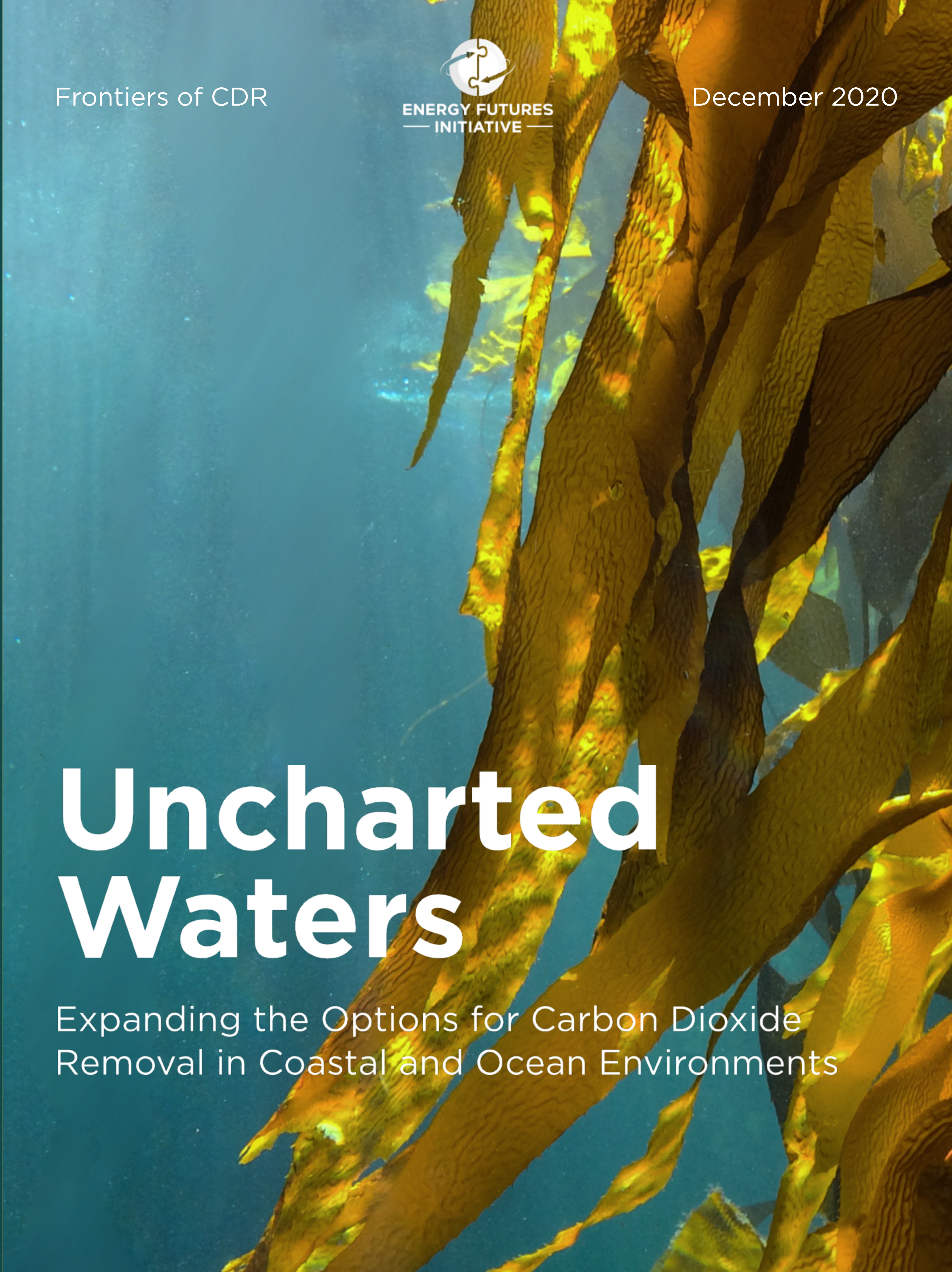

Frontiers of CDR

ENERGY FUTURES INITIATIVE

December 2020

Uncharted Waters

Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments

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About Energy Futures Initiative

The Energy Futures Initiative advances technically-grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, EFI conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI maintains editorial independence from its public and private sponsors.

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Cover Photo: Underwater kelp forest. Photo by barbaraaaa from Getty Images.

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About this Series

In September 2019, EFI published *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies*, a major report that outlined a 10-year, $11-billion research, development, and demonstration (RD&D) program to bring more carbon dioxide removal (CDR) approaches to deployment readiness.[1] Several of these approaches, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) are garnering increased funding support in Congress, but other pathways have received much less attention. Building on the work of the Clearing the Air report, EFI identified three CDR "frontiers" deserving of deeper evaluation: **(1) technologically enhanced terrestrial and biological CDR; (2) marine CDR; and (3) carbon mineralization.** The need for a broad portfolio of CDR options at Gt scale, compatible with the geography and geology of different regions of the U.S. and the world, underscores the need for increased investment in these relatively underexplored CDR "frontiers."

