental effects. They are also necessary elements of efforts to determine CDR additionality and durability based on longer term and far-field nutrient dynamics. Several current restraints impede the ability of models to fully meet diverse PCS evaluation requirements, including:
  - Current models used to predict PCS CDR benefits lack agreement on quantification of CDR benefits.
  - Most models currently in use lack sufficient biological and ecosystem inputs to adequately address BCP dynamics and PCS impacts.
  - Other Earth system modeling capacities and experiences have not been fully applied to PCS-based modeling efforts.

  Oceanographic and Earth systems models can be further developed to more fully meet critical PCS evaluation needs, particularly for far-field environmental impacts and CDR effects. Additionally, rapid advances in computing and artificial intelligence capacities offer potential for significant model improvements through enhanced treatment of large amounts of data, better integration and analyses of data from diverse sources, and improved capacity to develop and analyze multiple scenarios.
- **Recommendations:** Initiate a model improvement program specific to PCS to adequately assess and predict PCS impacts. 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.
- Identification of current model differences and feasible opportunities to reduce model uncertainty.
- Consensus in support of priority model innovations according to priority opportunities identified.
- Improved representation of biological processes in current oceanographic models.

3. Improve Understanding of the Ocean's Biological Carbon Pump

- **Findings:** PCS risks and benefits must be evaluated in the context of an accurate understanding of the current and future state of the ocean's biological carbon pump and future ocean health conditions. For example, fish stocks are already shifting in distribution and productivity due to climate-induced changes[58]. A better understanding of how ocean warming and acidification result in changes in the BCP and key associated biological conditions is needed as a baseline against which to project the impact and potential co-benefits of future PCS interventions.

  Furthermore, 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 a less-well incorporated aspect of PCS investigations. Incorporating learnings from numerous ongoing BCP studies can help address some aspects of CDR uncertainty. Natural analogs present opportunities to learn about PCS dynamics during predictable and unpredictable natural events.

  The assessment baseline should also include assumptions about ongoing climate mitigation activities as a base context for CDR action.

- **Recommendations:** The program should identify and develop partnerships to leverage ongoing BCP study efforts, including:

  » Support targeted ongoing BCP investigations and observing programs working to increase knowledge, communication, and characterization of BCP baseline conditions and trends. These efforts present catalytic opportunities to establish a better foundation to measure the effect of PCS interventions against 'business as usual' conditions. These findings can also be helpful to compare PCS interventions with other intervention pathway impacts. This work should be pursued through identification of targeted opportunities to leverage rather than recreate ongoing system studies.

  » Support BCP research synthesis and communication 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.

  » Support and build enhanced response capabilities to leverage study of unpredictable natural analogs of iron fertilization, such as ocean vents and volcanic eruptions and land-based events like large wildfires.

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.
- Improved understanding of BCP dynamics under perturbed conditions via research on natural analogs.
- Improved representation of BCP in models used to assess PCS interventions.

4. Advance Field Trials in Accordance with the PCS Research Framework

- **Findings:** There is strong consensus among experts in the field that field trials (Figure 2, Stage 2 and 3) are essential in testing PCS (e.g., proof-of-concept MRV, environmental impact assessment, evidence for co-benefits, technological considerations of bloom management, data input for model improvements). Field trials are also one of the most expensive research methods, carry unique responsibilities for public engagement, and will require significant regulatory and public processes. One example of field trial planning underway is a proposal by the international consortium ExOIS for a comprehensive, large-scale HNLC iron fertilization field trial in the northeast Pacific Ocean (Box 8).

  The extensive communities of practice developed through field trial efforts provide an important coordination mechanism for PCS RD&D. PCS field trials must be executed at the right moment in time, in the most effective place, with public support and engagement, and with adequate funds to maximize the scientific knowledge gains, particularly on local environmental impacts and with insights on risks to deep-sea ecosystems. Preparatory activities that include co-design with relevant local and international communities and navigating the trial's regulatory framework are critical to long-term success of any merited PCS intervention.

- **Recommendations:** Pursuing field trials should be a top priority for PCS research efforts. Decisions about specific field trial priorities should consider multiple factors that: reduce MRV uncertainty of CDR benefits; address the widest range of PCS environmental and socio-economic concerns and co-benefits; leverage additional funding; and build and sustain necessary community support and regulatory approvals.

