NOAA Carbon Dioxide Removal Research:

A White Paper documenting a Potential NOAA CDR Science Strategy as an element of NOAA's Climate Mitigation Portfolio

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About this document. This document was developed by the National Oceanic and Atmospheric Administration (NOAA) Carbon Dioxide Removal Task Force (CDR Task Force), a cross-NOAA interdisciplinary team with relevant expertise in climate and carbon, coastal and open ocean science, aquaculture development, and ocean conservation. In November of 2020, the task force was charged by the Senior Research Council of the NOAA Office of Ocean and Atmospheric Research (OAR) with devising a draft portfolio of CDR strategic research needs in support of a broader climate recovery strategy pursuant to Sect. 214 and 216 of White House Executive Order No. 14008, 86 FR 7619, which was endorsed by the NOAA Science Council in January 2022. This document also contains information relevant to White House memo M-21-32 “Multi-Agency Research and Development Priorities for the FY 2023 Budget.”

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List of Abbreviations

Terms.

AFOLU	Agriculture, Forest, and other Land Use
AR	Assessment Report
B	Billion
BCI	Blue Carbon Inventory
BPMED	Bipolar Membrane Electrodialysis
CBC	Coastal Blue Carbon
CFC	Chlorofluorocarbon
°C	Degrees Celsius
CCUS	Carbon Capture, Utilization, and Storage
CDR	Carbon Dioxide Removal
CDRMIP	Carbon Dioxide Removal Model Intercomparison Project
CH_4	Methane
CO_2	Carbon Dioxide
CM	Climate Model
CMIP	Climate Model Intercomparison Project
DAC	Direct Air Capture
DOC	Direct Ocean Capture
ENSO	El Niño Southern Oscillation
ESM	Earth System Model
EEZ	Exclusive Economic Zone
Fe	Iron
FOCE	Free Ocean CO_2 Enrichment
FY	Fiscal Year
GHG	Greenhouse Gas
GT	Gigaton
GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
HFC	Hydrofluorocarbon
kg	kilogram
lb	pound
IronEx	Iron Experiment
M	Million
MT	Megaton
MPA	Marine Protected Area
N	Nitrogen
NDC	Nationally Determined Contribution
NET	Negative Emissions Technology
NGGI	National Greenhouse Gas Inventories
NMS	National Marine Sanctuary
NPP	Net Primary Production

OA	Ocean Acidification
OAE	Ocean Alkalinity Enhancement
OIF	Ocean Iron Fertilization
OMF	Ocean Macronutrient Fertilization
P	Phosphate
Pg	Petagram
PPPs	Public-private partnerships
RD&D	Research, development and demonstration
ROMS	Regional Ocean Modeling System
SF6	Sulfur hexafluoride
SR	Special Report
SSP	Shared Socioeconomic Pathway
USV	Uncrewed Surface Vehicle
WG	Working Group
ZECMIP	Zero Emissions Commitment Model Intercomparison Project

Institutions and Programs.

USACE	U.S. Army Corps of Engineers
AOML	NOAA Atlantic Oceanographic and Meteorological Laboratory
ARPA-E	DOE Advanced Research Projects Agency – Energy
CCAP	NOAA Coastal Change Analysis Program
CCIWG	Carbon Cycle Interagency Working Group
CPO	NOAA Climate Program Office
DART	NOAA PMEL Deep-ocean Assessment and Reporting of Tsunamis
DOE	Department of Energy
EFI	Energy Futures Initiative
EPA	U.S. Environmental Protection Agency
ESRL	NOAA Earth System Research Laboratories
FWS	Fish and Wildlife Service
GFDL	NOAA Geophysical Fluid Dynamics Laboratory
GGGRN	Global Greenhouse Gas Reference Network
GML	NOAA Global Monitoring Laboratory
GOAON	Global Ocean Acidification Observing Network
GOMO	NOAA Global Ocean Monitoring and Observing
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
ICOS	Integrated Carbon Observation System
IOOS	NOAA Integrated Ocean Observing System
IOOS-RAs	IOOS Regional Associations
IPCC	Intergovernmental Panel on Climate Change
ITAE	Innovative Technology for Arctic Exploration
MICE	Models of Intermediate Complexity for Ecosystem Assessment
NACP	North American Carbon Program
NASEM	National Academies of Science, Engineering, and Mathematics

NCCOS	NOAA National Centers for Coastal Ocean Science
NMFS	NOAA National Marine Fisheries Service, also NOAA Fisheries
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NOS	NOAA National Ocean Service
NRDD	NOAA Research and Development Database
NSF	National Science Foundation
NWS	NOAA National Weather Service
OAP	NOAA Ocean Acidification Program
OAQ	NOAA Office of Aquaculture
OAR	NOAA Office of Oceanic and Atmospheric Research, also NOAA Research
OCM	NOAA Office for Coastal Management
OHC	NOAA Office of Habitat Conservation
PMEL	NOAA Pacific Marine Environmental Laboratory
SG	NOAA National Sea Grant College Program
SOOP	Ships of Opportunity Program
US	United States
USDA	United States Department of Agriculture
USGCRP	United States Global Change Research Program

Figures and Tables

A brief title and quick link to each of this report's tables and figures are provided below. To easily access any of these tables or figures, simply click on the Figure or Table number and the document will automatically advance to that image.

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Executive Summary

How to use this document.

This document is intended to serve as a reference for exploration of carbon removal research at NOAA. The report was drafted by authors from across NOAA to provide strategic direction to relevant labs and programs in multiple line offices. Our goal has been to assemble as much information as possible in order to facilitate conversations about Carbon Dioxide Removal (CDR) at a high level within the agency. It is our vision that this document will be used to develop an implementation plan for CDR research at NOAA in the event that Congress instructs the agency to engage in this emerging research front. This document may also be useful in aiding the future development of content for public release and / or various NOAA digital platforms.

This report does **not** endorse any specific CDR activity, technique, or application. Rather, it is similar to recent reports released by the National Academies of Science, Engineering, and Mathematics (NASEM); the Department of Energy; and the Energy Futures Initiatives, which note that more research is necessary. This report also does **not** compare or contrast nature-based and engineered CDR techniques focused on emissions reductions, such as carbon capture, utilization, and storage (CCUS). Our goal is to explore NOAA's role in assessing negative emissions strategies, which are techniques that remove carbon directly from the atmosphere and marine systems.

Report Contents.

This document is organized in four parts:

- An introductory section, including the scientific motivation for CDR research;
- A review of potential CDR techniques and current science;
- A synopsis of NOAA's key assets for CDR research; and
- A vision of CDR research at NOAA.

Key Findings

A summary of the key findings of this report is provided below.

Scientific motivation. Parts I and II of this report provide a summary of the scientific motivation for CDR research and a summary of the current status of several atmospheric, coastal, and oceanic CDR techniques. Human-induced climate changes already affect every part of the globe, with potentially dire consequences for many ecosystems and human communities. Under current emissions trajectories, global surface temperatures will continue to rise. With further warming of the Earth system, every region is projected to experience increasingly concurrent climate extremes, associated with clear impact drivers. Limiting warming to levels that avoid extreme risk requires immediate and substantial reductions of greenhouse emissions, as well as the removal of carbon dioxide from the atmosphere. While emissions-reduction approaches are the primary component for addressing this challenge,

negative emissions strategies will be essential for keeping global temperatures at or below target levels. Negative emission strategies refer to a portfolio of techniques that are used to remove greenhouse gasses from the atmosphere and lock them away from the atmosphere. Carbon dioxide removal (CDR), the focus of this report, specifically references techniques that remove legacy emissions of carbon dioxide from the atmosphere. Many of these techniques are promising in theory, but require additional research to evaluate their effectiveness and scalability, and explore potential co-benefits and environmental risk. This report includes a summary of several techniques, each of which is compared in Table 1, which shows our current understanding of the relative strengths and weaknesses of each technique, as well as NOAA's potential contributions.

NOAA's role. Part III of this report reviews NOAA's potential role in CDR research. NOAA is recognized around the world for its leadership in Earth system science and environmental stewardship. Its existing mandate already covers research and monitoring of Earth's carbon cycle and climate system. Accordingly, CDR techniques that change the climate system are already part of NOAA's purview. NOAA has been approached by multiple federal agencies and private sector interests to contribute our expertise to CDR research. In addition, NOAA is an internationally recognized leader in environmental stewardship and community resilience. We envision that research in the agency could use existing and innovative observations, models, ecosystem assessments, spatial planning tools, and stakeholder inputs to inform evidence-based decisions concerning the effectiveness and potential implementation of carbon removal techniques by federal and state governments, private sector interests, and nonprofit organizations.

A vision of NOAA CDR research in the future. In **Part IV** of this report, we offer a vision of how NOAA may engage CDR research in the future. Estimates indicate that between 400 and 1000 GT[1] C must be removed from the atmosphere and sequestered safely by 2100 to meet warming targets of 1.5 to 2 °C (Rogelj et al., 2018, 2015). Given the necessary pace of infrastructure development to meet these goals, the construction, engineering, and equipment manufacturing sectors associated with building CDR facilities could see at least 300,000 new jobs by 2050; overall, the value of the carbon management sector could rise to U.S. $259 B by 2050 (Larsen et al., 2019). To meet the challenges associated with this growing industry, we suggest that the global scientific community, including NOAA, will need to proceed with a parallel research paradigm. This would include multiple simultaneous streams of basic and applied research that address the effectiveness and potential impact of carbon removal projects from a variety of efforts. Such an effort would gradually build to field studies as each technique matures, and then broaden to application of sustainable, effective methods of carbon removal. Throughout this three-stage process, it will be imperative to act with the highest standards of

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[1] 1 gigaton (GT) of carbon dioxide (CO_2), which is used in this document, is identical to 1 petagram (Pg) of carbon dioxide (10^{15} g) and equivalent to 0.27 GT of carbon (C), a term that is used in some circles. To visualize this amount, 1 GT C can be represented by 1 km^3 of coal, or approximately 8.3 million train cars filled with coal. That train would wrap around Earth five times. The total amount of carbon needed to be removed today from the atmosphere to reach pre-industrial concentrations (~280 ppm) is ~1064 GT CO_2. To bring today's concentration of ~415 ppm down to 350 ppm, a number once touted by many as acceptable, would require the removal of ~514 GT CO_2.

transparency and scientific integrity in order to protect the public’s confidence in Earth system data.

Part I: Introduction

It is abundantly clear that climate change is a threat to modern society and will likely compromise key societal sectors in coming decades and centuries. Major IPCC Assessments since 1990 have successively reported on the increasingly dire impacts of climate change. Numerous subsidiary reports have built upon these to provide regional, national, or topical detail. All state that climate change will significantly affect our national security, both directly through impacts on our agriculture, environment, economy, public health and safety, and political stability, and indirectly, as a security threat multiplier to national security.

The recent IPCC's 6th Assessment Report acknowledged that society must act aggressively to hold warming to ~1.5 - 2 ℃ above pre-industrial levels by the end of the century. In discussion of Mitigation (WG3), nearly every scenario that achieved these goals included *"deep emissions reductions."* Certainly, there will be efforts to adapt to the consequences of rising temperatures, but society will also need to take action to mitigate them and, consequently, reduce their impacts. The IPCC AR6 report on Mitigation (WG3) emphasizes three primary actions that can help keep the temperature increase below 1.5 - 2 °C by the end of the century.

First, energy efficiencies help reduce the total overall demand for fossil energy. The IPCC's 6th Assessment Report highlights "decarbonization gains" that result from improved energy efficiency: The energy necessary to yield each unit of GDP has fallen by approximately 2% per year (WG3). Some studies suggest that complete implementation of all known energy efficiency strategies could provide 40% of the emissions abatement required to meet Paris Agreement climate targets (IEA). However, these gains can be masked by increased demand for energy-generating goods and services.

This leads to the second pathway: a shift from fossil fuels to renewable or non-carbon based energy as the primary source of power could dramatically reduce and ultimately eliminate most carbon dioxide emissions, despite increasing global energy demands. This falls largely on the transportation, power production, and power distribution sectors of our economy (IPCC AR6 WG3). This shift is already underway to some extent, in part because the cost of renewable energy with storage is falling below the cost of coal, oil, and natural gas. Accordingly, corporations, states, and municipalities are already engaging in robust efforts to advance renewable energy. Electric vehicle technology is advancing rapidly in the private sector, which, along with a power grid based on renewable energy, could make a substantial dent in emissions.

The third pathway is the removal and stable storage of legacy greenhouse gas emissions away from the atmosphere. According to the IPCC's recent AR6 report, carbon removal techniques are now essential components of almost all pathways that achieve 1.5 – 2 °C warming goals. If emissions rates continue to rise, meeting these goals will require increasing reliance on negative emissions technologies, or carbon dioxide removal (CDR).

While negative emissions technologies and carbon removal techniques are still in the early stages of development in most cases, the body of research around these techniques is growing fast (e.g., NASEM 2018, 2021), as is private and public interest in the development of carbon sequestration infrastructure. Still, there is a clear gap between the knowledge needed to successfully upscale this industry and the current pace of innovation. In one recent report summarizing the potential economic benefits of Direct Air Capture (DAC), the construction, engineering, and equipment manufacturing sectors associated with building CDR facilities could see at least 300,000 new jobs by 2050 (Larsen et al., 2019).

Given the potential economic and climate benefits of carbon management for the U.S., the Biden Administration has set a goal of Net Zero emissions from the United States by 2050 (WH, 2021a and b). The Infrastructure Innovation and Jobs Act also codified the potential benefits of Carbon Removal for both climate and economies (Sec 40301), in addition to funding the establishment of regional DAC infrastructure in the United States.

These early investments are essential, given that society has neither the technology nor the understanding to remove CO_2 on the scale needed today, nor do we understand the potential environmental and human impacts of such actions. Beyond developing the most effective CDR systems (if any can be developed at the necessary scale), there are huge challenges associated with this endeavor, including accurately tracking and providing accountability metrics for carbon removal. Given these clear research and development needs and broad potential impacts, there is a role in CDR research for almost every federal agency, for the private sector, and for state and local governments. This view was reflected in Congress's 2021 mandate that the Department of Energy prepare a report on cross-sector CDR science, emphasizing the role that federal research plays in the development and implementation of carbon dioxide removal (Energy Act of 2020 Section 5002).

As an internationally recognized leader in science, environmental stewardship, and community resilience, NOAA is well-positioned to lead in the analysis of impact, effectiveness, feasibility, and risk of many CDR techniques. NOAA is recognized around the world for its leadership in Earth system science and environmental stewardship. NOAA leadership and transparency in observing and studying the atmosphere and ocean make it a trusted agent for assessing the effectiveness of CDR approaches. Additionally, NOAA's deep connections to regional and local stakeholders across the nation connects decision makers with the data they need to pursue evidence-based, actionable solutions for climate adaptation and mitigation. Numerous public and private entities at multiple scales are already exploring various CDR techniques involving the biosphere, the ocean, and even direct capture from the atmosphere. NOAA's emphasis on big-picture, long-term monitoring and its research capabilities are ideally suited to understand, evaluate, and verify these efforts and their potential for success.

This document focuses on NOAA's potential role in CDR and how its mission and capabilities map to specific CDR needs. CDR is currently in its infancy, as are NOAA's efforts to support it. NOAA has a suite of capabilities that can be applied to understand and assess CDR and understand its impacts on ecosystems and society. In this report, we outline some key established techniques for carbon dioxide removal in land, marine, and coastal settings; discuss how these techniques intersect with NOAA's existing research mandates; and, finally, discuss what a mature CDR research and assessment strategy might look like at the agency. What becomes readily clear is that NOAA's climate and carbon cycle research are already foundational, respected, and world class. We now need to put these assets to work to address carbon dioxide removal as a key component of climate crisis adaptation and mitigation.

Part II: Overview of CDR Approaches

According to the recent IPCC Sixth Assessment Report (AR6), most emissions strategies that limit climate warming to 1.5 - 2 °C rely on CDR. In general, by the middle of the century, approximately 10 - 15 GT CO_2 removal is required each year[2]. Worldwide, most operational projects are currently small (i.e., sequestering on the order of 10,000 times less CO_2 than what is needed by the end of the century)[3]. It has been estimated that the industry must grow rapidly in order to meet these targets[4]: it will be necessary to not only increase the efficiency and number of these projects but also explore alternative technologies to achieve these ambitious goals by 2050 (Nemet et al., 2018).

It is extremely likely that these removal goals will be met by a portfolio of techniques, rather than emphasizing one universal application. Current strategies for capturing atmospheric CO_2 can be generally categorized into enhanced natural processes and human-assisted processes that leverage large-scale chemical transformation of atmospheric CO_2 into land, ocean, and coastal reservoirs. In the sections below, we profile each of these technical sectors in which NOAA may engage, including the stage of development of the technique, the possible co-benefits and risks, and key research necessary to attain GT-scale carbon capture. We group these into three categories: Land-based methods; ocean-based methods; and coastal methods. In this overview section, we provide some technical background that can inform the relative strengths and weaknesses of the methods described below.

Comparing CDR Techniques

Methods of carbon removal are traditionally evaluated on several success metrics, including (a) scalability; (b) the duration of potential storage; and (c) the cost per ton of removal (e.g., see Figure 1). Scalability refers both to how quickly these projects can be replicated annually and to the theoretical cap on the potential removal of these particular projects. In general, methods that have a very high theoretical cap as well as a high potential for annual proliferation have a high scale potential. Beyond scaling carbon dioxide removal, another key challenge is to find deposition reservoirs that minimize leakage back into the atmosphere. CO_2 has a lifetime in the atmosphere and oceans of 1000s of years, which makes it imperative that the reservoirs are sustainable over long periods. The duration of storage references how long the carbon removed by a particular technique can be stored. The longest storage times are essentially permanent removal, and preferred, while shorter storage times are considered less desirable and less efficient. Third, methods with a low cost-per-ton for removal are considered more economically

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[2] The pace and magnitude of necessary carbon removals to meet warming targets varies between climate scenarios. For example, scenario SSP1-1.9 requires about 430 GT CO_2 by the end of the century, whereas other scenarios may require as much as 1000 GT CO_2 (Rogelj et al., 2018).

[3] There are currently 15 direct air capture plants operating worldwide, capturing more than 9,000 T CO_2 / year, with a 1 MT CO_2 / year capture plant in advanced development in the United States that may become operational by 2023 (IEA, 2020). The largest DAC plant in the world opened in Iceland in 2021, which can by itself draw down 4,000 T CO_2 annually (ClimeWorks, 2021).

[4] A sustained 6% annual increase in carbon removal capacity between 2040 and 2060 is required; see Minx et al. 2018, Figure 9.

feasible[5]. Therefore, an ideal method would be highly scalable with long term storage at low cost. In addition to these 3 key metrics, all forms of CDR may have environmental co-benefits and risks associated with their infrastructure or operation.

A summary of how the different techniques we review below compare based on these metrics can be found in Table 1. Note that none of the methods we surveyed here fall into the highest category by all three of these metrics. Also included in Table 1 is an estimate of NOAA's potential overall impact with respect to each particular technique. Where the CDR Task Force felt that NOAA could assess the duration, scalability, costs, risks, and co-benefits of the approach, or (b) improve the readiness of the approach by providing decision support tools, we indicated that NOAA may have a high overall impact.