EFI organized six virtual workshops, involving over 100 scientific and technical experts, to address these pathways. The workshops identified the range of CDR approaches, their respective stages of development, and high-priority RD&D needs and opportunities ("big ideas").

This series of reports combines the findings of those workshops with analysis from EFI to provide policymakers with new insight into the potential benefits of these frontier CDR pathways and detail key priority research areas to promote their development. The report in this series are:

→ *From the Ground Up: Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal*

→ *Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments*

→ *Rock Solid: Enhancing Mineralization for Large-Scale Carbon Management*

Series Sponsors

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The content of this report is not attributable to any of the workshop participants, and the view expressed here are EFI's and do not reflect the views of the participants or their employers.

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Key Findings

- **Elevated atmospheric carbon dioxide (CO_2) concentrations have adversely affected the marine environment in three ways—ocean warming, ocean acidification and deoxygenation—all of which have had deleterious effects on the ocean's living resources.** The oceans have become 30 percent more acidic; 50 percent of tropical coral reef systems have been eliminated; and increased temperatures and altered ocean water mixing has adversely impacted marine habitats.

- **Marine CDR, the removal of CO_2 from upper ocean waters, is a key element of the CDR portfolio and, in particular, is an essential complement to reducing atmospheric CO_2 levels.** The carbon cycle is tightly linked between the atmosphere and the oceans. Oceans have and continue to absorb about 25 percent of anthropogenic CO_2 emissions on a net basis, much of which is temporarily stored in the upper layer of the ocean. Without corresponding enhanced marine CDR, reducing atmospheric CO_2 levels will cause oceans to respire a portion of this absorbed CO_2 back into the atmosphere.

- **Marine CDR pathways have significant potential to scale.** Marine CDR pathways can capture and sequester CO_2 at billion ton (Gt) scale in because of the sheer amount of available space in the ocean and the absence of land use complications. Additionally, there are numerous marine CDR pathways available.

- **Marine CDR pathways capture and store CO_2 in ways that may avoid deleterious environmental impacts and in fact have significant co-benefits for ocean ecosystems and fisheries.** Marine CDR pathways can convert absorbed CO_2 in ways that ameliorate ocean acidification that has resulted from the oceans' absorption of anthropogenic CO_2. Other ecosystem benefits include improving fisheries yields and producing feedstocks for food, fuel, and durable products.

- **Questions of public acceptance are among the most critical challenges facing marine CDR at present.** The oceans form a global commons, and large-scale experimentation in the oceans historically has often encountered social and political objections. Well-controlled and -documented research projects, beginning with smaller-scale experiments, will be critical for building public understanding. Efforts should also be made to pilot CDR in areas where co-benefits can directly help local communities.

Recommendations

- **Increased Federal investment in marine CDR RD&D is merited and should include a broad portfolio of emerging marine CDR methods that include both biological and non-biological approaches.** Each of the marine CDR pathways reviewed in this report, if successfully validated through the RD&D process, including scaled field experiments, have the potential to achieve Gt-scale carbon dioxide removal from large scale deployment

Biological pathways include:

- Enhanced coastal ecosystems (blue carbon) through wetlands, mangrove, kelp forest and other ecosystem restoration and better management of shoreline erosion and runoff;
- Enhanced microalgae cultivation, including fertilization of nutrient-limited waters;
- Increased macroalgae cultivation and harvesting of marine-based plants;
- Artificial upwelling of seawater to bring nutrients closer to the surface; and
- Downwelling of seawater as a means of sequestering CO_2 dissolved in upper ocean waters.

Non-biological pathways include:

- Ocean alkalinization through the addition of natural alkaline materials; and
- Electrochemical extraction of carbon from seawater.

→ **Federal funding of over $2 billion over the next decade will be required for research and development, field experiments and large-scale demonstration of the most promising marine CDR approaches.** The September 2019 EFI *Clearing the Air Report* recommended a total federal investment of $1.75 billion over 10 years across the marine CDR portfolio. The Clearing the Air Report also recommended a $2 billion, cross-cutting large-scale demonstration program; large-scale marine CDR demonstrations can compete for this funding as well. Based on the additional information evaluated through the 2020 EFI-sponsored expert workshops, the co-chairs recommended several changes to the allocation of funds within the portfolio to improve overall portfolio effectiveness. These changes were based on the perceived relative strengths and weaknesses of the various CDR pathways, their current technological readiness and their relative global potentials to ultimately contribute to CDR. A total ocean CDR RD&D budget allocation of $2 billion over the next ten years is recommended.