  All trial proposals under consideration should explicitly articulate a clear theory of impact as a means to effectively measure the value of scientific contributions to priority PCS research topics. The comprehensive study design should also clearly state the way that a proposed field trial would contribute to specific PCS pathways questions and advance the stage-gate process. A social engagement plan should also be included. Finally, consideration of cost-benefit considerations and leveraging opportunities should be included in field trial proposals.

  Work should continue to refine consensus on the role, timing, location, knowledge transferability, and cost-efficiency of large-scale field trials and other field-based research.

Outcomes:

- Determination of the most impactful and viable field trial sites under cost-benefit considerations and in the context of comprehensive PCS evaluation goals.
- Assessment of the socio-economic and environmental risks, co-benefits, and regional desirability of field trials.
- A sustained community of practice to prioritize, coordinate, and evaluate PCS RD&D.

II. PCS Pathway Priorities

5. Sharpen Understanding of Southern Ocean Iron Fertilization Scalability Potential

- **Findings:** Numerous models and studies identify Southern Ocean iron fertilization as the most scalable PCS opportunity. The Southern Ocean is projected to have gigaton-scale CDR 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 based on more targeted intervention strategies. Better understanding of the need for other additional nutrients is needed to address potential nutrient limitations (e.g., silica, aluminum). Despite a strong scientific knowledge foundation of Southern Ocean iron fertilization, many uncertainties remain. Work should focus on better understanding the realistic CDR potential in the highest potential regions of the Southern Ocean.

- **Recommendations:** Develop realistic deployment-scaling scenarios to better characterize and quantify CDR potential, operational requirements, consequences of Southern Ocean iron fertilization, and the need to supplement with additional nutrients (Figure 2, Stage 2). Align these investigations with the proposed sensitivity analysis and model improvement projects to better define projected CDR potential and environmental risks. More refined scenarios could then be used to identify potentially impacted communities.

  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 iron fertilization 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.
- Identification of affected communities to inform future co-design, permitting and consultation strategies.

6. Improve Understanding of Subtropical Nitrogen-Fixation-based Iron Fertilization

- **Findings:** Iron fertilization in subtropical, LNLC waters has received limited research attention compared to iron fertilization in HNLC waters but similarly benefits from potentially low-resource and cost requirements to achieve CDR. Based on observations of natural hydrothermal plumes in the Tonga-Kermadec Ridge fertilizing surrounding waters[59], iron fertilization in LNLC waters could potentially stimulate nitrogen fixation, thereby boosting phytoplankton growth more broadly. The production of additional nitrogen may address one aspect of nutrient robbing, though nutrient robbing impacts of the consumption of residual phosphorus remain. Preliminary work in select South Pacific Islands recently spurred interest in evaluating the potential for this PCS pathway.
- **Recommendations:** Support assessments of the viability and effects of subtropical nitrogen-fixation-based iron fertilization (Figure 2, Stage 1). Assess macronutrient dynamics, potential co-benefits, 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.

Outcomes:

- Viability testing and characterization of subtropical iron fertilization, 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.

7. Advance Work on Innovations that Enhance Export of Phytoplankton Carbon

- **Findings:** The magnitude and depth of POC export generated by phytoplankton blooms is a key driver of the CDR efficacy and costs of PCS[7]. 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, addition of aluminum).

  Innovations that enhance the export of carbon captured by phytoplankton into the deep ocean, through enhanced ballasting and reduced degradation of organic carbon, could improve the overall additionality, durability, and measurability of PCS pathways and therefore their techno-economic viability.
- **Recommendations:** Fund early-stage development, innovation, and testing of mechanisms to enhance the export of POC to prioritize approaches for further development.

Outcomes:

- Identification, development, and viability evaluation of one or more export-focused innovations.
- Characterization and assessment of environmental risks associated with ballast materials, including organic matter and nutrient cycling, impurities with environmental risk, and trophic disruptions resulting from introduced material and related processes.
- Early-stage scalability and TEA analysis and lab testing.
- Improved viability assessment of PCS.

8. Continue to Monitor and Assess Other Emerging PCS Pathways

- **Findings**: Macronutrient fertilization faces cost and scaling challenges as well as the MRV and environmental impact challenges faced by iron fertilization strategies. Other PCS ideas, such as artificial upwelling and light-based stimulation of blooms, are at low levels of technology readiness and lack strong foundational knowledge needed to suppose gigaton-scale CDR viability or identify and characterize their socio-economic and environmental risks.
- **Recommendations:** Monitor emerging PCS ideas and pathways and use the stage-gate approach to evaluate their progress for future funding consideration. Certain macronutrient fertilization research activities may provide utility in advancing PCS engagement, discussions, and knowledge gaps.