Beyond the relative scalability, duration, energy requirements, and cost of carbon removal approaches, there are other challenges associated with each technique. Some methods of carbon removal that seem promising may be at an extremely early stage of development, meaning that much more research will be required before they can be successfully scaled (and which may alter our understanding of this scalability). We emphasize here that this is especially true for ocean-based CDR methods. Additional study by the entire research community is needed to accelerate technical readiness and help better articulate the risks associated with each method. Further, the IPCC AR6 WG1 report emphasizes that there is a high confidence that most CDR projects will have additional risks that may impact sustainable development goals, particularly those that take place on land. Multiple reviews have posited how carbon removal strategies can incorporate environmental justice (e.g., Batres et al., 2021; Morrow et al., 2020; Bergman and Rinberg, 2021; and the White House Council on Environmental Justice, 2021). Most suggest that well-resourced community-driven decision making, equitable distribution of deployment, geopolitical responsibility sharing, and transparent technology transfer will be essential to inform deployment strategies and build safeguards against past, present, and future harms for marginalized communities and those already disproportionately impacted by climate change.

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[5] Costs per ton of removal are challenging to calculate, but overall should include the costs for both removal and storage of CO2 related to infrastructure, operations, and potentially negative environmental impacts. Generally, the costs of co-benefits (both sale of potential by-products as well as environmental co-benefits) are not included in the cost per ton of removal.

	Duration of Storage (years)	Scale Potential (Gt CO₂ / yr)	Estimated Cost ($ / tCO₂ removal)	Current Readiness	NOAA Potential Impact	NOAA Catalysts
Direct Air Capture [1,2,3,4,5]	◐ High, *using geologic storage* (> 1000 Years)	● Low - High (0 - 11)	● Low - High ($40 - $1000)	○ High	Moderate	*NOAA observing network (GGRN) sets global standard for verification*
Soil Carbon [2,6,7,8,9,10]	◐ Low, *potentially reversible* (< 30 - 40 years)	○ Moderate (2 - 6)	○ Low ($0-$100)	○ High	Low	*NOAA observing network (GGRN) sets global standard for verification*
Afforestation and Reforestation [2,11,12,13]	◐ Low - Moderate, *potentially reversible* (10 - 100 years)	○ Low - High (0 - 12)	○ Low - Moderate ($2 - $150)	○ High	Low	*NOAA observing network (GGRN) sets global standard for verification*
Macroalgal Cultivation [2,3,14,15,16]	● Low - Moderate (10 - 100)	● Low (0. 1 -0.6)	● Low - Moderate ($25 - $125)	● Moderate	High	*NOAA is the national clearinghouse for monitoring, spatial planning for macroalgal aquaculture*
Alkalinity Enhancement [2,14,17]	● High (>20,000)	● Moderate - High (1 - 15+)	● Low - Moderate ($25 - $160)	● Low - Moderate	High	*NOAA sets the global standard for ocean carbon system observations and sensor deployment*
Direct Ocean Capture [14,17,18]	◐ High, *using geologic storage* (> 1000 Years)	● Moderate (1 - 10)	◐ High ($400 - $600)	◐ Low - Moderate	Moderate	*NOAA sets the global standard for ocean carbon system observations and sensor development*
Ocean Fertilization [2,14,19]	● Low - Moderate (10 - 100)	● Low - Moderate (0.1 - 1+)	○ Low - Moderate ($50 - $125)	○ Moderate	Moderate	*NOAA sets the global standard for ocean carbon system observations and sensor development*
Artificial Upwelling / Downwelling [4]	◐ Low - Moderate (10 - 100)	◐ Low (0.1 - 1)	○ Moderate ($100 - $150)	○ Low	Low	*NOAA sets the global standard for ocean carbon system observations and sensor development*
Coastal Blue Carbon [14,16,19,20]	● High (> 1000)	● Low (0.1 - 0.4)	● Low ($10 - $50)	● High	High	*NOAA is a national Leader in coastal blue carbon monitoring, conservation, and restoration*
Ecosystem Recovery [14]	● Low - Moderate (10 - 100)	● Low (0.1 - 1)	● Low ($10 - $50)	● Moderate	High	*NOAA is a national Leader in coastal blue carbon monitoring, conservation, and restoration*
BECCS [22]	○ High, *using geologic storage* (> 1000 Years)	○ Moderate (3.4 - 5.2)	○ Low - Moderate ($20 - $200)	○ High	Low	*NOAA observing network (GGRN) sets global standard for verification*

[1] Minx et al., 2018, [2] Fuss et al., 2018, [3] Nemet et al., 2018, [4] Fasihi, Efimova, and Breyer, 2019, [5] Keith et al., 2018, [6] Smith, 2012, [7] Smith, 2016, [8] NASEM 2019, [9] Paustian et al., 2019, [10] UNEP, 2017, [11] Liu et al., 2016, [12] Smith et al., 2016b, [13] NASEM 2015, [14] NSEM 2021, [15] Krause-Jensen and Duarte, 2016, [16] NOAA CBC White Paper, [17] Eisamann, 2010, [18] de Lannoy et al., 2018, [19] NOAA 2010 OF White Paper, [20] Braswell et al., 2020, [21] Macreadie et al., 2019, [22] NRC 2019

○ ◐ ● NOAA readiness

Table 1. Summary of carbon dioxide removal methods by duration of storage, scale potential, estimated costs per ton of CO_2 removal, and overall technical readiness. Higher favorability (e.g., high technical readiness or low cost) is indicated by darker blue shading. Filled circles

indicate NOAA’s capabilities to address, validate, measure, or improve any of these characteristics (e.g., by increasing or validating storage duration, or by lowering costs of the method), though this may require additional capacity. NOAA’s potential overall impact is addressed in the last two columns, highlighting where key NOAA assets could catalyze research in each method, and where NOAA might have the highest overall impact. A detailed explanation of this review can be found here.

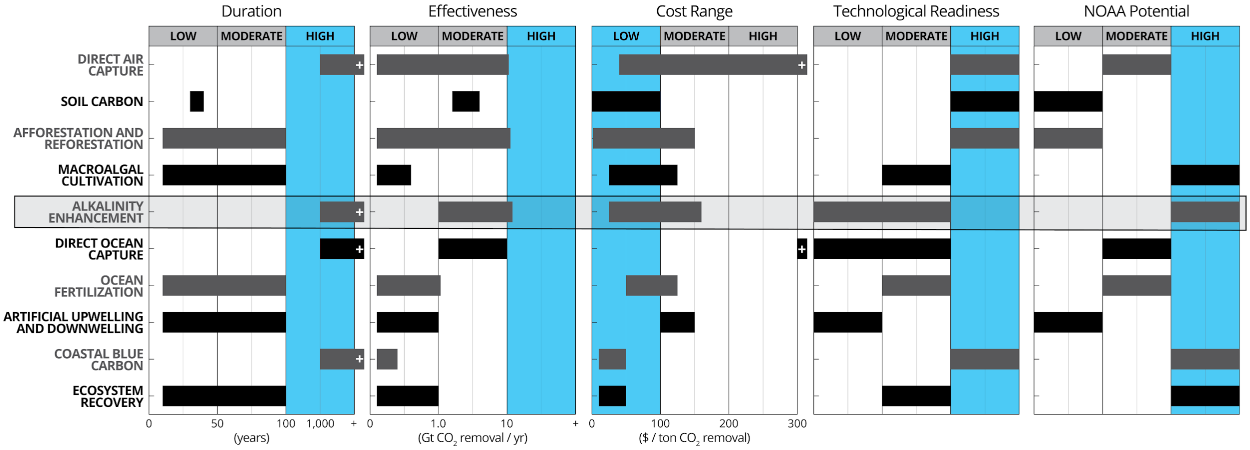
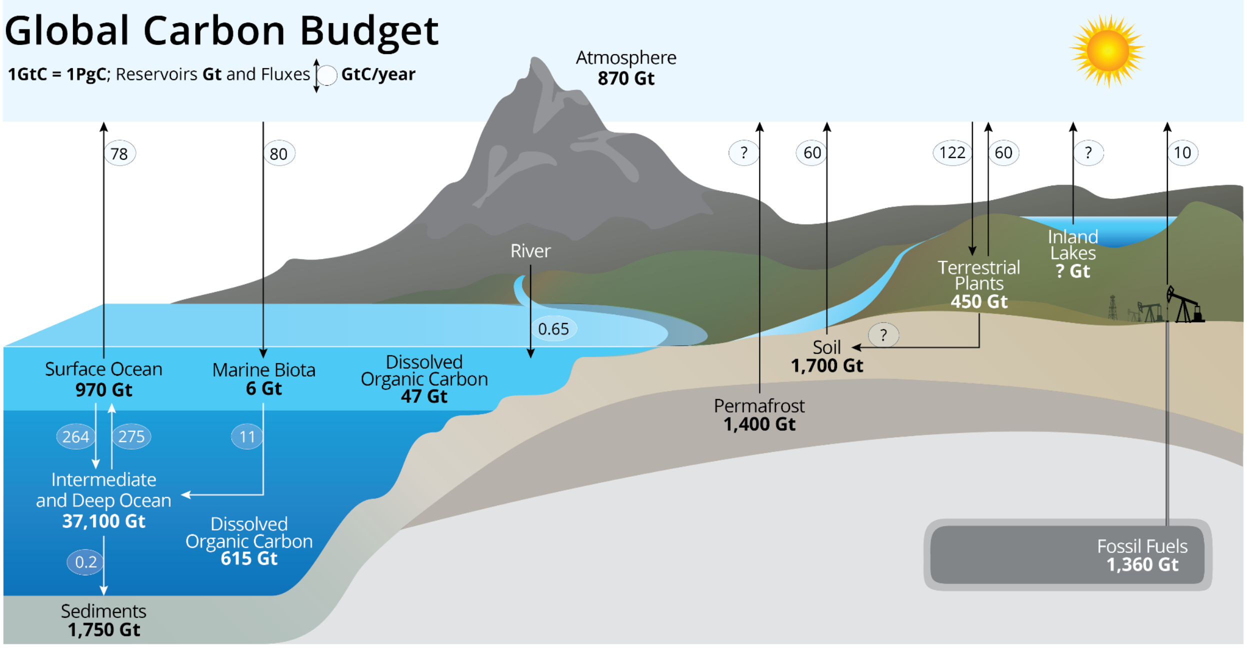


Figure 1. Comparison of various attributes of carbon removal methods, including the duration, effectiveness, cost range, technical readiness, and potential for NOAA to contribute for these methods. The data for this table are taken from Table 1. Note that the x-axis for effectiveness is shown on a logarithmic scale. Highlighted here is ocean alkalinity enhancement, one of the methods of carbon removal that is most related to NOAA’s existing mission.

A Note to Our Reviewers: This visualization is particularly challenging. Alternate visualizations for this data can be found here for comparison, including information on how this visualization was shaped by our reviewers.



Data from Hansell et al. (2015) and Friedlingstein et al. (2020)

Figure 2. Global carbon budget. The latest global carbon budget given for 2021 from Friedlingstein et al., 2020 and supplemented with data from Hansell et al., 2015. The estimated inventories of each of the reservoirs are in PgC (in bold) and the annual mean fluxes are in PgC/yr (in circles). Each of the CDR approaches described in this report seeks to store atmospheric carbon in one of these reservoirs.

Breakout Box: Our Natural Carbon Dioxide Removal System

Colm Sweeney

A broad perspective of carbon reservoirs and the present-day annual exchange of carbon between these reservoirs (Figure 2) provides some important context for understanding both the CDR processes that are naturally occurring and those reservoirs and exchange processes that can be further enhanced.

The natural 50% uptake, climate change, and carbon-climate feedbacks: Natural sequestration of atmospheric carbon dioxide in ocean and terrestrial environments captures just under 50% of the CO_2 that is added to the atmosphere every year through fossil fuels emissions. Without this natural CDR, Earth would already be facing a 1.5 °C warming due to the increase in atmospheric CO_2 that we project. However, climate change is already reducing land and ocean carbon uptake capacity, leading to a positive feedback that increases climate change. Permafrost may be a particularly potent example: permafrost soils contain enormous amounts of organic carbon that may respire as be released to the atmosphere as Earth's climate warms. Earth system models suggest that some of these feedbacks (like permafrost sequestration) are not reversible over decadal to centennial timescales, even under scenarios that project gigaton-scale carbon removal from the atmosphere. In some cases, removing carbon from the atmosphere could lead to CO_2 outgassing from other natural carbon reservoirs. These carbon-climate feedbacks, both those induced by climate change and those induced by CDR itself, may reduce the long-term efficiency of many of these CDR methods. NOAA's atmospheric and ocean observations and analysis over the past 60 years have played a critical role in understanding and quantifying the natural carbon cycle, and will continue to play a role in detecting changes that result from continued climate change and from CDR.

Ocean's role - Before atmospheric CO_2 started increasing, it had been assumed that the oceans were a source of CO_2 into the atmosphere due to the fact that on an annual basis ~0.65 Gt of C were being added to the surface oceans through riverine input. However, with the exponential increase in atmospheric CO_2 through fossil fuel emissions, the air-sea CO_2 gradient has increased over time leading to net uptake of atmospheric CO_2 by the ocean. This natural response of the ocean to take up more carbon as it is introduced into the atmosphere may lose efficiency and slow down and as solubility and biological transport processes change in response to surface ocean warming and the stratification that follows. It is imperative that NOAA and its collaborators continue to understand carbon-climate feedbacks to better understand the future response to warming and the long-term efficiency of carbon removal.

The reservoir sizes in the ocean also give us valuable insights into marine CDR opportunities. While the gross fluxes of carbon into the ocean are driven, in part, by the biological pump, the 6 GT CO_2 reservoir of biomass signals that the carrying capacity of that reservoir is small. While the dissolved and inorganic carbon reservoirs (~150 Gt C) are larger, and accordingly could be a more efficient way of sequestering carbon from the atmosphere, sequestration is only half the problem: transport of sequestered carbon to the deep ocean, and ultimately into ocean sediments, where it cannot escape back into the atmosphere will ultimately determine the durability of any sequestered carbon pool. It is this ability of the ocean to durably store carbon, rather than to simply absorb it, that is the driving mechanism for several of the CDR approaches described in this report.

Land's role - Like the oceans, the land biosphere has continued to absorb increasing amounts of CO_2 as concentrations in the atmosphere have increased. One mechanism driving this process is known as CO_2 fertilization, which leverages the ever increasing concentration of atmospheric CO_2 to drive uptake in productivity of plants. In principle, one expects land use constraints and nutrient and water limitation to provide a future threshold to this process. Likewise, as atmospheric CO_2 has increased, so have sources of atmospheric nitrogen which may also be playing a role in biospheric uptake. Meanwhile wildfires are burning more frequently and hotter, displacing massive amounts of soil carbon into the atmosphere.

Again, the simple picture of the carbon cycle (Figure 2) provides important insights to natural processes that could be exploited to advance CDR. One of these takeaways is the fact that terrestrial biota in the form of land plants provide an extremely efficient mechanism for taking CO_2 out of the atmosphere and this process as the first step of atmospheric CO_2 sequestration should be considered. The key here is capturing this carbon in forms that can be stored in deep reservoirs.

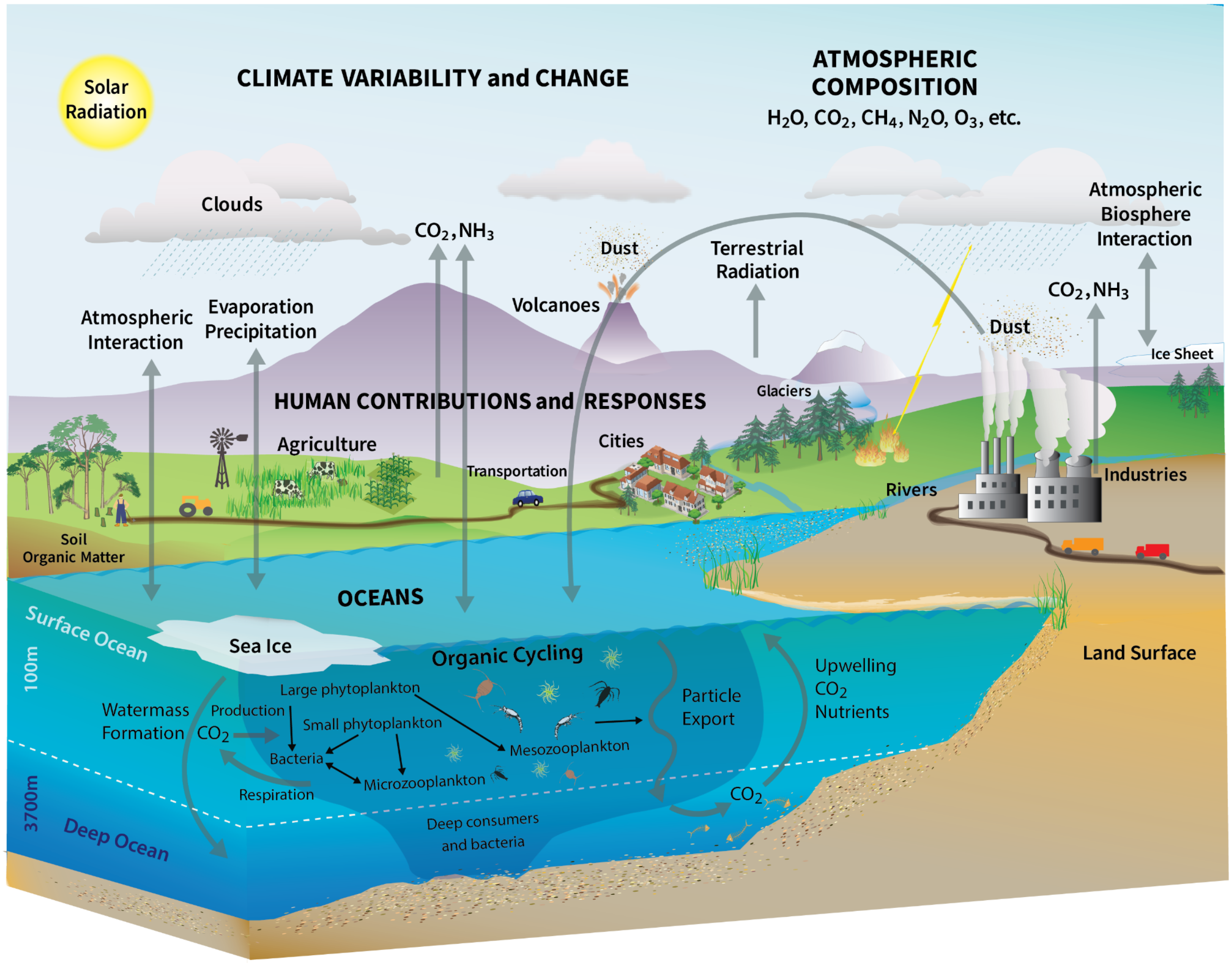


Figure 3. Processes influencing the climate system . Schematic of major natural and anthropogenic processes and influences on the climate system including CO_2, dust, iron, and nitrogen interactions between Earth system components modified from Dunne et al., 2020.

Land-Based Approaches

James Butler, Colm Sweeney

Numerous land-based CDR approaches have been proposed and are being tested on several scales. They involve changes to agriculture, forests, and other land-use activities (AFOLU, e.g., Smith et al 2018, IPCC AR5 Chapter 11), as well as direct air capture of CO_2. Some experimental efforts are funded by the federal government (e.g., ARPA-E, USDA), foreign governments, and many private organizations, who are seeking to support or develop CDR approaches. Most are being conducted only at research levels at this time, but as they develop, there will be a need for demonstrating their effectiveness, verifying that they work on the scales needed, and monitoring the success and environmental effects of each approach once implemented. Other challenges with land approaches include estimating the longevity of sinks, given the likelihood of destruction of natural land sinks (e.g., fires, degradation, respiration) and the resulting unanticipated impacts on terrestrial, coastal and oceanic ecosystems. Just as emission inventories of some greenhouse gases in the atmosphere, e.g., CFCs, HFCs, SF_6, are being improved with atmospheric measurements and inverse models, atmospheric removal inventories of CO_2 and CH_4 could be similarly estimated with additional adjustments to the way we currently monitor and report on atmospheric composition.