→ **An expert panel convened by the Energy Futures Initiative highlighted six key areas for emphasis in an interagency federal marine CDR RD&D initiative:**

1. Defining the RD&D portfolio of specific biological and nonbiological CDR pathways for technology development, optimization and scalability, including anticipating new and emerging pathways;
2. Improving the methods for monitoring, quantifying, and verifying CDR benefits, ecosystem effects, and lifecycle impacts;
3. Developing predictive modeling and planning tools for siting and operations;
4. Creating markets for co-products from ocean CDR pathways and integration into carbon markets;
5. Enhancing public engagement and support; and
6. Creating enabling national and international governance frameworks.

→ **The federal government, with extensive input from the scientific community, should adopt a protocol for open ocean marine CDR experimentation in order to open the door to necessary large scale research opportunities, while also starting to bring the U.S. in line with international agreements.** The U.S. has not formally joined several major international agreements governing activities, including marine research, in open ocean waters (waters beyond territorial limits, which in aggregate comprise about half of the earth's surface). These include the London, London Protocol, and United Nations Convention Law of the Sea. Marine CDR research could proceed independently of decisions by the U.S. government on whether to join these agreements under research protocols that parallel those of the international community to ensure that marine CDR RD&D will be conducted in a manner consistent with international norms. Federal agencies also can plan experiments within the confines of U.S. territorial waters as an interim measure.

→ **Marine CDR RD&D represents an important arena for international scientific collaboration, and the U.S. should seek to join ongoing international CDR research efforts.** The U.S. could formally join internationally led marine CDR experiments, such as the European Union OceanNETs program, as well as seek international participation in planning carefully controlled, limited-scale experiments within U.S. territorial waters.

→ **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.** NOAA has a wealth of experience in monitoring, modeling, and quantifying impacts, as well as existing RD&D infrastructure. NOAA should add marine CDR to its overall mission and establish a new Office of Ocean Technologies to coordinate agency efforts. These efforts should include harnessing existing research assets (such as laboratories and university collaborations) and existing programs on acidification, coastal environments, and ecosystem protection. NOAA also should establish a new funding mechanism to engage in outreach to stakeholders and local communities.

→ **Marine CDR RD&D will require extensive coordination and integration across the federal executive branch.** The Department of Energy (DOE) and the National Science Foundation (NSF) will be key contributors to marine CDR RD&D, with potential key roles for the Navy, Coast Guard, Army Corps of Engineers, and NASA. The September 2019 EFI *Clearing the Air* report recommended the establishment of a Subcommittee on Large-Scale Carbon Management under the National Science and Technology Committee, with a NOAA representative as a co-chair. The Subcommittee would have an Ocean CDR Working Group also co-chaired by NOAA. In addition, participants in the 2020 EFI expert workshops suggested that NOAA, DOE, and NSF create a "virtual" Advanced Research Projects Agency for Oceans (ARPA-O), as a closely linked collaboration vehicle for a broad range of cutting-edge oceans research and technology development, including marine CDR.