Outcomes:

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

Box 8. Field trial case study: Exploring Ocean Iron Solutions (ExOIS)

ExOIS is an academic research consortium housed at Woods Hole Oceanographic Institution that aims to evaluate the efficiency, safety, and scalability of iron fertilization. As described in their 2023 "Paths Forward for Exploring Ocean Iron Fertilization" report (ExOIS Paths Forward), ExOIS represents one of the most advanced PCS field trial concepts to date.

ExOIS presents the first recommended study site in the northeast Pacific Ocean, an HNLC region. This trial site has been selected to maximize control of the bloom and field observations and minimize downstream effects and for its access to support infrastructure and proximity to long-term ocean time-series. The goal is to address key questions on bloom generation and export and assess local environmental impacts using advanced measurement and modeling tools. The trial seeks to raise public awareness and provide proof-of-concept to further advance iron fertilization research in other locations. The trial would also generate insights to inform future governance.

The ExOIS program proposes a 10-tonne iron addition in a 2,500 km^2 patch in the northeast Pacific Ocean and estimates a total field trial cost of 40 to 45 million USD to fully fund two field trials over a three-year period. While the proposed field trial strategy would address many critical questions about iron fertilization, additional trials will ultimately be needed in the Southern Ocean where iron fertilization is most likely to be scalable.

III. Implementation Priorities

9. Prioritize Community Participation in Research Consideration and Design

- **Findings**: Co-designing PCS research with international scientific collaboration and non-scientific partners is essential to generate knowledge relevant for decision-making (Box 9). 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. Greater involvement of social scientists is needed and PCS research projects will need dedicated funds to support engagement activities and inclusive decision-making processes.
- **Recommendations:** Prioritize and support collaboration with social scientists and with local and potentially affected communities and other interested actors in PCS investigations, particularly in projects that involve field components. Adopt existing research codes of conducts and best practices for mCDR RD&D to effectively engage relevant non-scientific and local communities early to improve the utility of research outcomes to inform decisions. For any PCS RD&D program, 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. Advisory boards may also be relevant for specific PCS projects.

Outcomes:

- Improved legitimacy, credibility, and desire for outcome-agnostic PCS research.
- Collection of decision-relevant data to inform evaluation of PCS.
- Broader international scientific and non-scientific community engagement.
- Trust in the program's strategy to responsibly advance research.

10. Build Targeted Capacity in Affected Coastal Communities and Fisheries

- **Findings:** Coastal communities and fisheries are at the front lines of both risk and potential benefits 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 to better identify concerns and desirable co-benefits to be addressed in research. Engagement must be iterative throughout the arc of the research planning stage, execution, data analysis, and publication of results (Box 9).
- **Recommendations:** Build 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.

Outcomes:

- Increased capacity and durable engagement of key ocean users in mCDR discussions, research design, and decision making.
- Better alignment between scientific goals and community values via place-based research design that addresses local desirability, concerns, and opportunities.
- Clearer identification and evaluation of PCS risks and co-benefits for coastal and fishing communities to inform decisions.

11. Ensure PCS Impacts Are Contextualized Relative to Alternative Scenarios

- **Findings:** Environmental and socio-economic risks and co-benefits of any CDR, including PCS, must be understood in the context of alternative scenarios, such as emissions-reduction-only scenarios and other CDR options. Achieving a politically durable, 10 $GtCO_2$ portfolio annually by 2050[1] will require societal and political desirability for research, mechanisms for governance of research (and deployment), and tools and frameworks that allow for robust, but easily interpretable, comparative risk assessments to inform local to global discussions and decisions. Numerous efforts in the mCDR and broader CDR field are working to advance these needs.
- **Recommendations:** Contribute to efforts developing a comparative risk framework and ensure that PCS pathways are accurately represented within such a framework. Stay abreast of and collaborate actively with other CDR and mCDR entities to increase efficiencies across shared investigations and maximize future comparative capacities. Support and adopt best practices and other frameworks aimed at improving cohesion, comparisons, and utility of mCDR research outputs. Share PCS knowledge with groups working to enable mCDR RD&D and integration of mCDR in broader climate management governance and policy discussions.