Direct Air Capture

Direct air capture (DAC) describes a number of processes that remove CO_2 from the atmosphere and put the carbon into a more stable form or long-lived reservoir. There are several approaches for DAC, but all follow a rather straightforward approach, which involves passing large amounts of air through a bed of adsorbent (liquid or solid) where CO_2 is selectively removed from the air and purified into a stream of gas that can be transformed into biochar-like material or deposited in geologic reservoirs where it can be subject to long-term storage or remineralization (Figure 4). While these processes are generally well developed, one key challenge of DAC is the necessary high-energy inputs: for DAC to be carbon negative or even carbon neutral, the energy required to drive these systems must come from renewable or non-CO_2-emitting sources. This also contributes to the high estimated costs of DAC. In just a few years, estimated removal costs have fallen from a prohibitive U.S. $2202 / T C (NASEM 2016) to as low as U.S. $367 / T C or less (NASEM 2019, 2021)[6]. Several companies, philanthropic NGOs, and venture capital organizations are continuing to develop, refine, and improve approaches such that the price of DAC is likely to fall even further in coming years. DAC methods generally cause minimal ecosystem disruption but do require expansive land use, a potential development hurdle. Other detriments include limited availability of reactive substrates and relatively unknown longevity of removal and cost of long-term storage.

NOAA Capabilities Relevant to DAC:

- NOAA has a strong atmospheric monitoring capability that can be built upon to achieve the desired granularity and temporal resolution in atmospheric observations needed to track DAC removal of gases. NOAA's labs provide high quality, long term observations of the trends and distributions of CO_2 and other greenhouse gases (GHGs), make GHG observations from large and light aircraft, surface sites, and tall towers, conduct process studies to evaluate both point and distributed sources and sinks of GHGs and other climate influencing constituents in the atmosphere, and analyze and predict impacts of changing CO_2 concentrations. In tandem, NOAA's satellites provide broad spatial coverage of CO_2 in four dimensions, and the agency supports a strong aircraft capability for understanding changes in the Earth system.
- Much of what we know about CO_2 in Earth's atmosphere derives largely from NOAA's observations. Adding capacity to these capabilities will lead to a healthy system for monitoring and evaluating the success or failure and risk of various CDR approaches.

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[6] Originally expressed as U.S. $600 / ton CO_2 (NASEM 2016) and $100 / ton CO_2 or less (NASEM 2019, 2021.

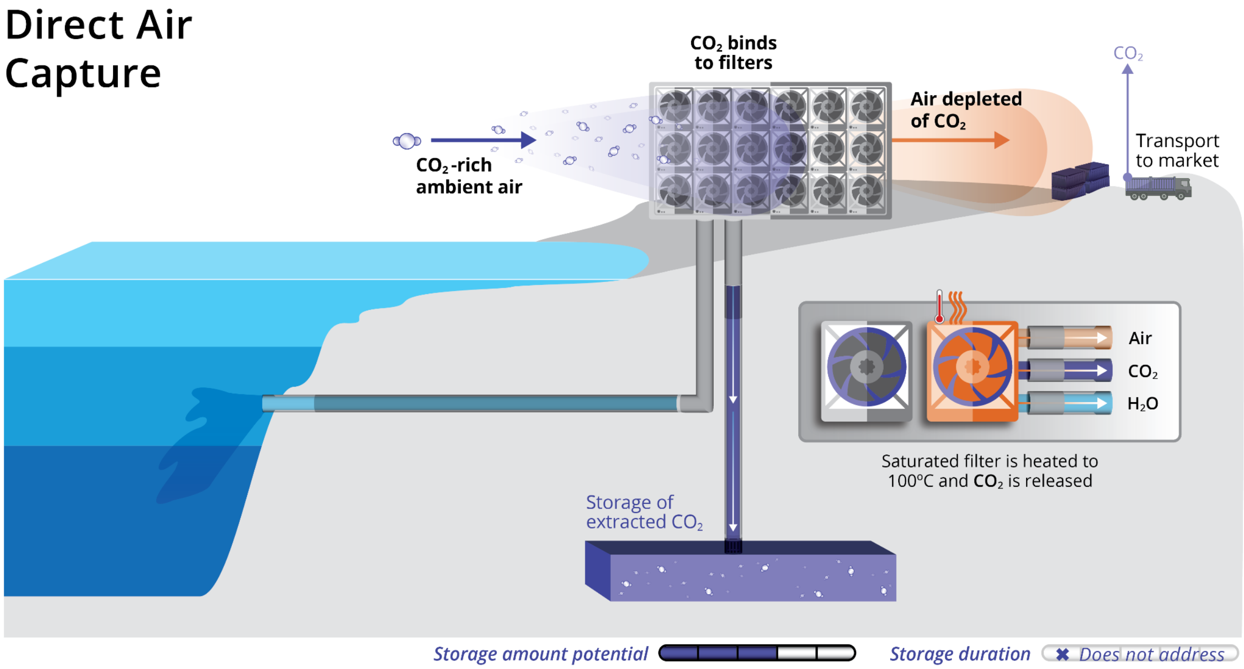

Figure 4. Direct Air Capture. Extracting dilute concentrations of CO_2 (~410 ppm) into pure CO_2 that can be transported to storage reservoirs requires technologies that can absorb CO_2 on solid or liquid reservoirs in one phase and release concentrated CO_2 in a second phase. The above example shows a filter-based approach that absorbs CO_2 at one temperature and releases captured CO_2 at a higher temperature.

Breakout Box: The role of geologic carbon storage

Tamara Baumberger and David Butterfield

Long-term storage is a key part of carbon removal strategy and planning. Along with burial of organic carbon in deep-sea sediments, reaction of carbon dioxide with rocks is a primary, natural mechanism to remove carbon dioxide from the atmosphere/hydrosphere (Sleep and Zahnle, 2001). The dissolved carbon dioxide in seawater that infiltrates the ocean crust reacts with basalt to form carbonate minerals, effectively permanently removing CO_2 and storing it as solid rock (Alt and Teagle, 2003). The process is thermodynamically favorable at low to moderate temperatures and requires no additional energy.

Large-scale experimental studies have been carried out in Iceland (Clark et al., 2020) and Washington state (Goldberg et al., 2018) to demonstrate that concentrated carbon dioxide pumped into basaltic formations reacts quickly to form carbonate minerals. Sub-seafloor storage of CO_2 within exploited oil reservoirs in the North Sea has been tested but the results are not published. The geochemistry of depleted oil reservoirs is substantially different from basaltic reservoirs, so the conversion of CO_2 to carbonate minerals is less certain. Given the huge extent of basaltic ocean crust and the known properties of permeability and porosity, the capacity of sub-seafloor basaltic reservoirs exceeds the gigaton-scale needed for significant carbon dioxide removal and storage (Goldberg et al., 2018). Off-shore, sub-seafloor storage of CO_2 does not require precious fresh-water resources associated with terrestrial reservoirs and does not threaten aquifers needed for agriculture and municipal water supplies.

The basaltic ocean crust along Cascadia Margin (off-shore Oregon, Washington, and British Columbia) has been studied and characterized. Scientific drill-holes penetrate through the thick sediment cover into the underlying basaltic crust (Hunter et al. 1999; Butterfield et al., 2001). The high pressures and low temperatures at the seafloor and within the crust stabilize pure CO_2 as a condensed liquid that is denser than surrounding seawater and, combined with the 200-m thick sediment cap, make it highly unlikely that stored CO_2 would migrate back into the deep ocean. Direct injection of CO_2 into the sub-seafloor may be more permanent and have fewer potential ecological impacts on the deep ocean than sinking equivalent quantities of marine organic material to the seafloor.

There are major technological challenges associated with scaling up carbon dioxide removal and pumping into a sub-seafloor reservoir. A pilot project led by Ocean Networks Canada with a diverse consortium of partners is directly addressing these issues, as well as the major socio-economic challenges associated with CDR and sub-seafloor storage. Although not part of CDR, industrial carbon capture in some coastal areas could also link to sub-seafloor storage (Goldberg et al., 2018) and reduce the amount of point-source CO_2 released to the atmosphere during the societal transition from fossil-fuel to carbon-free energy sources.

The Department of Energy (BOEM) and the USGS, with academic and industry partners, are conducting research and evaluating feasibility of carbon storage in basaltic reservoirs. As a result of extracting oil from the ocean crust, the oil and gas industry has relevant technologies and processes for piping CO_2 into the ocean crust.

NOAA has relevant expertise in the global and marine carbon cycle, seafloor mapping, geology, geochemistry of water/rock reactions, benthic ecosystems, ocean engineering, deep-sea technology, chemical monitoring and other areas needed to help site potential test projects for sub-seafloor storage and to monitor their effectiveness and safety. As the agency with responsibility for the health and sustainability of the oceans, NOAA has a mandate to be involved in evaluating potential CDR and carbon storage strategies.

Soil Carbon and Biospheric Approaches

Terrestrial systems in the northern hemisphere remove ~¼ of the carbon emitted to the atmosphere each year through anthropogenic activities (Tans et al 1990), including agriculture, forests, and other land-use activities (AFOLU) capable of storing carbon for long periods. However, this sink is particularly challenging to quantify. Regrowth of forests, storage in soils (e.g., Figure 5), destruction of biomass by fires, additional impacts of climate change, and other processes need to be better monitored and understood before they can be accelerated to remove additional CO_2 from the atmosphere. Changes in agricultural practices could possibly be used to store more carbon in forest trees and their root systems, to retain more carbon in soils, or to convert the biomass to stable forms (e.g., biochar). The practices will likely provide an important pathway for restoration of soil organic carbon as well as reduction of costs for agriculture. However, the longevity of these storage techniques and their broader impacts is poorly understood.

In all of these land-based efforts, monitoring and verification will be essential. Many of these techniques are in their infancy and the widespread nature of soils, forests, and the like make this particularly challenging. Inventory accounting will be necessary to track carbon captured through these systems, but equally important will be top-down approaches, i.e, validation from atmospheric observations. If CO_2 has been removed effectively from the atmosphere, that will be measurable in the atmosphere over large enough scales. If efforts are not working, then that will show up in the atmosphere, too.

NOAA's Capabilities Relevant to Biospheric Approaches

- NOAA's CarbonTracker product today provides quarterly estimates of CO_2 transfers to/from the atmosphere by the oceans and terrestrial biosphere. Currently, CarbonTracker can provide good estimates of net annual CO_2 uptake across North America, and coarser estimates of world emissions and uptake from the biosphere.

Next Steps for Developing NOAA's Capabilities

- With an appropriate observational framework with greater density and frequency of observations, along with carbon-14 of CO2, which separates fossil fuel burning emissions from natural emissions, CarbonTracker could provide excellent information on subcontinental and policy-relevant scales.

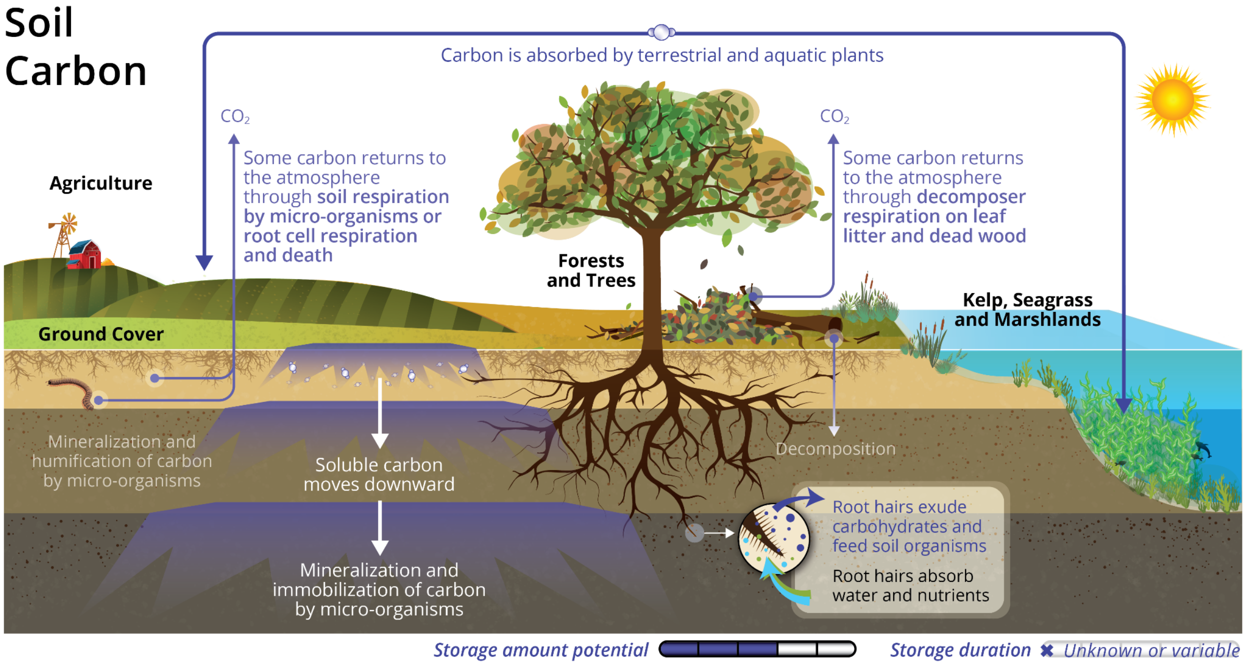

Figure 5. Soil Carbon.Soil carbon sequestration is a process in which carbon dioxide is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of soil organic carbon. Long-term storage of soil carbon requires mineralization of organic carbon or conversion of carbon into refractory forms like the bones and shells of animals, or chemical conversion by microorganisms.

Marine Approaches

Richard Feely

Marine carbon dioxide removal technological approaches augment the ocean's natural carbon cycle to complement mitigation efforts and reduce atmospheric CO_2 concentrations at gigaton levels of carbon removal. The broad approaches for marine CDR include technologically-enhanced natural processes and human-assisted technological approaches for carbon dioxide removal from the atmosphere and oceans. Presently storing ~¼ of annual CO_2 emissions, natural marine CO_2 sequestration pathways are not yet effective enough to offset all of the anthropogenic CO_2 sources and thus cannot keep the CO_2 from accumulating in the atmosphere (Figure 2). To accelerate this storage, the natural marine carbon cycle (Figure 3) can be technologically enhanced at local scales by increasing the growth of marine plants, including phytoplankton, or increasing ocean alkalinity concentrations. Ocean carbon dioxide removal can also be technologically enhanced through electrochemical separation of CO_2 from seawater. All of these pathways require some form of carbon sequestration or use of the byproducts to achieve permanent (i.e., the next century and beyond) removal of the carbon. In most cases, these approaches are in the very early phases of development and require testing for effectiveness, efficiency, and ecological risk. More research is required before they can be scaled up to the gigaton level.

Macroalgal Cultivation for Carbon Sequestration

Jordan Hollarsmith, Simone Alin, Hongjie Wang, Seth Theuerkauf

Macroalgae comprise a diverse group of marine photosynthesizers, many of which grow extremely quickly (centimeters / day), thereby rapidly taking up CO_2 from surface waters. It is estimated that 0.17 GT of macroalgal carbon per year, or 11% of total NPP, is currently sequestered globally in nearshore and deep ocean sediments, the majority of which results from naturally occurring (non-cultivated) macroalgae populations (Krause-Jensen and Duarte 2016)[7]. Accordingly, there is increasing interest in using macroalgae as a "low-tech" marine CDR strategy through aquaculture and habitat restoration. In the right conditions, a large fraction of macroalgae-derived carbon may be stored in benthic sediments for decades to millennia (Duarte et al. 2017). To better understand the potential and effectiveness of marine CDR from cultivated macroalgae, modeling and observational research is needed to identify the oceanographic, ecological, bathymetric, and methodological contexts in which future farms may be sited. Cultivated macroalgae may also be intentionally sunk into deep water with the goal of sequestering carbon. While this may be an efficient method to ensure that macroalgal carbon is sequestered, there may be unintended ecological consequences: for example, nutrient reallocation may simply shift production from microalgal to macroalgal settings, providing limited

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[7] Note that 2019 U.S. kelp farm production was 112,000 lbs (Alaska); 280,612 lbs (Maine); and 40,000 lbs (Washington). Kelp is also harvested at smaller scales Connecticut, California and New York. Because production estimates are not centralized, it is difficult to determine the exact spatial extent of active kelp farming that contributed to these harvest amounts (not all leases are active; not all actively leased areas produced meaningful harvest). These uncertainties in turn make it difficult to quickly estimate the area necessary to sequester or store 1 GT CO_2. However, the National Academies (2022) suggest that 63% of the global coastline, or a 0.5 km wide continuous belt of seaweed around the entire US coastline, would be required to sequester 0.1 Gt CO2 / yr. This may exceed the natural areal distributions of the 5 main species of kelp in kelp forests today.

sequestration benefit (Bach et al., 2021). Further, the removal of nutrients from the natural seasonal cycle may limit future local production. There may also be social resistance to this method as it involves the willful destruction of viable food sources. Restoration, conservation, and / or protection of natural macroalgae populations is also an important low-tech marine CDR strategy and comes with many other ecosystem services and benefits to coastal communities in the forms of fisheries, wild harvest possibilities, enhanced tourism, and natural beauty (Krause-Jensen and Duarte 2016). However, restoration is often extremely resource intensive with no method shown to be a guaranteed success, and protection can be politically difficult (e.g. MPAs) (Eger et al. 2020). Further, if carbon sequestration is an express goal of macroalgal restoration efforts, environmental observations of suitable resolution must be made to verify the magnitude and time scales of carbon sequestration. Macroalgae harvested for consumption represents sequestration on the order of months to a few years, deep ocean sequestration may be on the order of hundreds of years, and continental shelf and slope sediments may represent storage of decades to millennia, depending on depth, resuspension, and oxygen availability.

NOAA Capabilities surrounding Macroalgal Sequestration:

- NOAA is involved in kelp conservation and monitoring research in Washington and California, and in National Marine Sanctuaries, including in the Channel Islands, Monterey, and Olympic Coast National Marine Sanctuaries.
- Greater Farallones National Marine Sanctuaries has developed a methodology (and is improving that methodology) to estimate carbon sequestration via bull kelp export to deep-sea environments.
- The NOAA Aquaculture Program– inclusive of research at NOAA Fisheries, NOAA Research (Sea Grant), and the National Ocean Service (NOS)– leads extensive efforts to support macroalgae cultivation research, technology development, policy and regulatory support, outreach and education, and international coordination. Current efforts are focused on the Pacific Northwest, Alaska, and New England.

Next Steps for Developing NOAA's Capabilities:

- Build collaborations across NOAA line offices to measure carbon cycling and storage in and around macroalgae farms and natural macroalgal ecosystems (e.g., kelp forests, sargassum mats, etc.).
- Develop models to estimate sequestration duration and scaling potential across NOAA regions.
- Pair spatial analyses for siting macroalgae farms with modeling of optimal intentional sinking sites to maximize sequestration potential.
- Use benthic surveys and experiments to improve understanding of the ecological effects of added macroalgal biomass.