Technology-Driven Approaches for Marine-Based Carbon Dioxide Removal

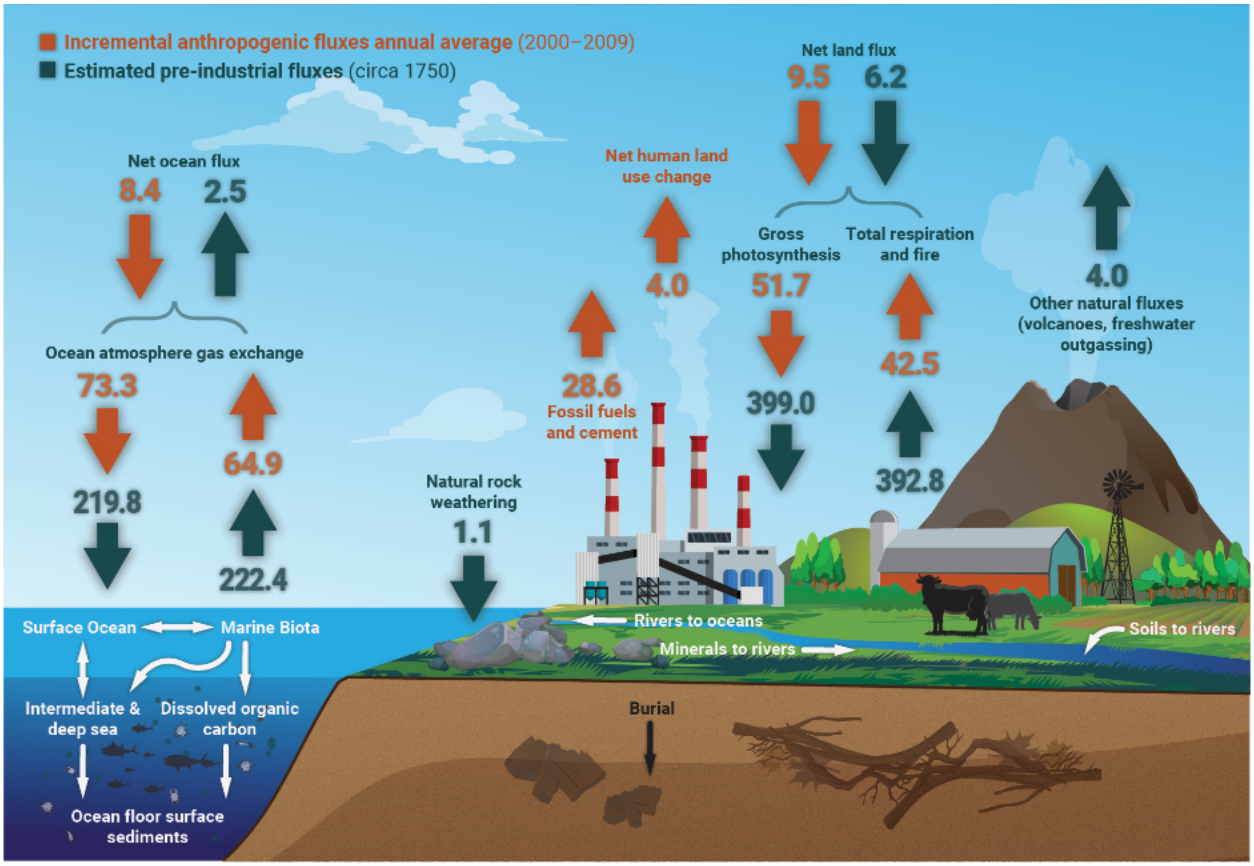
The Need for Marine CDR

The Role of Oceans in the Global Carbon Cycle

Over the last 150 years, the oceans have absorbed about a quarter of the carbon pollution emitted to the atmosphere from human activities, as well as performing the critical role of absorbing more than 90 percent of the warming caused by those emissions to date (Figure 1).[2] Natural ocean carbon removal works on several pathways. In coastal and nearshore ecosystems—such as mangrove forests, seagrass meadows, saltmarsh ecosystems, kelp forests and

FIGURE 1

Global Carbon Cycle



The global carbon cycle involves the exchange of CO_2 among the atmosphere, land, water, and subsurface. Green arrows denote estimated natural fluxes prior to the Industrial Era (circa 1750). Orange arrows denote anthropogenic fluxes averaged over the time period 2000-2009. Frontier CDR options can increase the existing negative fluxes—including terrestrial photosynthesis, rock weathering, and ocean fluxes—to combat climate change Source: EFI, 2020. Compiled using data from Intergovernmental Panel on Climate Change, 2013.

BOX 1

About Carbon Dioxide Removal

Carbon dioxide removal (CDR) refers to methods to remove carbon dioxide (CO_2) from the atmosphere and upper levels of the oceans and sequester or convert the CO_2 into an inert form. CDR is an essential complement to CO_2 emissions reductions to achieve net-zero emissions goals and subsequently net-negative emissions, thereby providing the opportunity to reverse some of the effects of historical greenhouse gas (GHG) emissions and "restore" the climate.

The 2018 Intergovernmental Panel on Climate Change (IPCC) *Special Report on Global Warming of 1.5°C* (SR1.5) outlined the importance of reaching net-zero emissions by 2050 in order to limit warming to 1.5 degrees.[3] SR1.5 estimated that 3 to 7 billion metric tons (gigatons, or Gt) of CDR per year would be required globally by 2050 and up to 15 Gt per year by the end of the century.[4]

There are a variety of well-established **natural CDR pathways** to increase the size of natural carbon sinks, such as planting more trees; adopting sustainable agricultural soil management; expanding coastal ecosystems; and increasing natural geochemical CO_2 removal. Expanding natural CDR pathways, while necessary, will not be sufficient to meet the SR1.5 goals, and certainly not to move towards climate restoration. The carbon removal capacity of natural systems can be **technologically enhanced**through the application of modern technology—including use of biotechnology to enhance CDR in soils, plants and trees; enhancing the reactivity of CO_2-absorbing rocks; increasing ocean biomass through cultivation or artificial fertilization; and reversing the trend toward increased acidity in the oceans. **Direct technological capture** pathways involve engineering extraction such as direct air capture (i.e., atmospheric scrubbing) and direct ocean capture through electrochemical conversion, both of which produce a concentrated stream of gaseous CO_2. The captured CO_2 can then be injected into subsurface saline aquifers or mineralizing rock formations. Alternatively, it can be converted into long-lived carbon-based materials.