Outcomes:

- Improved relevance of PCS research that is directly applicable to global CDR portfolio evaluations and CDR discussions more broadly.
- Enabled evaluation of PCS in the context of other CDR pathways and a global CDR portfolio.

12. Establish a Dedicated PCS RD&D Program

- **Findings:** Multiple PCS-relevant research efforts are underway to address critical PCS RD&D questions, and numerous resources are available to guide the execution of mCDR research broadly (Box 9). The PCS field currently lacks both sufficient coordination across all PCS areas of investigation and sufficient resources to carry out priority work. The field would benefit from enhanced coordination of activities, improved prioritization of needed RD&D, and a concerted effort to raise additional funds to execute that work. Additionally, PCS RD&D would benefit from close coordination with other mCDR and CDR pathway work to ensure inclusive and comparative risk consideration of PCS pathways.
- **Recommendations:** Establish a dedicated, outcome-agnostic, PCS RD&D program to facilitate improved collaboration, coordination, and prioritization across research pathways and organizations conducting PCS related work. Administer allocated funds to execute the proposed Action Plan, implement the stage-gate approach, and seek opportunities to effectively coordinate and leverage other available resources and highlight opportunities for additional investments needed.

  Assuming limited program funds (e.g., 1-5 million USD in total), a first-order funding priority would be to advance Action Plan recommendations 1, 2, 3, and 5, in the form of shorter duration projects whose outcomes collectively influence and determine the prioritization, of what is expected to require significantly greater research investments (e.g., 5-10+ million USD), in modeling and/or field-based research focused on reducing uncertainty of the viability of HNLC iron fertilization.

  With additional program funding (e.g., 5+ million USD in total), in parallel, recommendation 4, 6, and 7 could advance via the stage-gate approach and recommendations 9 and 10 could be executed to ensure inclusive co-design and decision-relevant research outcomes.

  Until significant pathway-specific offramps are encountered, all recommended activities (1-11) can scale iteratively and benefit from additional funding over time, as warranted by research outcomes and stage-gate assessments. Incremental advances across all recommendations can help unlock additional funds to support the necessary large-scale field trials (e.g., 40+ million USD). As such, it is imperative that each funded project makes a catalytic contribution to the understanding of PCS feasibility and desirability.

Box 9. CDR research program guidance, frameworks, and resources

Numerous resources are available to provide detailed guidance on how to ethically and effectively pursue and conduct mCDR research, community engagement, and knowledge sharing activities. These resources collectively contributed to the prioritization of inclusive PCS research design and community engagement, especially for PCS field trials.

PCS program implementation, engagement, and execution should integrate existing established principles and best practices, including but not limited to:

- American Geophysical Union's Ethical Framework Principles for Climate Intervention Research
- 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

Recommendations 8 and 11 are not expected to be high in cost and could be addressed by PCS program staff.

Program implementation recommendations include:

- Program manager(s) oversee and coordinate grantee progress and collaboration, lead inclusive decision-making processes on follow-up grants by implementing the stage-gate approach, and execute required monitoring activities (e.g., emergence of new PCS pathways, opportunistic field campaigns, and other CDR projects to leverage the advancement of PCS knowledge).
- 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 research and/or potential deployment 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 (e.g., small and large grants, rapid response funding).
- Flexibility to strategically pivot with emerging science and societal priorities.
- Scope co-funding opportunities, specifically with respect to government funded research programs and campaigns and broader geographic engagement of the scientific community on PCS studies.

Additional program considerations:

- Maintain an outcome-agnostic posture and be prepared to recommend against specific or overarching inquiries in response to findings and/or socio-economic conditions.
- Adopt and share 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.
- Engage 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.

Outcomes:

- Establishment of a credible PCS research field and additional research funds.
- New scientific knowledge that informs feasibility and desirability criteria of multiple PCS pathways.
- Inclusive and credible science-informed decisions on PCS pathway progression.