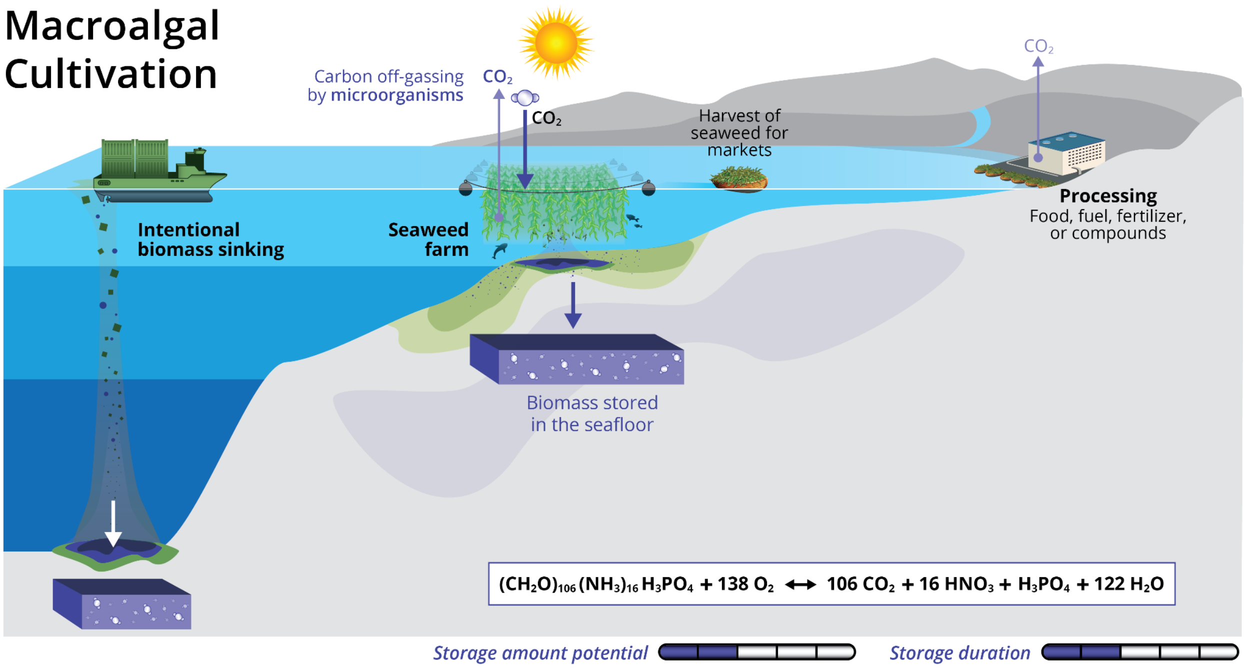


Figure 6. Macroalgal Cultivation. Marine carbon dioxide sequestration via the cultivation of macroalgae. Sequestration occurs during burial in sediment, either through intentional biomass sinking or auxiliary biomass sinking during the growing phase. Some storage effect is offset by carbon off-gassing due to aerobic remineralization of organic matter (indicated by the chemical equation). Macroalgal biomass can also be harvested and processed for food, fuel, fertilizer, or other compounds, which generally results in CO_2 release. Jordan to provide figure caption during review

Ocean Alkalinity Enhancement

Richard Feely, Brendan Carter

The ocean holds almost 45 times as much carbon as the atmosphere (Figure 2) in the form of dissolved “alkaline” minerals that naturally enter the ocean through rivers and groundwater over geologic timescales. “Ocean Alkalinity Enhancement” refers to efforts to increase this ocean storage capacity by increasing seawater alkalinity, thereby changing natural air-sea gas exchange into a CDR process. Strategies for increasing seawater alkalinity include electrochemical acid removal and accelerated weathering of alkaline minerals on land (Figure 7). Notably, seawater alkalinity is stable in the ocean for timescales of many thousands of years, meaning these approaches address both the removal and the storage aspects of CO_2 mitigation by shifting the balance of air-sea CO_2 exchange further toward the ocean. Overall, some estimates suggest that the timescale of carbon sequestration by alkalinity enhancement could be 100,000 years (Renforth and Henderson, 2017). Increasing seawater alkalinity has the co-benefit of mitigating ocean acidification by elevating pH. Possible shortcomings include high cost (both in terms of money and carbon footprint) associated with mining and transporting alkaline materials, trace element contamination from enhanced weathering approaches, the risk of altering chemical cycling, and the unknown biological effects of introducing large amounts of particulate material near the intervention site. Research on these approaches so far has been mostly limited to laboratory and modeling studies. Key unknowns include chemical and biological impacts of adding alkalinity or other byproducts, such as trace metals and silica, to the ocean (Renforth and Henderson, 2017). Key research needs include: 1) Initiating small-scale proof-of-concept field testing of ocean alkalinization to better quantify CDR potential as well as ecosystem impacts; 2) Developing models and observational tools capable of monitoring ocean alkalinization efforts and verifying carbon dioxide storage; 3) Improving models to help identify suitable locations for various ocean alkalinity enrichments and potential co-benefits and detriments to marine ecosystems (e.g., mitigating ocean acidification or enhancing trace metal toxicity); 4) Investigating upstream and downstream environmental impacts and CO_2 lifecycle accounting; and 5) Developing and optimizing autonomous platforms and strategies for monitoring ocean alkalinity enhancement.

NOAA Capabilities for Alkalinity Enhancement:

- NOAA has a well demonstrated ability to detect changes in ocean alkalinity and ocean carbon content on broad scales.

Next steps to develop NOAA's Capabilities:

- Conduct small-scale proof-of-concept closed-tank (e.g., MERL) and field testing of ocean alkalinization to better quantify CDR potential
- Develop models and new observational tools, including sensors, capable of monitoring ocean alkalinization efforts and verifying carbon dioxide storage.
- Develop models to help identify suitable locations for various ocean alkalinity enrichments, potential co-benefits, and detriments to marine ecosystems impacts.
- Sustain and expand ocean carbon observations and develop deployable, mobile autonomous platforms and strategies for monitoring and verification of ocean alkalinity.

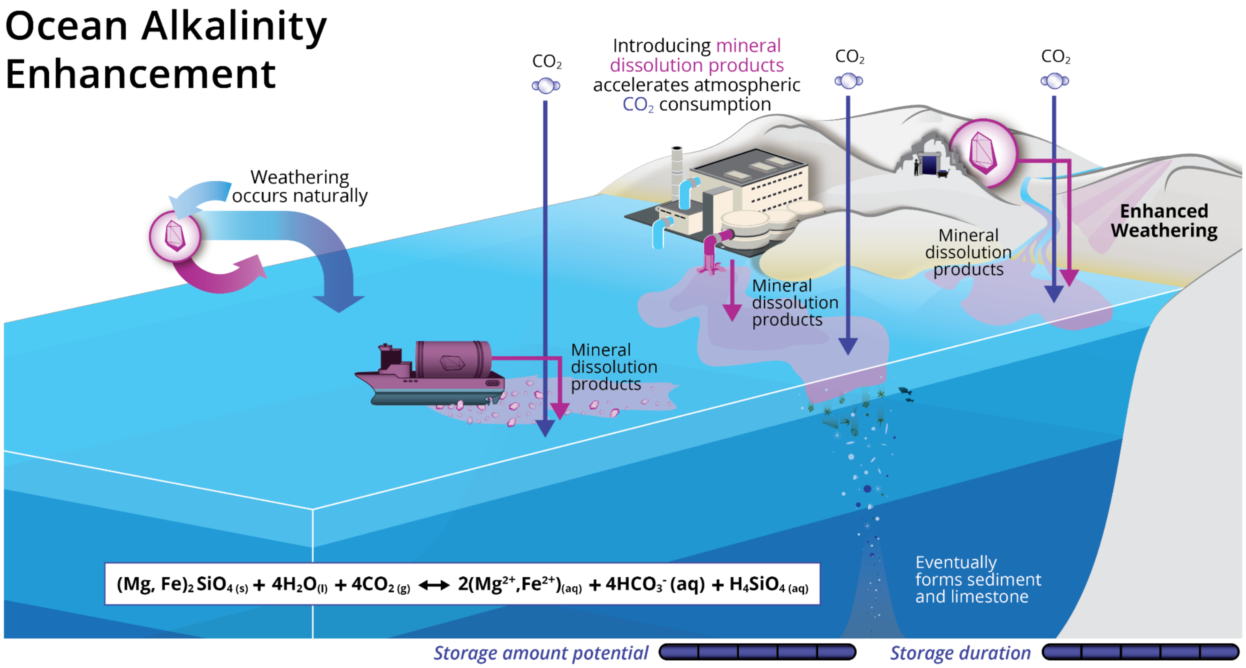


Figure 7. Ocean Alkalinity Enhancement. Ocean Alkalinity Enhancement by the addition of alkaline minerals on land or in the oceans to artificially enhance natural weathering and increase alkalinity. Increasing ocean alkalinity shifts natural air-sea CO_2 exchanges in favor of enhanced ocean storage. This diagram focuses on one approach whereby alkalinity is increased by reaction with olivine minerals, but there are many processes and mineral reactions under consideration that consume acid and thereby increase ocean alkalinity.

Breakout Box: Carbon Removal as Ocean Acidification Mitigation

Jessica Cross, Brendan Carter, Adrienne Sutton

Emissions reductions are the most direct, reliable, lasting (Mathesius et al., 2015, Hofmann et al., 2019), and well-understood way to mitigate ocean acidification. However, CDR methods that lower the concentration of CO_2 in the atmosphere have the potential to slow ocean acidification, and some marine CDR methods also have stronger local ocean acidification mitigation impacts. The scale, timing, and approach to carbon removal determines the efficiency and degree of ocean acidification mitigation on various temporal and spatial scales. There are many unknowns remaining regarding the OA mitigation potential for CDR and NOAA is well situated to answer these critical questions.

Individual CDR approaches may provide some local ocean acidification mitigation opportunities, although the impacts of these applications are nuanced. For example, seagrass meadows and their restoration have been shown to persistently buffer against ocean acidification (e.g., Ricart et al., 2021) in some cases, although other studies have found that seagrass net metabolism is typically close to zero on the global scale (e.g., Van Dam et al., 2021). Over longer timescales, alkalinity enhancement may also be a valuable, albeit slow, acidification mitigation mechanism: one recent study suggested that 30 years of alkalinization in the Mediterranean sea, facilitated by cargo ships releasing 200 Mt $Ca(OH)_2$ each year can hold mean surface pH values at present-day levels (Butenschön et al., 2021). Other interventions, such as kelp farming or ocean afforestation, may have impacts only seasonally or over short timescales, and may risk displacing existing phytoplankton productivity or produce other negative biogeochemical externalities (e.g., Boyd et al., 2022, Hurd et al., 2022, Bach et al., 2021).

However, it should be noted that even short-term or local-scale carbon removal could provide valuable acidification mitigation if occurring during times of heightened organism sensitivity or during episodic acidification events.

Despite these early uncertainties, multiple major assessments, including the UN 2030 Agenda (e.g., Soergel et al., 2021) and the IPCC (IPCC AR6 WG3), suggest that many CDR methods provide an opportunity for ocean acidification mitigation. When considering the potential of CDR co-benefits, it will also be important to acknowledge the risks of poorly implemented CDR (IPCC AR6 WG2). While some methods of marine carbon removal are relatively permanent (e.g., ocean alkalinity enhancement), others may have important feedbacks with the earth system (e.g., macroalgal sinking) that could worsen acidification and other associated stressors (e.g. deoxygenation) in subsurface and deep-sea environments. It will be essential to explore these carbon-climate feedbacks as CDR is implemented not only as a carbon removal tool, but as an acidification mitigation mechanism. NOAA's expertise in carbon cycle science, monitoring, and modeling affords an excellent opportunity for investigating these feedbacks. NOAA is also mandated to monitor and implement a strategic plan related to ocean acidification mitigation and adaptation under the The Federal Ocean Acidification Research And Monitoring Act (FOARAM) Act of 2009.

Direct Ocean Capture

Denis Pierrot

Direct Ocean Capture (DOC) refers to the process by which technologies remove and capture CO_2 directly from the ocean water (or other natural waters) by changing the pH of the treated water. The decarbonized water is then returned to the environment to enhance the air-sea CO_2 flux into the water. This technique leverages the ocean's natural capacity to absorb atmospheric CO_2 and is sometimes referred to as "Indirect Ocean Capture". The benefits of the technique are multiple. First, the method is scalable. Additionally, DOC has the potential to locally attenuate the effects of ocean acidification. Second, it is one of the few marine methods that could be deployed offshore, which would avoid expensive and competitive land use. Third, the captured CO_2 gas can be turned into valuable commercial products (e.g., fuel, chemicals), although that would make this process net-neutral rather than net-negative). Fourth, it is an electrical method which has the potential to be powered by fully renewable sources. However, this technology is not yet fully developed (de Lannoy et al., 2018). The main disadvantage of this technique right now is its cost. A recent cost analysis of a prototype-scale model puts it at around U.S. $600 / ton of CO_2 with a best case scenario of U.S. $400 / ton of CO_2. The high cost is mainly due to the huge amounts of water that must be circulated, the cost and efficiencies of the membranes, and the cost of chemical inputs (de Lannoy et al., 2018). These costs could be offset by co-locating the CDR plant with water-circulating platforms (e.g. desalination, ships) or ocean currents (Digdaya et al., 2020, de Lannoy et al., 2018, Eisaman et al., 2018). It is reasonable to think that RD&D in the near future will improve membrane materials and lower costs. The impact such a technique could have on an ecosystem is not currently known and research would have to be conducted on different scales.

NOAA’s Capabilities Relevant for DOC:

- NOAA has the ability to detect changes in ocean carbon content on broad scales.

Next Steps for NOAA on DOC:

- This kind of CDR method would benefit greatly from the field-based mesocosm experiments performed already by NOAA laboratories.
- Need to sustain and expand ocean carbon observations and develop deployable ocean carbon observing assets on shorter timescales to detect carbon removal.

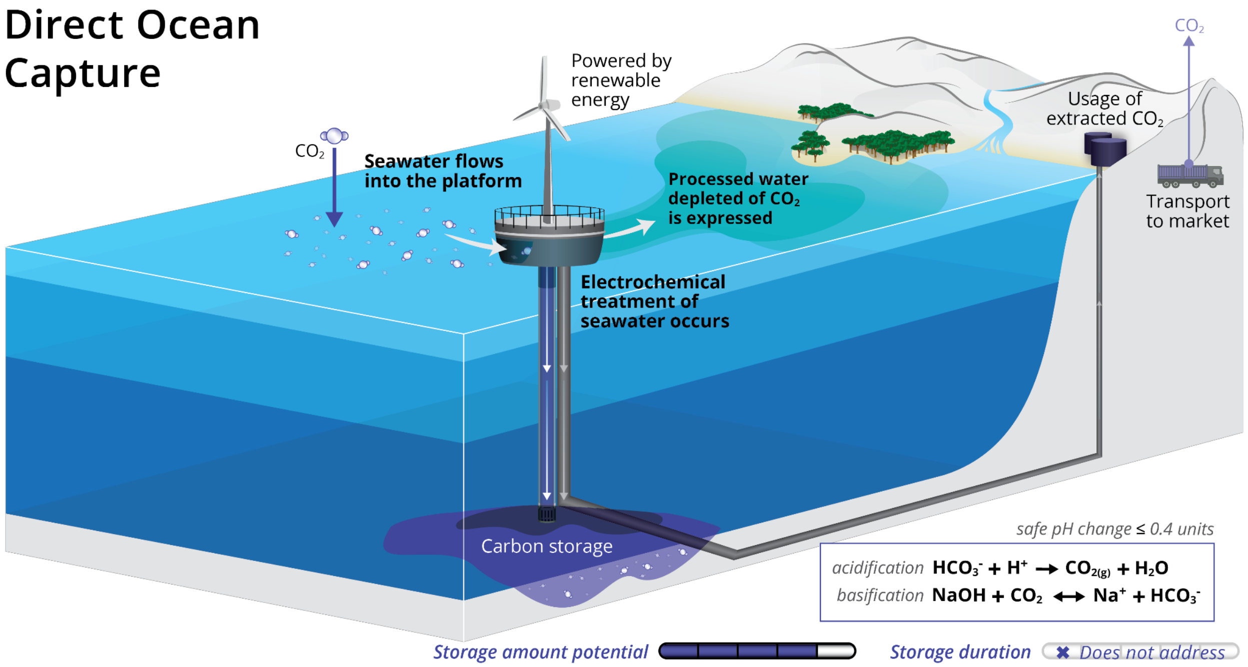


Figure 8. Direct Ocean Capture. Use of bipolar membrane electrodialysis (BPMED) allows the acidification of seawater to remove CO_2 and its sequential basification before release to the environment to absorb more CO_2 from the atmosphere.

Biological and Physical Carbon Pump Enhancement

Emily Osborne, Kathy Tedesco

Ocean fertilization (Figure 9), along with artificial upwelling and downwelling (Figure 10), deliberately enhances the ocean carbon sink by increasing the transfer of CO_2 from the atmosphere to the ocean via biological and physical carbon pumps. Ocean fertilization, which is carried out by the artificial addition of micro- (iron) or macro-nutrients (nitrogen or phosphorus) to increase phytoplankton growth, is intended to result in CO_2 fixation and ocean carbon export via the biological pump. Micro-nutrient fertilization is the most studied and scientifically advanced of these methods (e.g., ocean iron fertilization (OIF): Martin et al., 1990), and has been proposed as a technique to rapidly and efficiently reduce atmospheric CO_2 levels at a relatively low cost (Buesseler and Boyd, 2003). Ocean macronutrient fertilization (OMF) is fundamentally similar to OIF in that it triggers the biological carbon pump, however, OMF appears to more effectively increase carbon export efficiency and long-term carbon storage (Lawrence, 2014) compared to micronutrient fertilization. Possible OIF impacts of concern include the production of greenhouse gasses such as nitrous oxide (Jin and Gruber, 2003) and methane (Wingenter et al., 2004), significant regional reductions in seawater pH (Oschlies et al., 2010), development of hypoxia / anoxia within the water column (Keller et al., 2014), toxic algal blooms (Trick et al., 2010), as well as other unintended and unforeseen ecological and biogeochemical consequences from a process explicitly intended to alter food web dynamics. A critical downside of OMF is the quantity and cost of macronutrients (N or P) necessary to create sufficient biomass, particularly in comparison to OIF (Lampitt et al 2008; NAS, 2015). Studies that quantitatively evaluate environmental risks of OMF have been scarce and, therefore, limit the scale of implementation (Harrison et al., 2017).

Artificial upwelling has been proposed as one way to reduce the cost of nutrient fertilization by delivering cool, nutrient-rich subsurface waters to the photic zone where it has a fertilizing effect, enhancing primary production and carbon export via the biological pump (see Bauman et al., 2014 and Pan et al., 2016 for review). A major drawback is that nutrient-rich upwelled waters also have elevated CO_2 levels, in proportion to the available nutrients, that may outgas if the carbon is not sequestered by phytoplankton, and cancel out the benefit of biological carbon drawdown (Oschlies et al., 2010; Yool et al., 2009). Model simulations have shown concerning potential impacts following the cessation of artificial upwelling. Rather than reverting to pre-upwelling conditions, both surface temperature and atmospheric CO_2 rise to levels even higher than those of the control experiment (Oschlies et al., 2010). This pump can be further enhanced by pairing with artificial downwelling approaches that enhance carbon export via physical mixing and transport of water masses from the surface ocean to the deep ocean. A lack of experimentation and insufficient scientific literature leaves major unknowns regarding feasibility, efficiency, and risks associated with this method key uncertainties regarding their technological feasibility as well as potential prohibitively high implementation costs (NAS, 2015; Zhou and Flynn, 2005; Flynn and Zhou, 2010).