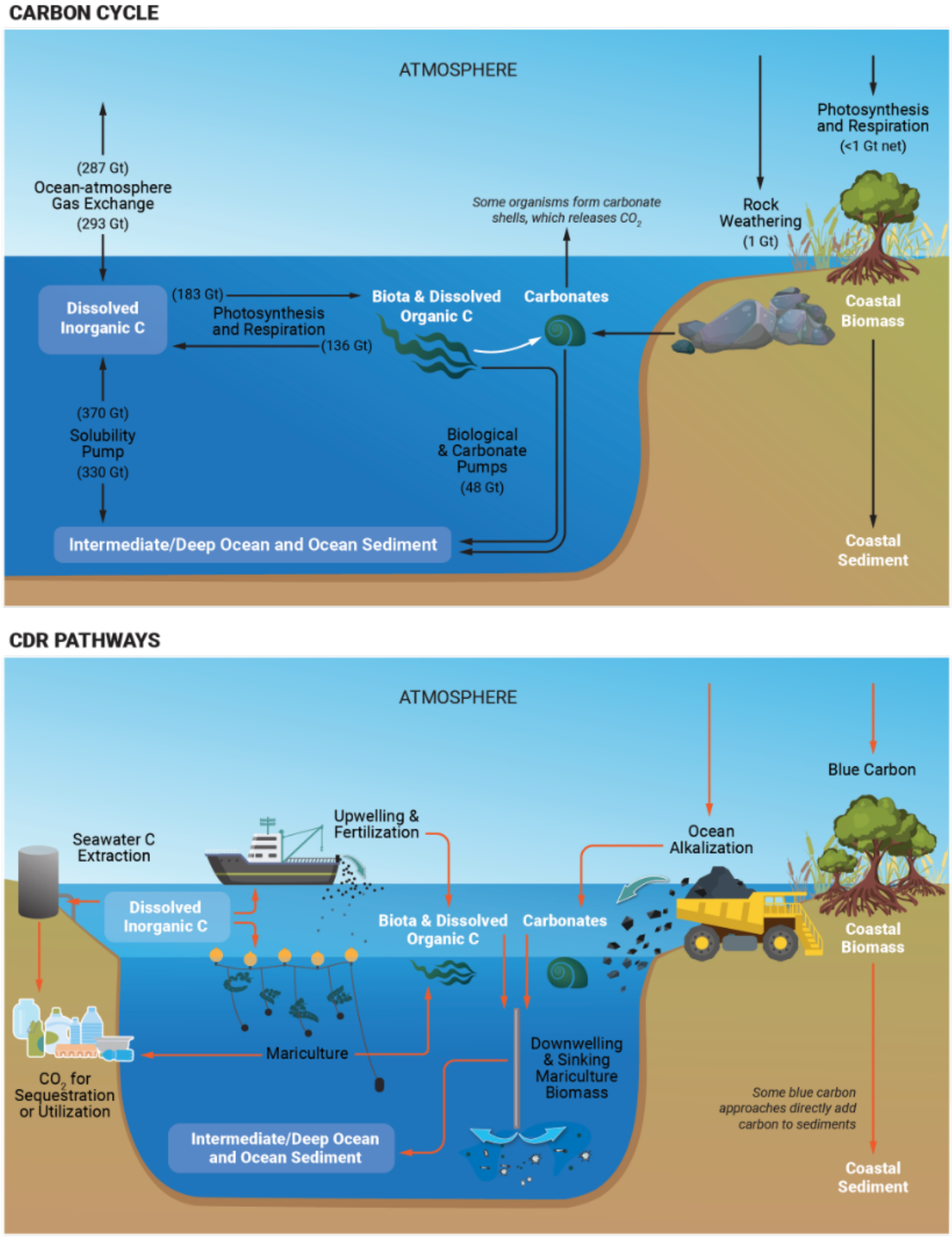
others—plants and other organisms use photosynthesis to convert CO_2 into biomass, some of which is eventually buried and stored in sediment.