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Table 2. PCS RD&D Action Plan

	Topic	Activities	Output	Outcome	Impact
Overarching Priorities	**1. CDR (and cost) Quantification Uncertainties**	Develop harmonized LCA-TEA framework for PCS to iteratively evaluate CDR potential over time and run scenarios to identify the most important uncertainties that can be reduced with additional research.	LCA-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 assessement informed by reduced uncertainty in: • CDR additionality, scalability, durability, and measureability • Socioeconomic and environmental risks and co-benefits • Economic viability
	2. Biogeochemical Models	Conduct a model improvement process, including intercomparison, evaluation of biological inputs and other means to improve models needed to better assess PCS impacts.	Identification of model input and process improvement priorities; Multiple model improvement projects.	Improved biogeochemical modeling tools for PCS impact evaluation and uncertainty reduction.	
	3. Biological Carbon Pump (BCP)	Support BCP research synthesis actvitities and advance characterization of the BCP through observation and in models to assess BCP baseline and trends under 'business as usual' climate scenarios.	Improved representation of BCP in assessments, and better characterization of risks under 'business as usual' scenarios and with PCS implementation.	Enhanced contexualization of PCS and climate change driven socio-economic and environmental impacts.	
	4. Advance Field Trials	Based on clear theories of impact, identify and support field trials that best advance CDR, socio-economic and environmental risk evaluation of PCS. Use stage-gate approach to evaluate and build additional support for field trials.	Numerous high-impact field trials that advance understanding of critical CDR, socio-environmental risks, co-benefits, and regional desirabilty of field trials; Advanced social support for PCS research.	Advanced understanding of CDR and MRV feasibility and environmental impacts.	

Continued on next page

	Topic	Activities	Output	Outcome	Impact
PCS Pathway Priorities	**5. Southern Ocean Iron Fertilization**	Advance the evaluation of iron fertilization through nitrogen fixation as a potentially scalable and desirable CDR pathway.	Realistic deployment scenarios and identification of development gaps (e.g., MRV); Updated characterization of socio-economic and environmental risks.	Improved realism of Southern Ocean iron fertilization that enables comparison to 'business as usual' scenarios and other CDR approaches.	Stage Gate 2 evaluation is enabled for multiple PCS pathways
	6. Subtropical Nitrogen Fixation Iron Fertilization	Advance the evaluation of iron fertilization through nitrogen fixation as a potentially scalable and desirable CDR pathway.	Scientific knowledge aligned with stage-gate metrics via place-based, locally co-designed research.	Advanced understanding of the viability of this pathway.	
	7. Export Innovation	Scope and advance mechanisms to better control export of particulate organic carbon.	Identification, development, and viability evaluation of one or more export-focused innovations.	Improved export performance for PCS pathways yielding more effective and efficient transport and durability.	
	8. Other Pathways	Monitor progress and emergence of other PCS pathways.	Opportunity to incoporate new PCS pathways into the RD&D portfolio.	Full awareness, development and evaluation of emerging PCS pathways.	
Implementation Priorities	**9. Community Participation**	Resource broader engagement for co-design and utilize an International Science Advisory Board for program decisions.	Co-designed PCS projects and decision-relevant data; Broader PCS capacity and engagement.	Improved trust and support for outcome-agnostic PCS RD&D.	Legitimacy and trust for scaling PCS RD&D is established, paving the way for more sustainable continuation of this area of climate research
	10. Targeted Coastal Community & Fisheries Engagement	Build international fisheries and coastal community capacity to engage on PCS and enable improved capacity to evaluate risk and participate in co-design of PCS research.	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.	
	11. Comparative CDR Considerations	Share knowledge, collaborate, and integrate broader CDR developments in the PCS program.	Improved contextualization of PCS in a global CDR portfolio.	PCS can be part of CDR decision-making discussion.	
	12. PCS RD&D Program	Estalish an RD&D Program to execute the PCS Action Plan according to the PCS Research Framework.	New PCS research funds, collaborations, and coordination of research.	Independent, credible scientific knowledge development.	

Appendices

Appendix A: Acknowledgements

The project team is grateful for the dozens of experts and individuals who engaged in this project and provided voluntary commentary, feedback, and recommendations that substantially influenced the findings and recommendations presented in the PCS Research Framework. This includes but is not limited to the following individuals:

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Appendix B: Assessment of PCS Pathways

The two tables below describe PCS pathways. Built on the framework used in NASEM's *Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*[3], 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 scientific knowledge on PCS approaches that aim to enhance primary production[3]. These include iron fertilization in HNLC regions, nitrogen-fixation-based iron fertilization in LNLC regions, macronutrient fertilization, and artificial upwelling. While some approaches, such as HNLC iron fertilization, have undergone numerous field trials, others remain largely untested.