NOAA Capabilities for Carbon Pump Enhancement:

- NOAA has the ability to detect and measure changes in ocean carbon content on broad scales.

Next Steps for NOAA relevant for Carbon Pump Enhancement:

- Sustain and expand the ocean carbon observing network of cruises, moorings and autonomous platforms to monitor the effectiveness and environmental impacts of carbon pump enhancement technologies. Identify natural laboratories and paleoclimate records that can be used to determine the influence of environmental variability and nutrient fertilization on biological pump strength to better constrain biogeochemical and biological responses to system perturbations

- Develop models capable of simulating respective approaches in order to quantitatively estimate carbon storage efficiency over long time-scales (centuries or longer) and the potential occurrence and magnitude of side effects
- Enhance the quantity and quality of autonomous carbon system sensor technology.

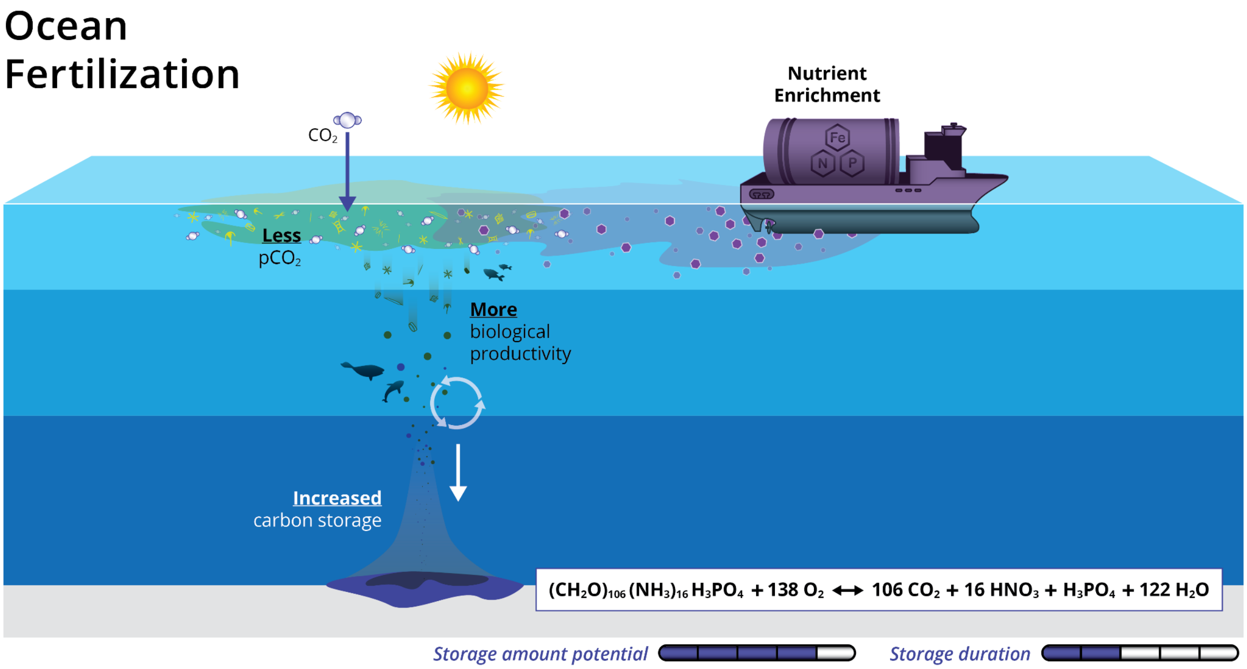


Figure 9. Ocean fertilization. The addition of nutrients (e.g. Fe, N, P) to the surface ocean to stimulate primary production resulting in CO_2 fixation and carbon export to depth via the biological pump.

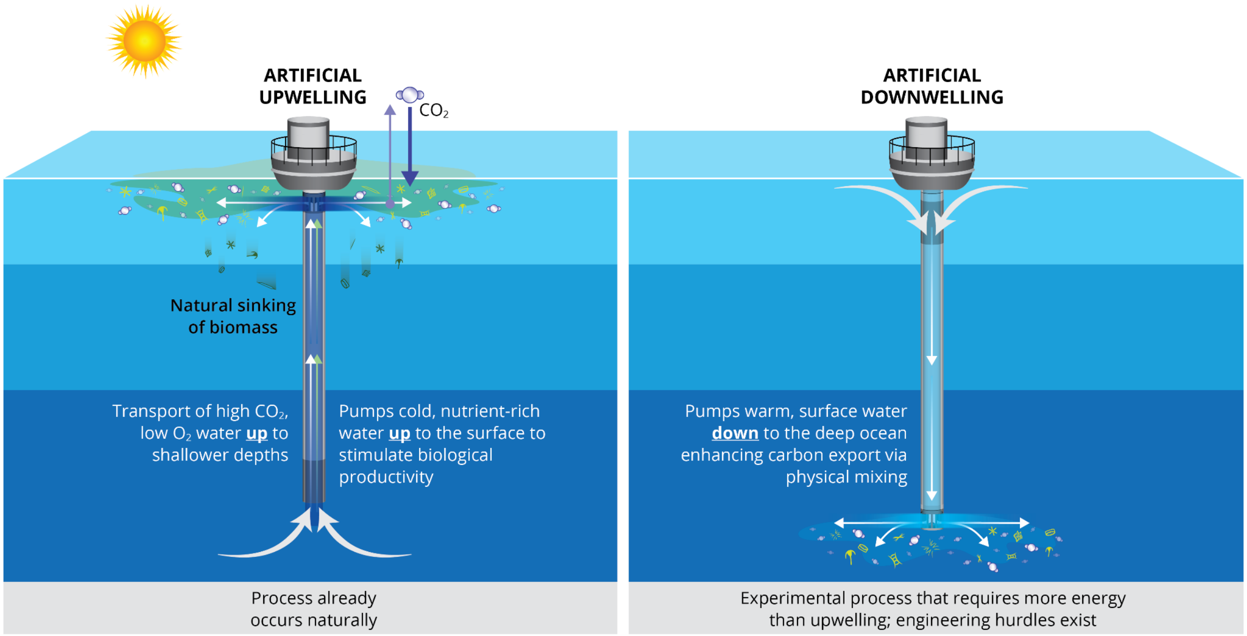


Figure 10. Artificial Upwelling and Downwelling. Technological transport of a) cold, nutrient-rich water to the surface to stimulate primary production and increased export of carbon to depth (Artificial Upwelling); b) CO_2-rich water from the surface to depth where it can be sequestered (Artificial Downwelling). Note that artificial upwelling can bring naturally high-CO_2, low-O_2 waters to shallower depths where they may impact surface biological systems, or outgas CO_2 back to the atmosphere prior to the onset of high primary productivity resulting from nutrient additions. Additionally, these methods can be energy intensive, and are therefore often recommended to be deployed in conjunction with renewable marine energy sources.

Coastal Blue Carbon

Janine Harris, Alec Shub and NOAA cross line office Coastal Blue Carbon Working Group

“Coastal blue carbon” is carbon that is sequestered, and stored in coastal wetlands including natural salt marshes, mangroves, and seagrass beds. Carbon is sequestered via photosynthesis and some carbon is imported from high watershed areas and retained in the sediments of these ecosystems (i.e., through lateral input). Coastal wetlands form deep, carbon-rich soils, and store carbon at a much greater rate per unit area than terrestrial habitats, which store carbon primarily in aboveground biomass (NASEM 2019). Wetland soils are largely anaerobic: carbon in the soils decomposes slowly and can persist for hundreds to thousands of years. Quantifying carbon stored and sequestered in coastal habitats has been a topic of research for more than a decade. Current estimates of the annual CO_2 removal by U.S. coastal wetlands is 0.024 - 0.050 GT / y (NASEM 2019; see also Figure 2). Research on quantification of carbon includes a need to understand the geographic extent of these habitats in the United States and globally. The extent of coastal wetlands and mangroves is understood well enough to be included in the U.S. Greenhouse Gas Inventory accounting of wetland emissions. Emergent coastal wetlands and mangroves are mapped nationally by the National Wetlands Inventory (FWS) and the Coastal Change Analysis Program (NOAA). However, the extent of seagrass beds is not well quantified. Based on the known extent of these habitats, the total U.S. (cumulative) potential additional carbon capacity for tidal wetlands and seagrass meadows is estimated at 0.410 GT CO_2 in 2030– if active ecosystem management, restoration, nature based adaptation, managed wetland transgression and carbon-rich projects are all implemented as described in the NAS 2019 report (NASEM 2019).

These coastal blue carbon habitats provide additional benefits, including fishery nursery habitat, improved water quality, recreation, tourism, and flood and erosion mitigation (NASEM 2019). Some techniques to enhance these habitats could have tradeoffs that continue to be researched, such as the potential for sediment contamination from fill materials, the effects of shoreline modifications on sediment deposition, and exchange of subtidal habitat areas for tidal wetlands carbon removal (NASEM 2019).

NOAA Capabilities Relevant for Coastal Blue Carbon:

- NOAA funds research on marsh response to sea level rise and carbon sequestration rates associated with natural and restored coastal wetlands.
- NOAA protects and restores coastal blue carbon habitats (coastal wetlands, seagrass beds, and mangroves) through projects that reconnect hydrology to coastal habitats and consultations on effects of development to these habitats that are important as fish habitat.
- NOAA distributes research funding through a network of university-affiliated programs, which have funded coastal blue carbon projects as well as other research related to coastal wetland habitats and marine geochemical dynamics.
- NOAA funds and manages research projects that produce relevant and timely climate science information, tools, data products, and expertise. For instance, NOAA supports the integration of coastal wetlands in the annual Inventory of the U.S. Greenhouse Gas Emissions and Sinks, using NOAA Coastal Change Analysis Program (C-CAP) data. NOAA is leading the Blue Carbon Inventory (BCI) Project, an interagency partnership supported by the U.S. Department of State to advance the development of tools, approaches and capacity for integrating coastal blue carbon into National Greenhouse Gas Inventories (NGGIs) in developing countries.
- NOAA protects and restores coastal blue carbon habitats. In addition, NOS C-CAP products are used to inventory and routinely update the wetlands contribution to the U.S. Greenhouse Gas Inventory reporting.

Next Steps to Develop NOAA's Capabilities:

- Increase funds for the Coastal Management Coastal Change Analysis Program (C-CAP) to improve resolution, seagrass coverage mapping, and our wetland reporting with each annual update to the Inventory of the U.S. Greenhouse Gas Emissions and Sinks.
- Target investments and enhanced strategic partnerships to support a strong community of practice, a better understanding of carbon sequestration and human-caused emissions from these ecosystems, insights into where to prioritize future restoration investments, and more comprehensive and precise data on the presence and condition of coastal wetlands– particularly salt marshes and seagrass meadows.
- Research the physical connection to oceanic carbon processes (e.g. the volume and location of storage of macroalgal and megafaunal carbon in deep ocean sediments) and greater quantification of the impacts of sediment disturbing activities can help us better quantify the amount and fate of carbon exported from coastal blue carbon habitats, as this "outwelled" carbon may account for a significant amount of the sequestration potential of these habitats
- Expand interdisciplinary research (including social science), stakeholder engagement, and capacity building to identify meaningful pathways to integrate blue carbon in community resilience strategies, including the consideration of trade offs, enhancing the

link between nationally determined contributions (NDCs) and climate finance, and developing sustainable blue economies.

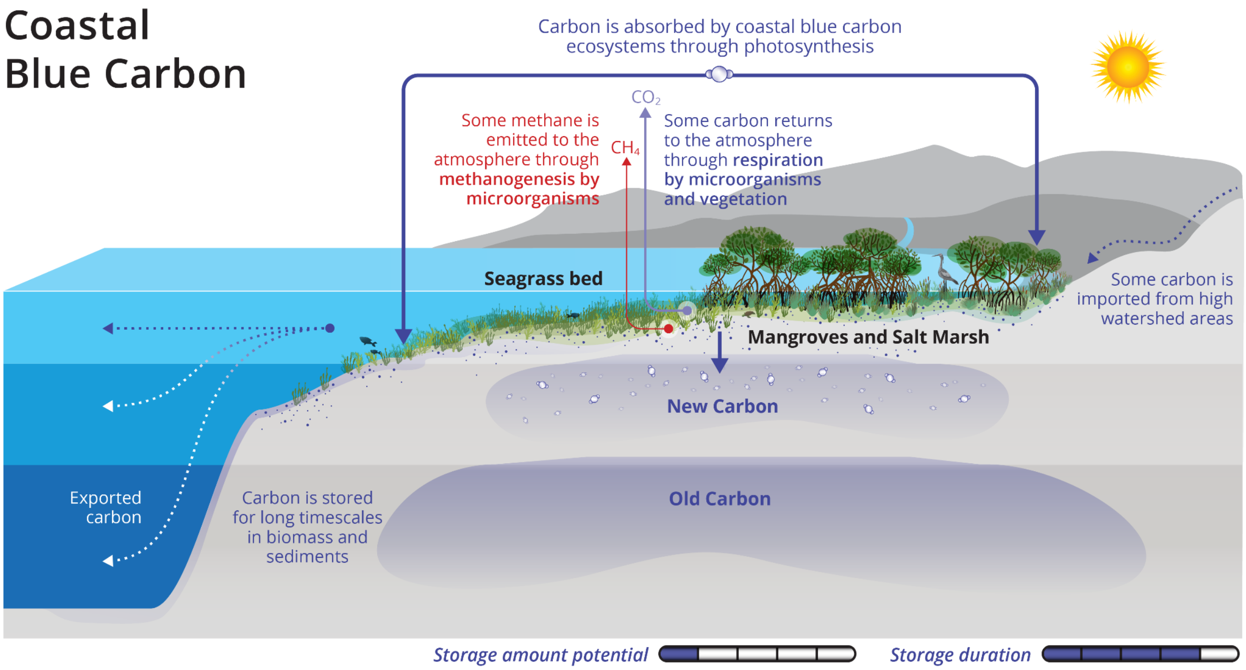


Figure 11. Coastal Blue Carbon.
The process by which coastal blue carbon ecosystems (e.g. seagrass, mangroves, and salt marshes) sequester and store carbon. Coastal blue carbon ecosystems absorb carbon from the atmosphere via photosynthesis. Additional carbon is imported through runoff from high watershed areas. Carbon is stored for long timescales in the sediments of these habitats, deep ocean sediments, and the biomass of mangroves, salt marshes, and seagrasses. Coastal blue carbon ecosystems emit some CH_4 and CO_2 back to the atmosphere. Some carbon is exported from these ecosystems to coastal waters and to depth.

Marine Ecosystem Biomass

Zachary J. Cannizzo, Michael Rust, and Sarah Hutto

A large fraction of the biomass in marine systems is generally comprised of non-photosynthetic organisms including animals, fungi, microbes, and protists. As illustrated in our diagram of the global carbon cycle (see Figure 2), the fraction of living biomass carbon (Blue Biomass) in the oceans is relatively small, especially when compared to other ocean carbon reservoirs, however the role of animals in transferring carbon from primary producers to other reservoirs, such as the deep sea and sediments, could be significant. The role of animals in biogeochemical cycles and ecosystem structure has been understudied, although recent work indicates that living biomass may be a larger opportunity to aid in ocean carbon removal than previously thought (NASEM 2022). Carbon stored in living marine ecosystems can be increased both through the protection and restoration of marine ecosystems (wild blue biomass) and through aquaculture (farmed blue biomass). For example, rebuilding populations of eight whale species could store and sequester 8.7 Mt C in living biomass (Pershing et al., 2010) with an ongoing portion of the carbon consumed by the animals being pumped to the sea floor in the form of feces and carcuses when the organisms die. These relationships need to be further investigated to understand the potential for using blue biomass to store and pump carbon to longer term reservoirs. Restoration of missing or degraded species and populations to marine ecosystems could not only restore biomass, but also increase the efficiency of ecosystem processes that enhance carbon sequestration and storage, including trophic interactions that increase the carbon sequestration of primary producers (e.g., Atwood et al., 2018; Wilmers et al., 2012). Although the potential carbon pools of marine animals are difficult to quantify, this uncertainty must be balanced against the relatively low cost (<$50 / ton), low risk, and valuable co-benefits of these methods (e.g., Gattuso et al., 2021, Gattuso et al., 2018).

One challenge is that if the biomass from the restoration of marine ecosystems or aquaculture is simply extracted as a new marine resource (e.g., enhanced fishing), the relative gains in carbon sequestration may be small or even neutral. Coupling restoration of wild organisms with increased farmed biomass from aquaculture to supply increasing demand for seafood and increase carbon cycling should be investigated. Accordingly, restoration must be paired with conservation to ensure net carbon negative benefits (e.g., Gattuso et al., 2021, Gattuso et al., 2018). Marine conservation efforts already work to protect marine carbon flows and natural carbon sequestration (e.g., Atwood et al., 2018; Wilmers et al., 2012), but conservation regulations have not historically focused on carbon sequestration. As current and new marine protected areas (MPAs) and aquatic farms are developed, it will be critical to value and target carbon sequestration, and its enhancement, as a key benefit and management priority.

NOAA Capabilities Relevant for Marine Ecosystem Recovery:

- NOAA serves as the trustee for a network of underwater parks encompassing more than 620,000 square miles of marine and Great Lakes waters through a system of 15 sanctuaries and 2 marine national monuments.
- NOAA protects and restores habitat to sustain fisheries, recover protected species, and maintain resilient coastal ecosystems and communities.
- NOAA conducts aquaculture research and development as a cross line office program.
- NOAA is responsible for the protection, conservation, and recovery of endangered and threatened marine and anadromous species under the Endangered Species Act. To implement the ESA, NOAA works with the U.S. Fish and Wildlife Service and other federal, tribal, state, and local agencies, as well as nongovernmental organizations and private citizens.
- NOAA represents a network of 30 coastal sites designated to protect and study estuarine systems.