A similar process occurs in open ocean waters, where a variety of microalgae grow, capture carbon, and are consumed by other organisms, with some of the carbon eventually sinking to the deep ocean in a process known as the "biological pump." As opposed to land plants that directly consume air CO_2, marine photosynthesizing organisms use dissolved inorganic carbon (DIC) that makes its way into the oceans through the exchanges with the atmosphere, with smaller amounts of inorganic carbon entering via rivers. This DIC also moves between the surface and deeper parts of the ocean through the "solubility pump." A countervailing force is the "carbonate pump," in which the formation of hard carbonate body parts (e.g., shells) by certain organisms releases CO_2 as a byproduct of the process.

The marine CDR pathways discussed in this paper address all of these processes, including accelerating or mimicking nearshore ecosystem's carbon storage potential, the biological pump, or the geological cycle

FIGURE 2

CDR and the Ocean Carbon Cycle



The top figure show how carbon moves around coastal and ocean systems naturally, with pre-industrial fluxes in $GtCO_2e$ shown with black arrows. The bottom figure shows representative CDR pathways discussed in this report, show with red arrows. These CDR methods harness existing carbon "pumps" in the ocean.
Source: EFI, 2020. Created using data from IPCC, 2013 and NASEM, 2019.

(Figure 2). There are also purely technological pathways to marine CDR, primarily electrochemical separation of CO_2 from seawater paired with geologic sequestration or some other method of disposal.

Opportunity for Increasing Marine CDR

The oceans are an obvious place to look for additional CDR capacity given their sheer size and major global role in cycling atmospheric CO_2. The already massive contributions of oceans to natural carbon removal suggest that high-capacity, cost-effective CDR opportunities can be found by mimicking and enhancing natural processes, by finding and employing novel engineered methods, and by the coupling of these two approaches. Most of the marine CDR research to date has focused on coastal ecosystems (often known as "blue carbon"), and on iron fertilization, with relatively little RD&D on other marine CDR pathways that may have much larger CDR potential.

Actions to stabilize if not reduce global atmospheric CO_2 will not be successful without also addressing CO_2 concentrations in the oceans, because carbon in the atmosphere and the surface waters of the ocean are tightly coupled. If atmospheric CO_2 levels were substantially reduced, the ocean would respire a near equivalent amount of the excess CO_2 stored in the upper layer of the ocean, back to the atmosphere, negating a significant portion of the atmospheric reduction. The coupling effect is illustrated in the data shown in Figure 1; in the pre-industrial era, there was a net release of CO_2 from oceans to the atmosphere; as atmospheric CO_2 levels increased due to anthropogenic emissions, the process reversed with the atmosphere contributing a net flux of CO_2 to the oceans.

The increased absorption of CO_2 by ocean waters, combined with the absorption of the excess heat created by atmospheric CO_2 levels, has come at a significant cost to marine ecosystems. The oceans have become 30 percent more acidic; 50 percent of tropical coral reef systems have been lost (and the remainder are at very high risk); and extreme ocean heating has led to deoxygenation, interrupted ocean mixing, and poleward migration of fish and other marine species. Combined with a warmer atmosphere, the warming ocean has increased the melting of Arctic and Antarctic sea and land ice, which combined with thermal expansion of seawater has led to significant sea level rise and changes to weather patterns and currents. **Marine CDR could provide viable means to help reverse these impacts.** Importantly, due to the interplay within the marine ecosystem, marine CDR pathways may also provide significant benefits to marine conservation efforts and have synergies with marine economic development as CDR removes CO_2-induced stress on the oceans and the planet.