Criteria	Iron fertilization - HNLC	Iron fertilization – LNLC	Macronutrient fertilization	Artificial Upwelling
Description	Adding iron to HNLC regions, such as the Southern Ocean, to stimulate phytoplankton growth.	Adding iron to stimulate nitrogen-fixing in LNLC regions, such as subtropical gyres.	Adding nutrients like phosphorous, nitrogen, and silica to fertilize phytoplankton.	Mechanically bringing nutrient-rich deep water to the surface.
Theoretical scalability	**High** 2–4 $GtCO_2e$ per year[10,60–62]	**Medium** 1.5 $GtCO_2e$ per year (John et al., pers. comm)	**Medium-High** 2.6±1.5 $GtCO_2e$ per year (nitrogen only); 5.9±1.5 $GtCO_2e$ (nitrogen and phosphorus)[63]	**Low** 0.05 $GtCO_2e$ per year[64]
Durability	**Variable** Durability will depend on the fate of the additional organic carbon and the ability to quantify this[3]. Export efficiency is highly variability across ocean regions and durability is likely to vary by fertilization stimulants and location. There is currently low certainty that a durability of 100+ years is achievable and quantifiable[38], and research is needed to better constrain this.			
Technological readiness	**Medium** Iron fertilization has been tested in field trials, but scalable CDR effectiveness is largely untested[38]	**Low** Iron fertilization in LNLC regions is still in the early stages of conceptual design and experimentation[38].	**Low** There have been two field trials using phosphorus[23].	**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[65,66].
Cost	**Low** Cost estimates are as low as 10 to 25 USD per ton CO_2, and as high as 53,000 USD[7,8]. Export efficiency is the biggest cost driver.	**Unknown** Costs may potentially be similar to iron fertilization in HNLC regions.	**Medium** Nitrogen and phosphorus source costs may be orders of magnitude higher than iron and more material will be needed[3]. Export efficiency is a large cost driver.	**High** High logistical and energy input costs of installing and operating upwelling pumps[7].

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Criteria	Iron fertilization - HNLC	Iron fertilization – LNLC	Macronutrient fertilization	Artificial Upwelling
Environmental risks	**Medium** These approaches boost productivity by changing surface ocean biology. This can cause surface, deep-ocean, and far reaching geochemical and ecological impacts[3].			**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 and subtropical oligotrophic gyres	Tropical and subtropical oligotrophic gyres	Subtropical gyres, Southern Ocean

Table A2. Export-based PCS pathways. This table provides an overview of two emerging approaches — Enhanced Sinking and Avoided Degradation— that focus on enhancing export and long-term sequestration of organic matter in deeper ocean layers. Export-based approaches could potentially be applied in combination with production-based PCS pathways. Overall, there is limited scientific research on export-based PCS pathways.

Criteria	Enhanced Sinking	Avoided Degradation
Description	Addition of particles to enhance the aggregation, ballasting, or sinking of phytoplankton biomass and organic carbon[31,33,52]	Addition of other materials to reduce the breakdown of phytoplankton-derived organic carbon.
Theoretical scalability	**Unknown** Scalability estimates have not been published for approached to enhance sinking of organic carbon.	**Unknow** One hypothesis suggests the addition of aluminum with iron enhances phytoplankton growth and reduces decomposition[67,68]. As such, its scalability may be similar as iron fertilization, but this is untested.
Technological readiness	**Low-Medium** Use of clay to increase flocculation and marine snow has been tested in applications for managing harmful algal blooms[69], but applications for CDR have only been testing in the lab, using clay[31] and proposed via a theoretical application of engineered nanoparticles[33]. Proprietary approaches developed by the company Gigablue have been tested in field mesocosms, but the research has not yet been published.	**Low** Only a few laboratory experiments have been conducted[34,70].

Continued on next page

<table>
<tr><th>Criteria</th><th>Enhanced Sinking</th><th>Avoided Degradation</th></tr>
<tr><td>Durability</td><td colspan="2">Unknown
Durability will ultimately depend how much export efficiency is enhanced and remineralization is reduced.</td></tr>
<tr><td>Cost</td><td colspan="2">Unknown
Cost have not been estimated.</td></tr>
<tr><td>Environmental risks</td><td>Unknown
Environmental risks have not been explored. Beyond an increase of organic carbon alone, the addition of flocculation and ballasting material could pose risk to mesopelagic, deep sea, and benthic communities.</td><td rowspan="2">Unknown
Risks associated with the addition of aluminum to phytoplankton blooms have not been explored.</td></tr>
<tr><td>Social risks</td><td>Unknown
Social risks have not yet been explored, however, since sinking methods can be applied in combination with ocean fertilization, the corresponding social risks, such as fisheries impacts, may apply.</td></tr>
</table>

Appendix C: Landscape of PCS projects

The following tables provide a non-exhaustive overview of PCS-related projects and initiatives. It includes 38 scientific research efforts (Table A3), and 11 research supportive efforts, including commercial entities (Table A4).