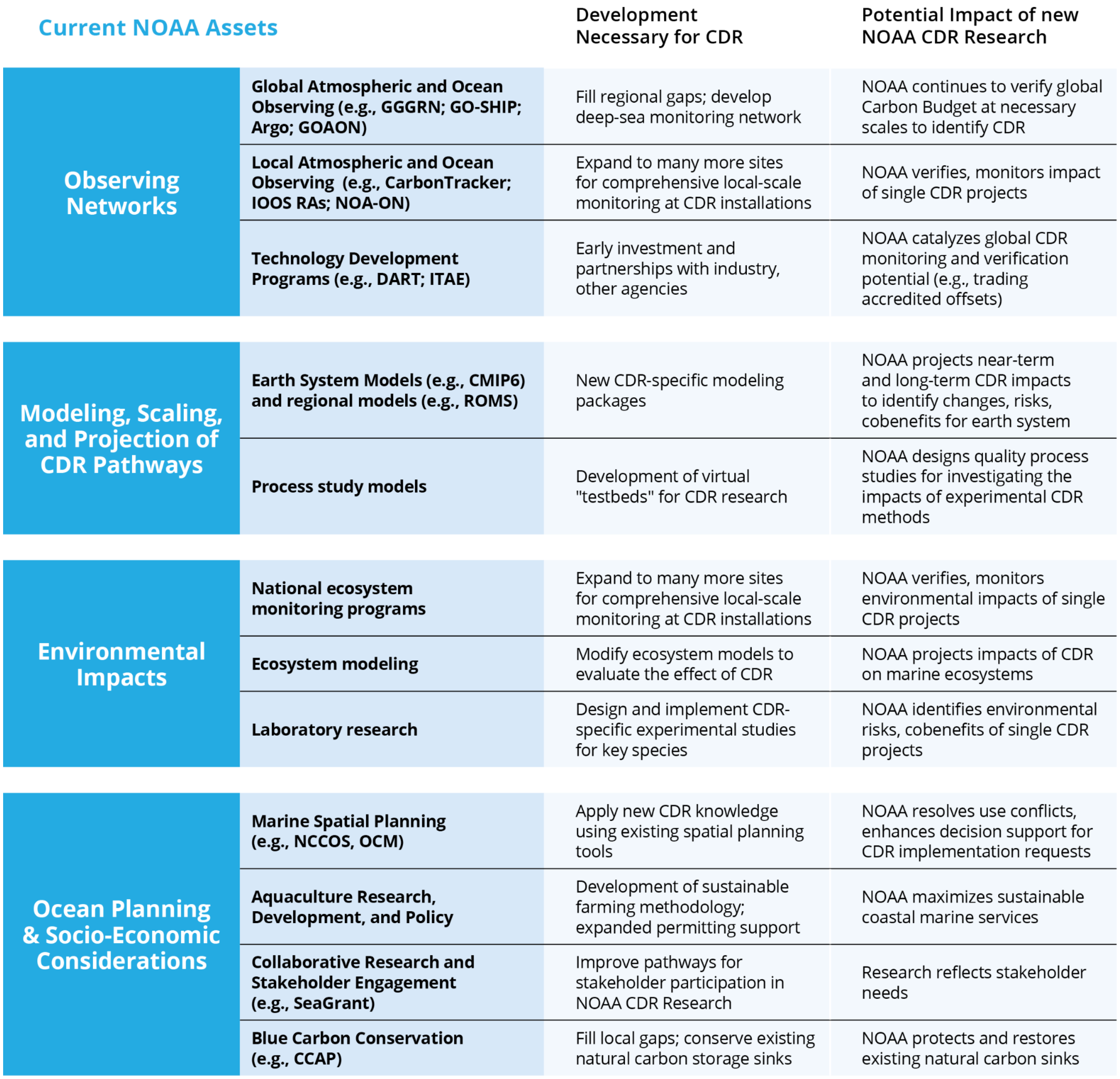
Next Steps to Develop NOAA's Capabilities:

- Develop advanced mass balance models for marine biomass connected by food webs and in aquaculture ecosystems to determine the scale and potential for wild and farmed blue biomass to enhance carbon sequestration.
- Inclusion of carbon sequestration and storage as a key benefit, target, and management priority of current and future marine protected areas and farms, including identification of key habitats or marine processes that could substantively increase atmospheric carbon sequestration.
- Establish carbon sequestration measurements at farms and key sentinel sites within the National Marine Sanctuary System and National Estuarine Research Reserve System to identify early changes to carbon pools and fluxes.
- Research the interplay between key restoration activities, such as opening rivers, reconnecting wetlands, restoring shallow corals, and rebuilding shellfish populations to understand the net efficiencies of methods that both release and sequester carbon.

Part III: NOAA’s Role in CDR Research

Given NOAA’s wealth of experience in monitoring, modeling, and quantifying impacts of the global carbon cycle on human communities, as well as NOAA’s existing R&D infrastructure, the scientific community is calling on NOAA to extend its research explicitly into the CDR field (e.g. EFI, 2019; NASEM, 2019; EFI, 2020a, 2020b). NOAA’s existing research assets and programs are ideally suited to this task, and many already tangentially address carbon sequestration and removal. Here we address how NOAA’s existing mandates, programs, and activities intersect with CDR research, with additional capacity:

- **NOAA’s global to coastal observing networks** and data assimilation capabilities could monitor and verify the actual carbon drawdown of CDR installations
- **NOAA’s earth system and regional ocean modeling capabilities** could be used to assess and inform the scale up of land and ocean based methodologies.
- **NOAA’s ecosystem research** is well suited to study the potential ecosystem impacts of atmospheric and marine CDR deployments
- **NOAA’s technology development** enterprise could ensure that observing networks and research activities have the necessary tools to address these scientific questions and assess risk
- **NOAA’s management role and stakeholder relationships** could help resolve use, siting, management and conservation challenges; conduct necessary socioeconomic research; educate public and private partners; maintain trust in climate data; and ensure high standards of scientific integrity and ethics.



Current NOAA Assets		Development Necessary for CDR	Potential Impact of new NOAA CDR Research
Observing Networks	**Global Atmospheric and Ocean Observing (e.g., GGGRN; GO-SHIP; Argo; GOAON)**	Fill regional gaps; develop deep-sea monitoring network	NOAA continues to verify global Carbon Budget at necessary scales to identify CDR
	Local Atmospheric and Ocean Observing (e.g., CarbonTracker; IOOS RAs; NOA-ON)	Expand to many more sites for comprehensive local-scale monitoring at CDR installations	NOAA verifies, monitors impact of single CDR projects
	Technology Development Programs (e.g., DART; ITAE)	Early investment and partnerships with industry, other agencies	NOAA catalyzes global CDR monitoring and verification potential (e.g., trading accredited offsets)
Modeling, Scaling, and Projection of CDR Pathways	**Earth System Models (e.g., CMIP6) and regional models (e.g., ROMS)**	New CDR-specific modeling packages	NOAA projects near-term and long-term CDR impacts to identify changes, risks, cobenefits for earth system
	Process study models	Development of virtual "testbeds" for CDR research	NOAA designs quality process studies for investigating the impacts of experimental CDR methods
Environmental Impacts	**National ecosystem monitoring programs**	Expand to many more sites for comprehensive local-scale monitoring at CDR installations	NOAA verifies, monitors environmental impacts of single CDR projects
	Ecosystem modeling	Modify ecosystem models to evaluate the effect of CDR	NOAA projects impacts of CDR on marine ecosystems
	Laboratory research	Design and implement CDR-specific experimental studies for key species	NOAA identifies environmental risks, cobenefits of single CDR projects
Ocean Planning & Socio-Economic Considerations	**Marine Spatial Planning (e.g., NCCOS, OCM)**	Apply new CDR knowledge using existing spatial planning tools	NOAA resolves use conflicts, enhances decision support for CDR implementation requests
	Aquaculture Research, Development, and Policy	Development of sustainable farming methodology; expanded permitting support	NOAA maximizes sustainable coastal marine services
	Collaborative Research and Stakeholder Engagement (e.g., SeaGrant)	Improve pathways for stakeholder participation in NOAA CDR Research	Research reflects stakeholder needs
	Blue Carbon Conservation (e.g., CCAP)	Fill local gaps; conserve existing natural carbon storage sinks	NOAA protects and restores existing natural carbon sinks

Table 2. A summary of NOAA's current assets, how those aspects may need to be expanded to address CDR research, and the overall impact and outcomes of the development of these systems.

Observing Networks

Richard Feely, Adrienne Sutton, Colm Sweeney, Leticia Barbero, Denis Pierrot, Kathy Tedesco, James Butler

NOAA is the lead federal agency for determining the changing concentrations, sources, sinks and fate of greenhouse gas (GHG) emissions in the atmosphere, oceans, and terrestrial biosphere to better understand changes in weather, climate, and ocean and coastal ecosystems. As such, it has the primary responsibility for maintaining global observing networks to determine the long-term changes and fate of the carbon system and its impacts on global and regional climate. As CDR removal technologies are scaled up over time, the Global Carbon Observing Networks and modeling capabilities will need to be modified and significantly enhanced to be able to quantitatively assess the additional amounts of carbon dioxide removed from the atmosphere and their eventual fate on land and in the sea. Long-term monitoring and scientific analysis of ocean carbon fluxes and inventories is critical for understanding how the ocean sink functions, to determine if ocean uptake of CO_2 is keeping pace with emissions, and how we can best anticipate, mitigate, and adapt to potential future changes. Similarly, long term atmospheric monitoring will be necessary to verify terrestrial and global uptake of carbon and process studies will be increasingly essential for improving models.

Ocean Observing Networks

Richard Feely, Adrienne Sutton, Brendan Carter, Colm Sweeney, Leticia Barbero, Denis Pierrot, Kathy Tedesco

NOAA's Global Ocean Carbon Network provides long-term monitoring and scientific analysis of ocean carbon fluxes and inventories at a range of spatial and temporal scales, representing over half of all global ocean carbon observations. The *Surface Ocean* CO_2 *Observing Network* measures the temperature, salinity, and partial pressure of CO_2, pCO_2, in surface water and air from Ships of Opportunity (SOOP), including research and commercial vessels, and autonomous platforms to determine the carbon exchange between the ocean and atmosphere. These observations are used to quantify the amount of atmospheric CO_2 sequestered by the ocean on seasonal scales, document changes in the surface ocean carbon chemistry, and evaluate the variability in air-sea fluxes to provide meaningful projections of future atmospheric CO_2. *U.S. GO-SHIP Repeat Hydrography Program*, part of the international GO-SHIP network of sustained hydrographic sections, collects high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column on a global scale. These ocean interior carbon measurements monitor changes in anthropogenic CO_2 inventories throughout the water column. This long-term monitoring of the natural cycle is critical to determine impacts and efficacy of enhanced CO_2 removal.

To support CDR research, NOAA should:
- **Continue** and enhance the ocean carbon observing network of cruises, moorings and and autonomous platforms to determine the efficiency and efficacy of carbon removal and biological responses in both the open and coastal oceans.
- **Expand / Start / Grow / Improve** the ocean carbon network to provide a more detailed understanding of carbon dioxide removal in coastal, undersampled and climate sensitive regions where marine CDR process studies will be deployed, especially the deep sea. Fill key gaps in the ocean carbon network in order to track the regional to global-scale impacts of CDR projects.
- **Enhance** the quantity, quality and short term deployability of autonomous carbon system sensor technology (see next section on Advanced Monitoring).

Atmospheric Observing Networks

James Butler, Colm Sweeney

Although there is no “land” in NOAA’s name, gas-emitting and uptake activities on land impact the atmosphere, which is in NOAA’s domain. NOAA maintains long-term, *in-situ* atmospheric monitoring networks for greenhouse gasses, stratospheric ozone, ozone-depleting substances, radiation at Earth’s surface, and aerosols. Monitoring sites, many of which have been running for over 50 years, are distributed globally and sampled frequently to detect changes in climate, ozone-depletion, and baseline air quality. The networks are spread across the U.S. to attribute observed changes in atmospheric composition to changes in natural or anthropogenic sources and sinks within the U.S.. However, to verify or validate results from the numerous and diverse CDR efforts in the U.S., NOAA needs a more dense set of observations on the surface and from aircraft to support detailed analyses. CDR efforts in the U.S. will also require high-fidelity transport modeling to help identify source regions. Atmospheric transport modeling exists in many areas but improvements can be made with data from satellites and NWS surface networks already in place.

The detection limits of NOAA’s existing atmospheric monitoring system, already the world’s best, are currently not sufficient to provide routine, robust estimates of changes in localized carbon fluxes. Nevertheless, such a capability can be built largely with increases in capacity. Two transformative opportunities stand out: initiating the collection of greenhouse gas data from commercial aircraft and increasing observations of C-14 in CO_2 by a factor of five or more. A recent study demonstrated that NOAA could then report on the success of fossil fuel emission reductions and of net biospheric CO_2 uptake (Basu et al, 2016, 2020) not just on a national scale, which NOAA does already, but on policy relevant, sub-continental scales as well. Additionally, CDR-focused mobile networks will be needed following approaches that have been used to identify point and distributed source emissions from urban and oil and gas emissions. This not only will enable direct “top down” assessment of CDR approaches but also the detection of fugitive emissions.

To support CDR research, NOAA can do the following:

- **Continue** to provide information on global trends and distributions of GHGs in the atmosphere and on the sources and sinks of these gasses on land and in the ocean, particularly over the U.S.. This information derives from ~140 sites in ~40 countries which are sufficient to accurately describe global phenomena and U.S. trends.
- **Expand / Start / Grow / Improve** the density and frequency of atmospheric GHG observations so as to verify the effectiveness of subcontinental scale (e.g., California, New England, Pacific Northwest) emission reduction efforts and CDR activities and be able to separate fossil fuel influences from ecosystem feedbacks. This may also require filling some gaps in the global network.

Transformative Opportunities for Advanced Monitoring

Chris Meinig, Adrienne Sutton, Sophie Chu, James Butler, Paul McElhany

The outcome of a NOAA-led observing system will be a state-of-the-art CDR observing technology that prepares scientists to assess and track the effectiveness of ocean, land, and coastal-based CDR pilot studies in the lab, in controlled tanks, in ocean pilot and large scale ocean studies. NOAA has a long history of forming public-private partnerships (PPPs) that have quickly delivered novel technology that has been vetted by peer-reviewed processes (e.g., Meinig et al., 2019), especially with the support of the National Oceanographic Partnership Program (NOPP) that leverages present proven ocean observing capabilities. With a structured and disciplined approach, these efforts will lead to a new generation of sensor and autonomous platforms for an array of atmospheric, water, and sediment sampling in harsh offshore locations. NOAA is ideally poised to develop a broad array of new technologies, provide independent and objective evaluation of CDR project performance, and develop a complete strategy for potential implementation at planetary scale.

Ocean

Chris Meinig, Adrienne Sutton, Sophie Chu

New technologies and restoration approaches to enhance ocean and coastal carbon sequestration lack robust and reliable methods of assessment. Ocean observing technologies necessary for this effort are not fully developed, and before CDR approaches can be tested in the ocean, these observing technologies must be matured. The desired outcome of the work is state-of-the-art ocean observing technology that prepares public sector scientists to assess the effectiveness of ocean and coastal-based CDR proposals, work closely with industry and innovators on project design through public-private partnerships, provide independent and objective evaluation of CDR project performance, and develop a strategy for potential implementation at scale.

To support CDR research, NOAA can do the following:

- **Continue** and accelerate autonomous ocean carbon observing technology development currently underway.
- **Launch** a partnership that leverages the ocean observing capabilities of NOAA and the energy harnessing expertise of DOE to catalyze ocean observing technology innovation. Effectively evaluating ocean and coastal-based CDR projects will require a new generation of ocean sensors and platforms able to function far offshore in harsh conditions and over immense temporal and spatial scales—necessitating innovative solutions in platform and sensor development, data integration, adaptive sampling, anti-biofouling, and energy generation and storage-at-sea using renewable energy.

Atmosphere

Jim Butler, Colm Sweeney

Outfitting commercial aircraft with sensors to automatically measure CO_2 and other GHGs in real-time or near-real-time would be a game changer for understanding GHG fluxes. This has the potential to multiply the number of vertical profiles that would be available for analysis by a factor of 100s to1000s, would provide a uniform coverage of the U.S., and would be relatively inexpensive. (NOAA currently gets vertical profiles from 14 sites, but only once every two weeks at best.) NWS is already doing this with measurements of water vapor, which has improved weather forecasts significantly at minimal cost. It is also being done for GHGs on a small scale by the Europeans who have outfitted several long-range aircraft (e.g., A-330), but the instruments are large and cumbersome and provide only two vertical profiles per day at select locations. If NOAA can equip 10-20 Boeing 737s or Airbus A-321s with small packages, it would revolutionize the analysis of GHG fluxes and provide the capability to report on subcontinental scale emission reduction and CDR efforts. NOAA scientists are already experimenting with this approach with existing instrumentation in cooperation with an aircraft manufacturer and an airline, but a smaller package would go a long way toward making this approach more acceptable to several airlines.

Another transformative opportunity is to use atmospheric observations to separate ecosystem influences from fossil fuel influences on subcontinental scales. This is necessary for supporting both emission reduction efforts and CDR. It requires increasing current observations of C-14 in CO_2 by about a factor of five (Basu 2019). C-14 is present in the atmosphere and in the biosphere, but absent in fossil fuels. Hence, reduced fossil fuel emissions will show up in the atmospheric inventory, which in turn allows for separation of ecosystem processes from fossil fuel interference. Urban emissions reductions could be objectively quantified by aircraft campaigns upwind and downwind of the area, including the use of C-14, and repeated at suitable intervals, to support local emissions reduction policies. This, too, would be relatively inexpensive and would go a long way toward determining the effectiveness of certain CDR approaches and supporting the U.S. stocktake.

To support CDR research, NOAA can do the following:

- **Continue:** Supporting GHG research networks, specifically aircraft programs that collect vertical profiles of greenhouse gasses in the atmosphere.
- **Expand / Start / Grow / Improve:** Outfitting commercial aircraft with sensors to automatically measure CO_2 and other GHGs in real-time or near-real-time; use atmospheric carbon-14 observations to separate ecosystem influences from fossil fuel influences on subcontinental scales

CDR Risks and Co-Benefits for Marine Ecosystems

Paul McElhany, Seth Theuerkauf

NOAA is responsible for the stewardship of the nation's coastal and marine ecosystems and resources. In fulfilling that responsibility, NOAA can play a key role in research on the benefits and risks of CDR on marine ecosystems, as well as development of tools, models, and science advice products to support CDR permitting decision making. NOAA National Marine Fisheries Service's mandates under the Magnuson-Stevens Fishery Conservation and Management Act, Endangered Species Act (ESA), and Marine Mammal Protection Act would likely require consultation on and permitting of certain pilot projects and other CDR-related activity in the marine environment (those that affect Essential Fish Habitat, species listed under the ESA and their critical habitat, and marine mammals).

NOAA currently uses modeling, experiments and monitoring to evaluate the consequences of CO_2 emissions on marine ecosystems, primarily by investigating how CO_2 driven warming, deoxygenation and acidification affect important resources. NOAA can use these tools to estimate potential benefits to marine ecosystems of lower CO_2 from either land-based or marine CDR. In addition to considering how reduced CO_2 in general may benefit marine ecosystems, NOAA Fisheries is in a unique position to evaluate the ecological consequences (both positive and negative) associated with any particular marine CDR strategy. If any of the proposed marine CDR approaches are implemented at a large enough scale to affect the global carbon cycle, they will likely have substantial direct and indirect effects on marine ecosystems. Further, certain CDR approaches (e.g., macroalgal cultivation) have the potential for ecosystem-scale co-benefits, such as nutrient removal from eutrophic systems (e.g., Gulf of Mexico) and provision of habitat for wildlife. Ecosystem monitoring and environmental interactions research will be required to understand the scaling potential of these co-benefits, as well as potential risks.

Although the potential benefits of marine CDR may be quite high, so are the potential risks of approaches such as ocean fertilization or artificial upwelling to marine ecosystems. The history of unexpected consequences from ecological interventions suggests we approach CDR with as much information about the trade-offs of each method as possible.

Marine Ecosystem Monitoring

In fulfillment of its mission, NOAA and its partners conduct extensive and varied marine ecosystem monitoring associated with the management of fisheries, support of protected resources, understanding the ecology of marine sanctuaries and basic ocean exploration. A robust ecological monitoring program is essential to documenting expected benefits from CDR operations, and, perhaps more critically, detecting and responding to any unexpected ecological changes that occur from CDR implementation. The different CDR methods would require different levels and types of ecological monitoring and, although there is a variety of implementation approaches within each method, the estimated rank order from most to least monitoring needs is as follows: 1) *Nutrient enrichment* is highest because the explicit intent is to fundamentally change biological communities, 2) *Macroalgal cultivation* is also intended to change biological communities but at a relatively more localized scale, 3) *Alkalinity enhancement*, though not directly manipulating the biological system, is likely to affect biological communities at a potentially large geographic scale, 4) *Coastal Carbon Burial* is a biologically-based approach whose effectiveness and benefits should be monitored, but there is generally less ecological risk than other methods, and 5) *Direct ocean capture* may not explicitly manipulate the biological system but could have impacts on more localized spatial scales.