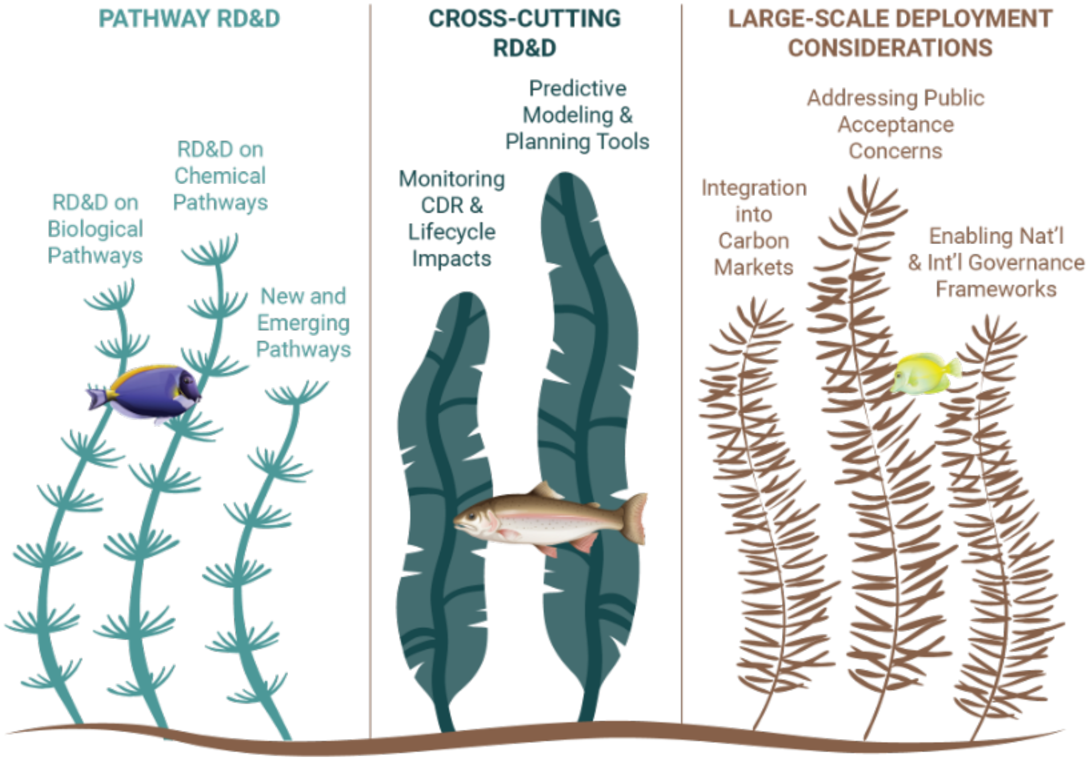
EFI Marine CDR Expert Workshops

Several methods have been proposed for using innovation and technology to augment the ocean's already immense CDR function. These technologies have not, to date, received the attention or RD&D investment necessary to bring them to fruition. Marine CDR also requires special attention to enable governance and legal frameworks because the oceans are a global commons and collective heritage, playing a central role in the viability of the biosphere and the planet.

Following the publication of the September 2019 EFI *Clearing the Air* report, EFI initiated a follow-on dialogue with leading scientific experts to explore in more detail the opportunities for marine CDR. The expert panel convened for this report identified several key areas for action to address the

FIGURE 3

RD&D Opportunities for Marine CDR



The priorities for marine ocean CDR RD&D fall under a range of categories that involve scientific discovery, proof of concept, optimization of cost-effective management potential and development of monitoring, reporting and verification protocols to enable governance frameworks. Source: EFI, 2020.

technological, policy, and social challenges to deploying marine CDR (see Figure 2):

1. Defining the RD&D portfolio of specific biological and nonbiological CDR pathways for technology development, optimization and scalability, including anticipating new and emerging pathways;
2. Improving the methods for monitoring, quantifying, and verifying CDR benefits, ecosystem effects, and lifecycle impacts;
3. Developing predictive modeling and planning tools for siting and operations;
4. Creating markets for co-products from ocean CDR pathways and integration into carbon markets;
5. Enhancing public engagement and support; and
6. Creating enabling national and international governance frameworks.

In addition, this report covers implementation recommendations for a federal RD&D program on marine CDR, including recommendations for interagency and international collaboration, as well as budget reprioritization.

RD&D Priorities for Specific Marine CDR Pathways

Marine CDR pathways can be divided into two broad categories, biological and nonbiological, with overlaps between the two.

Biological pathways include:

- Enhancing coastal ecosystems (blue carbon) through wetland, mangrove, kelp and other ecosystem restoration, and protection of these ecosystems through better management of adjacent activities, shoreline erosion and runoff;
- Enhanced microalgae cultivation, inland or by upwelling or fertilization of nutrient-limited waters with intentional carbon sequestration;
- Increased macroalgae cultivation for carbon removal and harvesting of marine-based plants;
- Artificial upwelling of seawater to bring nutrients closer to the surface; and
- Artificial downwelling of seawater as a means of sequestering CO_2 dissolved in upper ocean waters.

Chemical pathways include:

- Ocean alkalinization through the addition of natural or synthetic alkaline materials; and
- Electrochemical extraction of CO_2 from seawater.

A summary overview of these key pathways, their performance potentials, co-benefits, state of technological readiness as well as potential negative impacts and tradeoffs, are summarized in Table 1. Additional evaluations can be found in EFI's prior Clearing the Air report, as well as in work from Gattuso et al., NASEM, Carnegie Climate Governance Initiative (C2G2), Ocean Visions' Ocean CDR Technology Road-Mapping and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP).[5,6,7,8,9,10] Because this field is in its infancy, such evaluations are likely to change as new concepts and information emerge and, accordingly, RD&D planning and focus will need to be periodically refined.