Table A3. A summary of scientific research efforts.

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
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
Global ONCE; ONCE (China)	Global ONCE is an international initiative led by Xiamen University, focusing on enhancing mCDR through the BCP and other related processes (e.g., microbial carbon pump). 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
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
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

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Project	Description	Timeline	Geography
Joint Exploration of the Twilight Zone Ocean Network (JETZON)	JETZON is an international research program focused on the mesopelagic "twilight zone" (~200–1,000 m depth), coordinating scientists globally to study its ecology, biogeochemistry, and role in biological carbon pump. Among its projects, JETZON supports initiatives like ORCAS, which validates biogeochemical models of organic carbon flux using autonomous sensors, and CarbOcean, which develops novel BGC-Argo floats to quantify both organic and carbonate carbon pumps in the twilight zone.	2021 - current	Global
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 concentrations globally from 1997 to 2020.	2020 - current	Global
Helmholtz "Changing Earth – Sustaining our Future" (Germany)	Topic 6 of the Hemholtz's "Changing Earth – Sustaining our Future" Program focuses on "Marine and Polar Life: Sustaining Biodiversity, Biotic Interactions, Biogeochemical Functions".	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
Ocean Twilight Zone (OTZ) (US)	The OTZ project at Woods Hole Oceanographic Institution investigates how mesopelagic organisms contribute to carbon export in the ocean. Using tools like the Mesobot underwater robot, sediment traps, acoustic sensors, and drifting MINION floats, the group aims to quantify how marine snow contributes to export.	2018 - current	Global
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
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
Ocean Carbon and Biogeochemistry (OCB) (US)	The OCB 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
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
Instituto de Investigaciones Marinas y Costeras "José Benito Vives de Andréis" (INVEMAR) (Colombia)	INVEMAR is Colombia's national marine and coastal research institute, conducting basic and applied science on biodiversity, environmental quality, geoscience, and sustainable use of marine resources. Through its CLIMARES program, the institute has built a multi-decadal coastal climate research platform that tracks how changing environmental conditions (e.g., temperature, nutrient fluxes) influence phytoplankton productivity.	1994 - current	Caribbean
Continuous Plankton Recorder (CPR) (UK)	The CPR Survey is a long-running and geographically extensive marine plankton monitoring program, first launched in 1931. It is operated today by the Marine Biological Association in Plymouth, UK, and produces high-resolution, long-term data on phytoplankton and zooplankton communities to support research on climate change, pollution, harmful algal blooms, and fisheries.	1931 - 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			
[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
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

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Project	Description	Timeline	Geography
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
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
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
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
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
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.	2004 - current	Global
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 Observing System (GOOS)(Global)	The Global Ocean Observing System (GOOS) is an international program coordinated by the Intergovernmental Oceanographic Commission (IOC) to systematically collect, integrate, and share oceanographic data for climate, weather, ecosystem, and societal applications. GOOS monitors physical, chemical, and biological aspects of the ocean, including temperature, currents, sea level, biogeochemistry, and marine life, to support research, forecasting, and sustainable ocean management. Its work is organized through Regional Alliances, such as GOOS-Africa, EuroGOOS, and the North Pacific GOOS, which tailor observing efforts to regional priorities while contributing to the global observing network.	1991- current	Global