Ecological monitoring for marine CDR projects will need to be broad in scope, designed to sample at all trophic levels, and able to detect the unexpected. Unexpected ecological responses are an issue both during the pilot phase, when novel ecological manipulations are being attempted and at the implementation phase because a change in scale has the potential for a qualitatively different result from pilot studies. Ecological monitoring also has to contend with naturally high levels of variability driven by environmental processes not related to marine CDR and by complex biological interactions. Because of this variability, assessing ecological impacts can often require relatively long time series before and after a perturbation. This creates challenges given the potentially competing need to address atmospheric CO_2 quickly and the need for thorough ecological evaluation. Evaluating ocean and atmospheric carbon monitoring data may operate at different time scales from the ecological monitoring data.

To meet the monitoring challenges, NOAA will need to accelerate development and deployment of remote and autonomous ecological sensor methodologies to detect changes both in a broad suite of general ecological indicators and in targeted indicators particular to concerns associated with a specific marine CDR application (e.g. concern about harmful algae and ocean fertilization). Autonomous eDNA sensors, video systems, acoustics and other methods deployed on a variety of platforms, including ships of opportunity, will need to augment traditional, ship-based research cruises. The scale of ecological perturbation required to meaningfully shift concentrations of atmospheric CO_2 using marine CDR requires multiple approaches and a marine ecological monitoring system to match.

To support CDR research, NOAA can do the following:

- **Continue:** NOAA currently conducts ecosystem monitoring at all trophic levels at a variety of spatial and temporal scales.
- **Expand / Start / Grow / Improve:** NOAA will need to work with partners to plan and implement targeted ecological monitoring, including in the deep sea, initially at the pilot project scale and ultimately at the scale of operational CDR. NOAA will also need to work with partners to accelerate development and deployment of autonomous ecological sensing systems to monitor at the anticipated scale.

Ecosystem Modeling and Risk Assessment

NOAA (in particular NOAA Fisheries) develops and maintains ecosystem models at a variety of spatial scales and with differing degrees of complexity that can be used to evaluate proposed CDR activities. Some of the end-to-end ecosystem models explicitly include biogeochemistry and can help predict the effectiveness of CDR activities at removing CO_2. Models that focus on the dynamics of species that play an important role in carbon cycling (e.g. coccolithophores) can also aid in assessing CDR effectiveness. In addition to these models that can directly contribute to understanding carbon dynamics, a much broader suite of ecosystem and single-species models used by NOAA and collaborators can help assess secondary ecological impacts of CDR activities. Several marine CDR methods (e.g. fertilization, macroalgae cultivation) explicitly manipulate the marine ecosystem and impacts from CDR are certain to ripple through the food web in ways that have nothing directly to do with global carbon cycling. Even methods not explicitly trying to change the food web could have indirect ecological effects. For example, ocean alkalinization could have impacts through the introduction of particulates, potential metals contamination, altered ship traffic, localized chemistry shifts, etc. Many of the ecosystem models, single-species models, and Models of Intermediate Complexity for Ecosystem assessment (MICE) are designed to evaluate the response of the system to perturbation and CDR activities can be modeled as a specific type of perturbation to the environment.

NOAA's expertise in modeling the impact of environmental change on natural marine resources can be directed at understanding if CDR will achieve the goal of reducing CO_2, if CDR will generate any secondary co-benefits to the ecosystem (e.g. enhanced fish habitat) or if CDR presents additional risks or hazards to the ecosystem that need to be weighed in cost-benefit analyses. As part of that cost-benefit consideration, NOAA could continue its current modeling of the risks of climate change and acidification, i.e. the risk of not using CDR to reduce atmospheric CO_2. NOAA's ecosystem models commonly include an evaluation of the economic and social consequences of alternative management actions– valuable information for assessing CDR approaches.

To support CDR research, NOAA can do the following:

- **Continue** developing and analyzing ecosystem models of environmental effects on marine resources.
- **Improve** focusing ecosystem models on understanding ecological and societal impacts of specific CDR activities.

Ecosystem and Species-focused Experimentation

Some questions about potential ecosystem impacts of CDR can be addressed through laboratory and field experimentation. NOAA already conducts experiments to evaluate the risks of acidification and warming on species of particular economic and ecological concern (e.g. bivalves, crabs, salmon). These experiments help quantify the risk of increasing atmospheric carbon and the potential benefits of CDR. These same types of experiments, where species or groups of species are reared under controlled conditions in aquaculture-like settings can be used to evaluate secondary effects of marine CDR activities. For example, alkalization involves dispersal of buffer material in the ocean. This process can be mimicked at a small scale in the lab to determine how sensitive species respond to exposure, which presents a new physical substrate for biological interaction and may contain impurities (e.g. metals). NOAA has laboratories dedicated to this sort of marine ecotoxicological research. Each of the proposed marine CDR approaches presents specific risk concerns that can be evaluated in the lab.

Although much more challenging and therefore less common, manipulative experiments can be conducted in the field to evaluate the potential effect of marine CDR perturbations in a more natural setting. To create environments with controlled conditions for experimental comparisons, parts of a natural ecosystem can be enclosed (e.g. ocean acidification FOCE experiments), natural locations with limited circulation can used (e.g. reef alkalization experiments), or short-term manipulations can take place on the open ocean (e.g. fertilization experiments). If these experiments are designed to monitor carbon fluxes and the ecosystem, they would be considered CDR pilot projects, however, they also can be designed to evaluate potential secondary effects of CDR activities.

Data on species responses from lab and field experiments will be critical inputs into the models used for predictions of ecosystem response to CDR. The lab and field experiments can also be conducted to explicitly address questions about biological processes in the carbon cycle (e.g. productivity of kelp in given conditions, rates of phytoplankton calcification, etc.)

To support CDR research, NOAA can do the following:

- **Continue** conducting laboratory and field experiments on species responses to warming, acidification, and other environmental changes.
- **Improve** and begin conducting lab and field experiments to explicitly address CDR method specific questions.

Modeling, Scaling, and Projection of CDR Pathways

John Dunne, Jasmin John, Darren Pilcher

NOAA has already made critical investments in ocean biogeochemical and ecosystem models as well as fully coupled chemistry-climate-carbon Earth System Models (ESMs) that can be brought to bear on CDR science. These ESMs are crucial to simulate present-day climate, as well as reliable future predictions and projections of climate change and ecosystem consequences. Better understanding of the implications of greenhouse gas emissions and CDR for the coupled carbon-climate Earth system are key to provide reliable guidance to policymakers and other stakeholders on sensitivity to projected changes, vulnerabilities, and human dimensions for societal resilience. Because individual marine CDR methods are local rather than global in scale, however, a hierarchy of modeling tools will be necessary. While the existing global scale tools provide the climate context for CDR impacts, answering questions about the effectiveness and biogeochemical and ecosystem impacts of local to regional CDR activities may require both higher resolution and regional modeling as well as incorporation of additional processes. These tools will allow the combination of CDR scenario assessment, detection and attribution, observation system simulation, and process study to increase understanding and inform sound policy.

Earth System Modeling

John Dunne, Jasmin John

NOAA is a world-leader in understanding and applying the science that underlies the development of comprehensive coupled global Earth System models, and conducting relevant climate change simulations towards achieving NOAA mission goals to understand and predict changes in climate, weather, oceans and coasts. For the sixth phase of the international Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016), NOAA developed two state-of-the-art fully-coupled models: an earth system model focusing on increased comprehensiveness (ESM4, Dunne et al., 2020), and a higher resolution but limited comprehensiveness physical climate model (CM4, Held et al., 2019). These models have participated in several model intercomparison projects relevant to CDR, including projection scenarios (ScenarioMIP, O'Neill et al., 2016), carbon dioxide removal (CDRMIP, Keller et al., 2018), and quantifying committed climate changes following zero carbon emissions (ZECMIP, Jones et al., 2019). These experiments are essential for understanding the implications of CDR for atmospheric CO_2 and climate change in general.

In addition to leveraging existing CMIP6 simulations for regional to global coupled carbon-climate projections, higher resolution tools could increase process level understanding, detection and attribution, and impact studies in support of potential CDR strategies and associated monitoring and enforcement activities. With sufficient resources, NOAA could undertake an extensive suite of fully coupled carbon-climate Earth system modeling sensitivity studies at 0.25 degree ocean resolution and potentially higher resolution models in global ocean only or regional configuration comparing possible sites of 1 GT C / yr) surface ocean alkalinization, 2) artificial upwelling, 3) macroalgae aquaculture, 4) wetland restoration, 5) iron fertilization, and / or 6) deep CO_2 injection for their efficacy, associated observational detection / attribution requirements, and potential biogeochemical and ecosystem consequences. These proposed activities would provide critical quantification and guidance on the benefits, risks, and monitoring challenges associated with CDR in the Earth system context.

NOAA extends the ability of its laboratories to develop and offer cutting-edge modeling systems, analysis, and derived products by engaging the broad external community in research, knowledge creation, and product development. Research investments through these programs will (a) engage the broad community with simulations planned by NOAA and described above, (b) enable improvements in understanding of CDR techniques and external collaboration for NOAA scientists, and (c) connect CDR activities with other cross-laboratory and cross-Line Office efforts. NOAA has funded a broad array of research activities focused on climate projections and model data analysis resulting in actionable products and inputs to efforts such as the National Climate Assessment. Similar focused research-to-applications efforts are needed in support of CDR activities.

To support CDR research, NOAA can do the following:

- **Continue** to apply fully coupled comprehensive global Earth System models towards improved understanding of CDR processes, impacts, and consequences to society, as well as to provide guidance to stakeholders and policymakers.
- **Expand** efforts to include high-resolution and / or regional model development with targeted idealized or site specific case studies to understand CDR effects and impacts at the local scale.
- **Engage** the broad research community with NOAA models and data products to better understand CDR dynamics, help improve modeling platforms and systems by expanding

the user base for those platforms and systems, and ensuring connectivity with external and cross-Line Office efforts.

Process Study Modeling

Darren Pilcher

Many marine CDR techniques exploit existing ocean physical and biogeochemical processes to amplify ocean carbon uptake. Detailed process level understanding and modeling are necessary to fully resolve these pathways and explore potential impacts before CDR techniques are implemented at large-scale. Process study modeling of CDR techniques supports NOAA's mission goal of climate adaptation and mitigation by advancing the knowledge of key ocean and biogeochemical components of the climate system and how these components can be altered to mitigate climate change. Simulating these changes with confidence before they are implemented can help ensure that CDR techniques do not damage living marine resources and the blue economy. This further supports NOAA's goal of healthy ocean and productive ecosystems and services, since changes to the ocean physical-biogeochemical system can impact the marine ecosystem.

NOAA laboratories, cooperative institutes, and programs contain the scientific expertise, observing system capacity, modeling infrastructure required to gain a process level understanding and elucidate the complete effects of CDR techniques. These scientific capabilities are crucial to fully resolve any unintended effects of the CDR process, while also capturing the downstream impacts. Process-based models also serve as virtual testbeds to conduct proof of concept studies and environmental sensitivity tests for CDR techniques before they are implemented. Model simulations without the new CDR processes serve as control runs, which, when directly compared to simulations with an implemented CDR technique, allow for quantifying net changes. Including tracer variables can also provide a mechanism for tracking specific carbon removed from a CDR process. Tagging and tracking this carbon ensures that the carbon is ultimately removed from the atmosphere and buried within a sufficient Process-level research in collaboration time frame, and not effluxed back into the atmosphere at a later time and place.

To support CDR research, NOAA can do the following:

- **Continue** conducting process studies that resolve critical gaps in our understanding of marine biogeochemical cycling and uncertainty in proposed CDR techniques.
- **Improve** coordination between observational scientists and modelers to ensure that process studies are designed and implemented to capture the specific variables and rates required for incorporating CDR processes in models.
- **Develop model- and observationally-based** tools and information products that can provide a sense of impacts and efficacy of CDR techniques to assist CDR policy and implementation.

Ocean Planning and Socio-Economic Considerations

James Morris, Seth Theuerkauf, Jordan Hollarsmith, Mike Litzow, Janine Harris, Alec Shub, NOAA cross line office Coastal Blue Carbon Working Group, Rebecca Briggs, Alison Krepp, and Katherine Longmire

To ensure CDR activities develop sustainably, appropriately applied planning tools and related policy and stakeholder engagement processes will be required to conceptualize the reality for CDR in the U.S. This planning in collaboration with stakeholders can identify areas that may be suitable for various marine CDR research and the scale at which impacts on the carbon system and the environment may be detectable. marine CDR strategies, such as large-scale macroalgal cultivation, face many of the same challenges as the nascent and growing U.S. marine aquaculture sector– much of NOAA's aquaculture regulatory and permitting support (e.g science advice products to aid NEPA analysis), outreach and education, and international coordination could be readily leveraged with additional resources to support marine CDR. Similarly, existing spatial planning resources within NOAA currently targeted towards aquaculture planning could be leveraged, including extensive and relevant geospatial data resources, spatial analytical capabilities, and experience with applying these analyses towards permitting and regulatory decision making needs. Further, NOAA recognizes the need to integrate the socioeconomic impacts (including Environmental Justice impacts) of different CDR activities, alone and collectively, into planning efforts. For example, coastal blue carbon habitat conservation can have substantial co-benefits, such as improved fisheries, increased recreational opportunities ,and enhanced coastal community resilience. Continuing to understand these co-benefits and how they are affected by different carbon dioxide removal strategies is important for continued marine CDR planning.

Marine Spatial Planning

James Morris

NOAA develops and maintains the largest marine spatial datasets in the world (e.g. Coastal Change Analysis Program) including publicly facing tools such as Marine Cadastre and OceanReports. These data and tools can be used to characterize ocean neighborhoods which, just like neighborhoods on land, are intrinsically unique. For example, some ocean neighborhoods have protected areas, some are important highways for ships, some areas are important fishing grounds or where we extract energy from under the sea floor. Spatial planning will be required to conceptualize the reality for marine CDR in the U.S and to provide information needed for supporting permitting and regulatory decision making. Suitability models can be developed capable of identifying areas with the highest opportunity taking into consideration other ocean uses and conservation efforts. Regardless of the complexity or scale of the planning objective, the planning process often follows the general workflow of 1) identifying the planning objective, 2) inventory of available, relevant data, 3) analysis and mapping of data, 4) interpretation, and 5) delivery of map products and reports. Expertise exists (with data support from the various other programs, line offices and external partners) to support ocean planning at all scales– including coordination with relevant regulatory agencies, such as the U.S. Army Corps of Engineers (USACE), and U.S. Environmental Protection Agency (EPA). Recent region-wide suitability modeling conducted by NCCOS are producing marine atlases that analyze ocean regions and neighborhoods for a specific planning purpose (i.e., Aquaculture Opportunity Areas). An atlas-based planning approach for marine CDR combined with established NOAA environmental regulatory processes would identify where realistic marine CDR approaches could develop given the suite of existing ocean uses and environmental interactions, grounding model-based estimates and providing pragmatic upper limits of marine CDR scaling potential.

To support CDR research, NOAA can do the following:

- **Continue**
    - We have existing spatial planning resources within NOAA that could be leveraged, including extensive and relevant geospatial data , spatial analytical capabilities, and experience with applying these analyses towards permitting and regulatory decision making.
- **Expand / Start / Grow / Improve**
    - Increase spatial planning capacity to include coordination of marine CDR subject matter expertise and potential expansion of data resources.

Aquaculture (Research and Development, Policy)

Seth Theuerkauf, Jordan Hollarsmith, Mike Litzow

NOAA's role in aquaculture regulation centers around ensuring domestic aquaculture production is conducted as a complement to NOAA's marine stewardship responsibilities, which include the protection of the environment while balancing multiple uses of coastal and ocean waters. For over four decades, NOAA has been an international leader in aquaculture research to support science based regulation and industry development. NOAA's Aquaculture Program's current research initiatives focus on strengthening in-house aquaculture research capabilities at the agency's regional FSCs and other labs, as well as research and development through competitive grant programs.

NOAA field, lab, and modeling capabilities could provide significant value in evaluating the effectiveness and scaling the potential of macroalgae-based CDR approaches. Evaluation and possible expansion of marine CDR approaches parallel the nascent and growing U.S. marine and Great Lakes aquaculture sector. In particular, CDR approaches that require aquatic infrastructure may involve similar permitting requirements and information needs for environmental consultations to those of aquaculture operations. This may allow for opportunities to leverage spatial planning and siting capabilities within NOAA, as well as provide permitting decision support tools focused on evaluation of protected resources, environmental interactions, and other key considerations. Further, cultivation-based CDR approaches are of considerable interest, and rely upon leveraging aquaculture research and development. NOAA's capabilities provide an unparalleled opportunity for collaboration across disciplines, facilities, and coasts that is beyond the scope of individual institutions to address key questions regarding the potential for marine CDR.

To support CDR research, NOAA can do the following:

- **Continue:**
    - Field and lab capabilities: NOAA lab and field research programs in the Pacific Northwest, Alaska, New England, Gulf of Mexico and Hawaii provide large wet lab spaces (e.g., isotope analysis) and access to diverse oceanographic conditions for evaluation of macroalgae and aquatic animal cultivation techniques, including biogeochemical cycling around farms, new species exploration, and polyculture.
    - Modeling capabilities: NOAA has leaders in the field of carbon system modeling in open ocean contexts and nationally-recognized expertise in aquaculture spatial analysis, siting, and permitting– keys to determining the true scaling potential of macroalgae-based marine CDR approaches
- **Expand / Start / Grow / Improve:**
    - Marine CDR strategies, such as large-scale macroalgal cultivation, face many of the same challenges as the nascent and growing U.S. marine aquaculture sector– much of NOAA's aquaculture regulatory and permitting support, outreach and education, and international coordination could be readily leveraged with additional resources to support marine CDR as a goal for development of marine aquaculture.
    - Research and technology development opportunities include improved evaluation of the mass balance and cycling of carbon in aquaculture settings, carbon life cycle analyses for aquatic farms, and the development of farming methodology and siting to maximize carbon sequestration.

Coastal Blue Carbon / Conservation

Janine Harris, Alec Shub and NOAA cross line office Coastal Blue Carbon Working Group

NOAA's coastal blue carbon (As in Part II, coastal blue carbon is carbon that is sequestered, via photosynthesis, and stored in coastal wetlands including salt marshes, mangroves, and seagrass beds) work cuts across line offices and includes partnerships with other federal agencies and non government partners to better understand the geographic distribution, carbon dynamics, condition of, and threats to these coastal blue carbon habitats (NOAA 2021b). NOAA funds partners, and leads research to quantify carbon storage and sequestration in coastal blue carbon habitats (Kauffman et al. 2020) and how changes, like sea level rise (Peck et al. 2020), increased nitrogen availability (Czapla et al. 2020a, b), and sediment deposition on salt marshes, alter the carbon sequestration and storage in these habitats. NOAA's leadership in science, measurement, national and international policy, and management associated with carbon storage and sequestration in coastal blue carbon habitats can be an asset for CDR research. NOAA also funds and collaborates with partners to understand the carbon storage and sequestration rates before and after habitat restoration efforts (Brophy et al. 2018). Recently, NOAA played a lead role in supporting the inclusion of wetlands in the U.S. National Greenhouse Gas (GHG) Inventory, which now serves as a reference for state greenhouse gas inventories, and continues to support the process. The inventory uses NOAA OCM Coastal

Change Analysis Program (CCAP) (NOAA OCM) data as a baseline to determine the extent of carbon storage and sequestration benefits in these habitats for the United States (EPA 2021). NOAA's involvement in the inclusion of wetlands in the U.S. GHG Inventory puts the agency in a position to share this foundational information nationally and internationally through capacity building activities, including a recently established partnership between NOAA and the U.S. Department of State called the Blue Carbon Inventory (BCI) Project that is designed to help developing countries integrate coastal wetlands into GHG Inventories.