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Project	Description	Timeline	Geography
Council for Scientific and Industrial Research (CSIR) (South Africa)	The Council for Scientific and Industrial Research (CSIR) in Cape Town is a scientific and technology research organization with a program focused on ocean systems and climate modeling. Through its Southern Ocean Carbon & Climate Observatory (SOCCO), the CSIR deploys autonomous robotic platforms (e.g., seagliders and wave gliders) to collect high-resolution data on phytoplankton biomass, CO_2, oxygen, and other biogeochemical variables. Their research has revealed a multidecadal increase in iron stress among Southern Ocean phytoplankton, suggesting declining productivity over time that could weaken the ocean's capacity to sequester carbon. CSIR scientists have documented shifts in the timing and duration of phytoplankton blooms, which likely reduce the efficiency of carbon export in this region.	1945- current	Southern Ocean
Studying and testing PCS pathways			
Growing Oceans (US)	Growing Oceans is a non-profit research initiative to study nitrogen fixation-based iron fertilization in nature and as a potential CDR solution. Lead by US scientists, the team is planning a research expedition in the South Pacific where hydrothermal vents naturally supply iron and phosphorus to surface waters and stimulate nitrogen fixation and phytoplankton blooms.	2025 - current	South Pacific
Exploring Ocean Iron Solutions (ExOIS) (US)	ExOIS is an international consortium of scientists, housed at Woods Hole Oceanographic Institution. The group investigates the feasibility, impacts, and governance of ocean iron fertilization. The group is planning a field trial to raise awareness, demonstrate iron fertilization 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
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 iron fertilization field trial in the Southern Ocean. This field trial was, ultimately, not implemented.	2016	Southern Ocean

Table A4. A summary of research supportive activities, including commercial entities.

Project	Description	Timeline	Geography
MARINIX Ocean Tech (Norway, Croatia)	MARINIX Ocean Tech is a company that proposes technology to trigger the formation of marine snow in the Southern Ocean and enhance export of organic carbon to the deep ocean. The approach involves the addition of iron chelates to induce the release of extracellular organic carbon in marine phytoplankton and bacteria, rather than stimulate phytoplankton blooms. The team published a white paper on their approach in 2025 and aims to raise 11 million Euros for RD&D.	2024 - current	Southern Ocean
Oceanry (Finland)	Oceanry focuses on advancing research into the climate and biodiversity impacts of iron fertilization. The project aims to increase awareness, promote research, and support the development of regulations and standards for iron fertilization as a potential large-scale carbon sequestration method.	2024 - current	North Atlantic
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
Positive Polar (US)	Positive Polar intends to combine commercial polar expeditions and using their expedition vessels to conduct iron fertilization research and spread awareness, although specific research objectives and activities conducted via the vessels is unclear.	2023 - current	Arctic
GigaBlue (US)	GigaBlue is an mCDR startup developing floating substrates intended to fertilize phytoplankton and provide structure for biomass aggregation for carbon export. They have conducted field experiments in New Zealand's waters at mesocosm scales through their operational arm, Gigablue Aotearoa South Pacific. The company signed a pre-purchase agreement with aviation sustainability investor SkiesFifty for 200,000 tons of carbon removal credits from 2025 to 2028.	2022 - current	Southern Ocean
Ocean Abundance Restoration (OAR) Alliance (Global)	OAR Alliance, previously known as the Ocean Iron Fertilization Alliance, is a volunteer group that promotes alliance building to enable research projects on 'climate restoration'.	2022 - current	Global
Lillianah (US)	Lillianah Technologies is a company that cultivates native diatoms in custom photobioreactors and disperses them into polluted nearshore waters, where they uptake excess nutrients and drive carbon fixation. Lillianah is currently operating small field trials (e.g., on the Gulf Coast) with the intention to generate carbon removal credits and has early carbon removal agreements with Clearyst.	2021 - current	North Atlantic
Ecopia (UK)	Ecopia is a startup that is developing a method called Tele-illumination to promote phytoplankton growth below the thermocline. Their light-emitting floating and submerged platforms, known as ECOPINs, stimulate the growth of phytoplankton by introducing light in aphotic regions of the ocean. However, how this approach achieves the atmospheric CO_2 exchange at the sea surface necessary to achieve CDR is unclear.	2020 - current	Global
Oceaneos (Canada)	Oceaneos is a marine research organization that is developing and testing ocean iron fertilization technologies to stimulate phytoplankton, with the hypothesis that it will enhance wild fish populations. They are currently conducting small-scale, in situ trials in controlled environments	2018 - current	Global

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Project	Description	Timeline	Geography
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. In September 2025, Puro.earth approved a Microalgae Carbon Fixation and Sinking (MCFS) methodology, originally initiated by GigaBlue. The organization approved two other methodologies for ocean-based carbon dioxide removal: Marine Anoxic Carbon Storage and Direct Air Capture and Ocean Storage.	2017 - current	Global
Ocean Nourishment Corporation (ONC)	ONC is an Australian biotech company that is testing macronutrient fertilization using ammonia derived from hydrogen and deployed via ships and offshore platforms. The intention is to sequester carbon dioxide for removal credits.	2004 - current	Southern Ocean


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