To support CDR research, NOAA can do the following:

- **Continue**
    - NOAA regularly updates and sustains the Coastal Change Analysis Program (CCAP) which is critical for understanding the extent of coastal blue carbon habitats for accounting. We also collaborate with international partners on coastal blue carbon science applications for mitigation and adaptation and provide technical assistance and engage in peer-to-peer learning opportunities which are necessary to support global coastal blue carbon collaboration.
- **Expand / Start / Grow / Improve**
    - To expand and improve NOAA's coastal blue carbon research capabilities, NOAA needs enhancement of CCAP capabilities for increased resolution and seagrass coverage mapping; support to expand wetland reporting with each annual update to the Inventory of the U.S. Greenhouse Gas Emissions and Sinks; increased support for large scale coastal restoration projects that store and sequester carbon dioxide at scale; and support for integration of coastal and open sea carbon research.

Collaborative Research and Stakeholder Engagement

Rebecca Briggs, Alison Krepp, and Katherine Longmire

NOAA strives to transition research and development into operations, applications, commercialization, and other uses that have a positive impact on the lives of the American people every day (NOAA Research and Development Plan). Aligning NOAA's research capabilities with the evolving needs of stakeholders requires continual engagement, strong collaboration and partnerships to develop and deliver data and services in a way that stakeholders expect to consume them (Jones et al. 2021, NOAA Data Strategy). NOAA has the capacity to build and sustain CDR relevant partnerships (including industry and academia) through existing community-based programs with engagement and collaborative research capabilities which build and cultivate long-term relationships at local and regional scales that can systematically identify relevant CDR stakeholders, better understand CDR research needs and gaps, and facilitate transition pathways for science-based information on the complex scientific approaches of CDR, including co-production of knowledge and co-development of products.

Many of the current barriers to large scale implementation of CDR approaches are driven by limitations in technology, economic scaling, and societal perception (NASEM 2019). NOAA has the capacity to address these limitations by harnessing its broader research networks. Scaling the most effective strategies for advancing CDR across multiple sectors requires assessing critical social-technological linkages. Absent a socio-economic or transdisciplinary research agenda that addresses implementation barriers, such as stakeholder perceptions and economic analyses of alternatives, the state of the science supporting CDR implementation is incomplete.

To support CDR research, NOAA can do the following:

- **Continue**
    - Continue to support strong partnership programs that deliver data and services that are relevant and accessible to stakeholders.
    - Improve iterative pathways for end-users to participate in aligning NOAA's research capabilities with stakeholder needs.
- **Expand / Start / Grow / Improve**
    - Grow relationships with NOAA's community-based programs to inform co-production and co-development processes
    - Start a socio-economic or transdisciplinary CDR research agenda

Part IV: Next Steps: Proposal for Development of CDR Research and Coordination at NOAA

NOAA is uniquely positioned to provide decision-makers with the best available science related to the risks and benefits offered by climate intervention strategies. As a trusted agent and purveyor of the underlying science, data, tools, and information to help people understand and prepare for climate variability and change, NOAA has the internationally recognized expertise to collect the observations and conduct the research needed to understand the efficacy and implications of climate interventions.

Synthesized Research Strategy

One of the key challenges of carbon dioxide removal research is the urgency of implementation. Based on an analysis of an ensemble of global climate models, gross negative emissions need to grow by ~6% per year starting in 2020 in order to curb annual emissions to less than 2 °C of warming (Minx et al., 2018; Figure 12, right). Given these benchmark analyses, demand for well-researched carbon dioxide removal techniques is certainly growing. The market for carbon offsets has more than tripled since 2017, and is projected to continue to grow at this rapid pace (McKinsey, 2021).

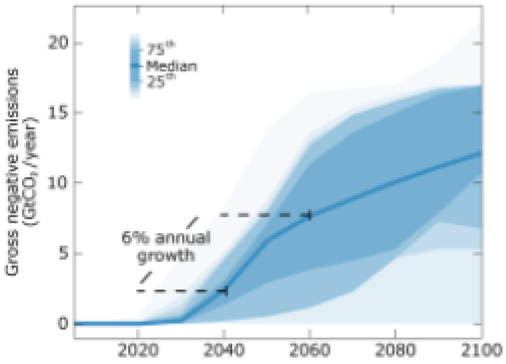


Figure 12. Ensemble projections of necessary carbon removal over time based on emissions targets that achieve 1.5 - 2 C warming. From Minx et al., 2018.

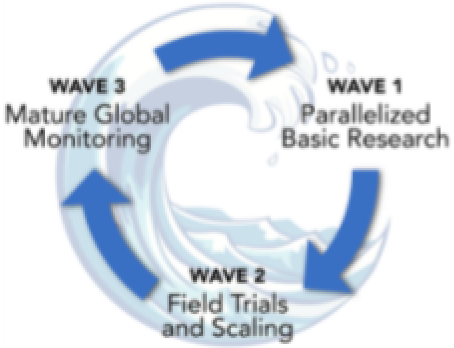


Figure 13. Three waves of CDR research.

Although the demand factors that can help scale the market for CDR are growing, supply factors that require substantial RD&D and scientific expertise are not keeping pace . A substantial gap exists between the upscaling and rapid diffusion of NETs implied in scenarios and the actual progress in innovation and deployment (Minx et al., 2018), especially for the ocean space (NASEM, 2019). NOAA research under our existing mandates can help accelerate each of these supply factors. The Task Force envisions a 3-wave science strategy (Figure 13, left), starting with parallel research (Wave 1) that can accelerate progress towards demonstration projects (Wave 2) and ultimately scale up to a mature observing and monitoring system (Wave 3) to track the efficiency, efficacy, and environmental impact of industry-scale CDR. Given the recommendations made for NOAA's potential role for CDR research in the previous section, some synthesis bullet points for essential activities in each wave are provided here. A much larger table synthesizing all of the research recommendations above is provided in Appendix B.

Wave 1: Parallel Research

In the broader landscape of CDR research, NOAA's unique role will be primarily to assess the efficiency, effectiveness, and environmental impact of CDR techniques proposed by non-NOAA entities. This is likely to require a portfolio of NOAA science, including carbon observations, environmental monitoring, modeling, technology development, and marine spatial planning. However, to meet these challenges, all of these different tool sets at NOAA will require substantial development. In wave 1, we envision initiating a well-coordinated body of research that helps to identify key unknowns and iteratively develop observations, biogeochemical models, and marine spatial planning tools (breakout box 1). This is likely to require a significant planning effort and strong connections to external partners, including other agencies; academic researchers; nonprofit funders; and private sector technologists. Importantly, key stakeholders at local, state, and regional levels will be essential for building public trust in our early research results and establishing the social license for carbon removal.

In many ways, this initial step is the most complex part of NOAA's engagement with the CDR process as it will involve so many unknowns and separate pieces. The temptation to simplify this stage by separating these research pathways is particularly strong; however, we note that this could create parallel stovepipes of excellence that could hinder integration and synthesis. Strong central coordination and clear, scaled communication practices will be necessary to overcome these challenges.

Essential Wave 1 Activities:

- Create inventory of existing, planned, and potential CDR activities by the private sector and other agencies
    - Rank the urgency of NOAA efforts relative to the state and likelihood of these activities going forward
- Centralized planning and coordination of research across CDR techniques
- Seek early stakeholder engagement
- Conduct laboratory bench studies assessing key reactions and processes in multiple CDR techniques
- Design and grow local to regional scale ocean and air carbon observations through expansion of fixed networks and deployment of suites of mobile observing platforms to establish a baseline for assessing the impacts of various CDR efforts.
- Develop modeling packages that can simulate CDR techniques
- Initiate early scaling studies that can help scope future technological needs and initiate technology development
- Initiate marine spatial planning and governance research

Wave 1 Example: An iterative research strategy for assessing macroalgal carbon removal

Early results from other projects have shown how difficult it is to measure and monitor carbon removal from macroalgal projects. Site selection and experimental design are key.

- A strong knowledge of local background processes and of macroalgal modification processes, including growth and sinking, are required, so that these signals can eventually be separated.
- Ideally, a regional or local model would be used to combine these factors to design successful experiments, but many model factors are currently unknown, and can vary by location, species of macroalgae, and duration of the project.
- Biogeochemical models can help define scales at which these key factors can be tested in the laboratory (e.g., rates of respiration); these results can then be applied in the models.
- Once biogeochemical and environmental impacts can be better projected, marine spatial planning tools can be developed to help site these projects in the complex legal space of the U.S. EEZ, where international regulations may prevent these projects in the open ocean (e.g., London protocol prohibits dumping of material, such as macroalgal biomass).
- Combined, these models and marine spatial planning tools can help site small, controlled field programs that answer important research questions.

Wave 2: Synthesis, Field Trials and Risk Assessments

As controlled field experiments produce hopefully promising early results, the demand to scale these projects will be extremely strong given the emerging economic demand. The primary link between Wave 1 and Wave 2 will be a synthesis of these results that drive development of larger scale field demonstrations alongside robust risk assessments. It is primarily in Wave 2 that environmental monitoring is likely to become increasingly necessary to avoid deleterious or harmful impacts on marine resources. Environmental risk assessments will be a key part of these targeted process studies. In this phase, researchers may also be better able to target possible co benefits of carbon removal techniques, including the potential mitigation of ocean acidification at least on local timescales. Additionally, the results from these experiments can help inform important cost-benefit analyses that will shape the potential of the tested methods to scale.

Essential Wave 2 activities:

- Continue stakeholder engagement to identify and evaluate concerns, potential, and likelihood of various approaches
- Synthesize research results
- Target, design, and conduct process studies focusing on ecosystem impacts and providing information to evaluated effectiveness
- Take part in large-scale, controlled demonstration projects with complementary scale ocean and atmospheric carbon observations
- Assess risks associated with the various approaches
- Provide, compare, and contrast results of cost-benefit analyses for the various approaches

Wave 2 Example: Rapid Technology Development through Public Private Partnerships-Saildrone USV as a case study and template

- Public-Private Partnerships and interagency agreements can be powerful collaborations to rapidly advance technologies by harnessing the strength of each type of organization, driving towards a shared vision of rapidly developing ocean observing technology. Saildrone Inc and NOAA Research combined complimentary skills in science and engineering to rapidly develop global-classes of uncrewed surface vehicles (USV) for ocean research. NOAA Research has foundational knowledge to design, operate and improve global ocean observing systems for high impact phenomena such as ENSO, tsunami and carbon flux. Saildrone has the ability to leverage private capital and invest in the complex design and manufacturing of uncrewed vehicles, associated state of the art software and electronics and rapidly scale to meet the density of observations required to advance research and improve ocean forecasting.
- In just 6 years, NOAA and Saildrone have checked off an impressive set of accomplishments while building a global community of practice using USVs, including: setting endurance records in the harshest oceans on the planet, the highest northerly USV deployment, a circumnavigation of Antarctica, and surviving inside a Category 4 hurricane. Multiple sensors and data streams have been collaboratively developed, tested, verified and documented in numerous peer reviewed journals.
- By emphasizing shared needs, complementary strengths, and a clear vision for a sustainable future observing system, this case study can serve as a

blueprint for public and private partners to conduct field field experiments and develop novel technology to accurately measure the fate of carbon.

Wave 3: Mature CDR Research and Monitoring

Gigaton-scale carbon dioxide removal is likely to perturb the global carbon system, shifting storage in multiple reservoirs. For example, carbon removal projects could rival the size of today's total annual land and ocean sinks for carbon (Minx et al., 2018). NOAA should be prepared to measure and monitor these shifts both to ensure that CDR projects are effective at sequestration of carbon from the atmosphere over sufficient timescales, as well as to monitor the potential ecological impacts of CDR operations.

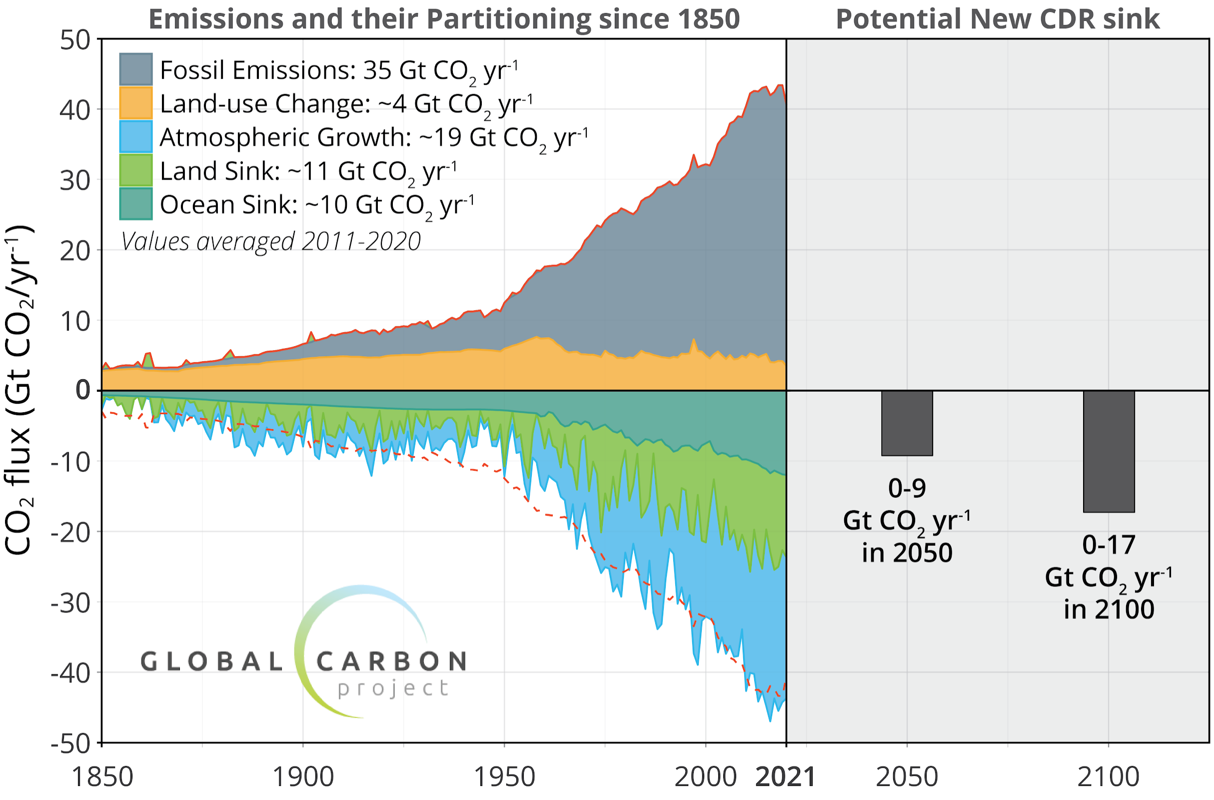


Figure 14. CDR is a new carbon sink: The latest global carbon budget given for 2021 from Friedlingstein et al., 2020, compared to NET goals projected for 2050 and 2100, updated from Minx et al., 2018.

This likely will require an adjustment of our current ocean and atmospheric monitoring systems, given that many CDR projects could take place in areas that are more difficult to monitor (e.g., coastal zone subsurface ocean, terrestrial soils). The measurement, monitoring, modeling and management techniques that we develop during Phase 1 and 2 should be cohesively targeted at better understanding the needs for this necessary observing project, as well as economically feasible ways of achieving the necessary scale of this work.

Essential Wave 3 activities

- Continued stakeholder engagement
- Clear public-private partnerships that enable monitoring of CDR industry
- Expansion of the global observing system

Coordinating Research Efforts at NOAA

Beyond NOAA's science capacity, it is clear that a successful CDR research strategy at the agency will require centralized leadership, strong communication, and early stakeholder engagement. Accordingly, it is the recommendation of this Task Force that new investment from Congress should likely sponsor the formation of a new CDR Program Office within the Ocean and Atmospheric Research Division that can provide this essential internal coordination. We want to emphasize that this program will likely rely on leveraged partnerships with existing NOAA research, including, but not limited to, the Global Ocean Monitoring and Observing (GOMO) Program and the Ocean Acidification Program (OAP). Connections to other line offices will be integral, including strong connections to the ecological research programs of NOAA Fisheries and the coastal management and marine spatial planning activities of the NOS National Centers for Coastal Ocean Science (NCCOS) and Integrated Ocean Observing System. NOAA laboratories are likely to play a strong role in implementing the NOAA CDR Research strategy and will be key program partners.

In addition to coordinating the agency response, we envision that a new NOAA CDR Program Office will engage competitive and targeted research from external research institutions, such as the NOAA Cooperative Science Centers, National Sea Grant College Program, as well as our academic research colleagues. These targeted research programs will help bring necessary external expertise to the table to achieve NOAA's research priorities in CDR and contribute to NOAA's leadership in the scientific community. A NOAA CDR Program Office may also be able to pursue targeted public-private partnerships that can rapidly accelerate research outcomes.

The NASEM (2019) as well as other groups (EFI, 2019; 2020a, 2020b) project that gigaton-scale CDR is likely to be a whole-of-government effort, with important pieces connecting to the missions of as many as 12 different federal agencies, in addition to state partners. Most of these research recommendations indicate that NOAA, the Department of Energy, and the Department of Agriculture are likely to lead the CDR effort, with NOAA playing a critical role. In particular, EFI recommends that "*The National Atmospheric and Oceanic Administration (NOAA) should lead coordination efforts for the federal interagency marine CDR RD&D effort, and should establish a new high level office within NOAA to manage marine CDR RD&D and to* *coordinate with other federal agencies"* (EFI, 2021a). A centralized NOAA CDR Program Office will provide an essential coordinating office to facilitate parallel research efforts and inter-agency coordination.

Given that social license can often make or break the success of a key research strategy, one of the most critical roles of a NOAA CDR Program Office will be engagement with key stakeholders. This is where NOAA will be able to leverage and maintain its high standard of scientific integrity and maintain public trust through frequent communication efforts, transparent data and information sharing, and coproduction of research strategies and recommendations. Fortunately, NOAA has an exemplary infrastructure for conducting this stakeholder engagement, as described in the Collaborative Research and Stakeholder Engagement section of this document..

Essential program coordination activities:

- Serve as a 'home base' for funding and coordinating carbon removal research strategies across the agency, modeled after the Ocean Acidification Program.
- Connect NOAA Research programs with existing research portfolios that support CDR research
- Connect and perhaps fund cross-line-office efforts to study and monitor CDR
- Sponsor competitive and targeted research to achieve NOAA's CDR objectives
- Develop clear relationships with DOE, USDA, NSF and other federal and state agencies to jointly achieve national CDR research goals
- Provide international leadership and coordination.
- Facilitate consistent stakeholder engagement that maintains public trust in NOAA missions and environmental stewardship and supports environmental justice