Biological Marine CDR Pathways

Microalgae: Ocean Fertilization

Single-cell marine photosynthetic organisms play a foundational role in marine food webs and in the global carbon cycle. In large areas of the ocean, the addition of micronutrients (e.g., iron) or macronutrients (phosphorus or nitrogen) increases photosynthesis and growth rate of phytoplankton, enhancing uptake of CO_2 (Figure 4). Natural sinking of some portion of this carbon-rich biomass to the deep sea then sequesters carbon from the atmosphere for hundreds to thousands of years. Research into the geologic record has shown that past stimulation of marine photosynthesis—such as via increased iron delivery—has been at least partly responsible for significant atmospheric CO_2 drawdowns.[11] If using iron, the uptake ratio of carbon to iron in marine organisms is very large (up to 500,000:1), thus it requires very little iron to stimulate significant phytoplankton growth and carbon uptake, potentially making this a relatively cost-effective approach.

At least 13 open-ocean iron fertilization (OIF) experiments have been conducted to test various degrees of enhanced CO_2 uptake and storage as well as other effects on the marine environment. While the experiments showed significant promise for OIF, many of the experiments were not well-monitored and the

TABLE 1

Summary of Characteristics of Selected Mineralization CDR Methods

CDR Method	Form and Duration of Carbon Storage	Potential Co-benefits	Issues and Uncertainties	Scale Potential (Gt/yr)	Current Estimated Cost (per tCO2)	Technology Readiness
Microalgae: ocean fertilization	Inorganic and Biomass C; <1,000 yrs.	Surface ocean de-acidification, eco/fisheries restoration	Ecosystem modification, deep-sea acidification, anoxia, low C storage efficiency	Moderate	Moderate	Moderate
Microalgae: culture	Organic C and derivatives; <= permanent	Food, fuel, fiber; reduction in land use; deacidification	Source of nutrients?; downstream impacts; energy intensity; cost	Moderate	Moderate-High	Moderate
Blue carbon	Biomass C; <1,000 yrs.	Eco/fisheries restoration; sea level rise, storm surge reduction; deacidification	Sea level rise; anaerobiosis and GHGs; conflict with other coastal uses	Low	Low-High	High
Macroalgae culture	Biomass C and derivatives; < permanent	Food, fuel, fiber; reduction in land use; fisheries restoration; deacidification	Source of nutrients?; downstream and deep-ocean impacts; security of structures; entanglement	Moderate-High	Moderate	Moderate
Upwelling/ downwelling	Biomass and inorganic C; <1,000 yrs.	Reducing anoxia/GHG production; surface water cooling; synergies w/ ocean thermal energy conversion; marine energy	Biogeochemical, ecological impacts; security of structures	Moderate	Low-Moderate	Moderate (Upwelling) Low (Downwelling)
Ocean alkalization: natural sources	DIC, mineralized carbonate; 100,000 yrs.	Neutralizes ocean acidity; synergies w/ beach restoration	Impacts of mineral extraction; logistics; safe ocean addition rates?; leaching of trace metals and silica	Moderate	Low-Moderate	Low
Ocean alkalization: synthetic sources	DIC, mineralized carbonate; =>100,000 yrs.	Neutralizes ocean acidity; synergies w/ ocean energy; shipping; desalination	Safe alkalinity levels?; energy and cost of prod., transport; impact/fate of coproducts, impurities	Moderate-High	Moderate-High	Low

TABLE 1

Summary of Characteristics of Selected Mineralization CDR Methods

Seawater carbon extraction	CO_2, derivatives; <= permanent (e.g. land storage)	Cable of mitigating seawater acidity; synergies w/ desalination, aquaculture, and existing seawater pumping	High-volume seawater processing; energy and $ cost; impact of high-pH seawater effluent	Moderate	Moderate-High	Moderate

DIC = dissolved inorganic carbon

CDR Capacity Legend
Low: less than 1Gt CO_2 /yr.
Moderate: 1-5Gt CO_2/yr.
High: Greater than 5Gt CO_2/yr.

CDR Cost Legend
Low: less than $25/t CO_2
Moderate: $25-$125/t CO_2
High: Greater than $125/t CO_2

Note: These designations represent best estimates as of August 2020 based on expert discussions and review of available literature.[b] It is **important** to remember that most of these ranges are preliminary and tentative because most of these CDR pathways are still in early stages of development and few have been field-deployed at any scale. More RD&D is needed to further test and refine these approaches which in turn will provide more precise capacity and cost estimates. These can then better inform ocean CDR policy and RD&D decisions.

Source: EFI CDR Workshops, 2020.

findings were not robust. More CDR-focused field trials are needed at larger and longer scales with careful monitoring of the actual fate and transport of CO_2 and associated positive and negative impacts. Uncertainties include efficiency of carbon storage, impacts on species composition and food webs, and downstream availability of macronutrients.

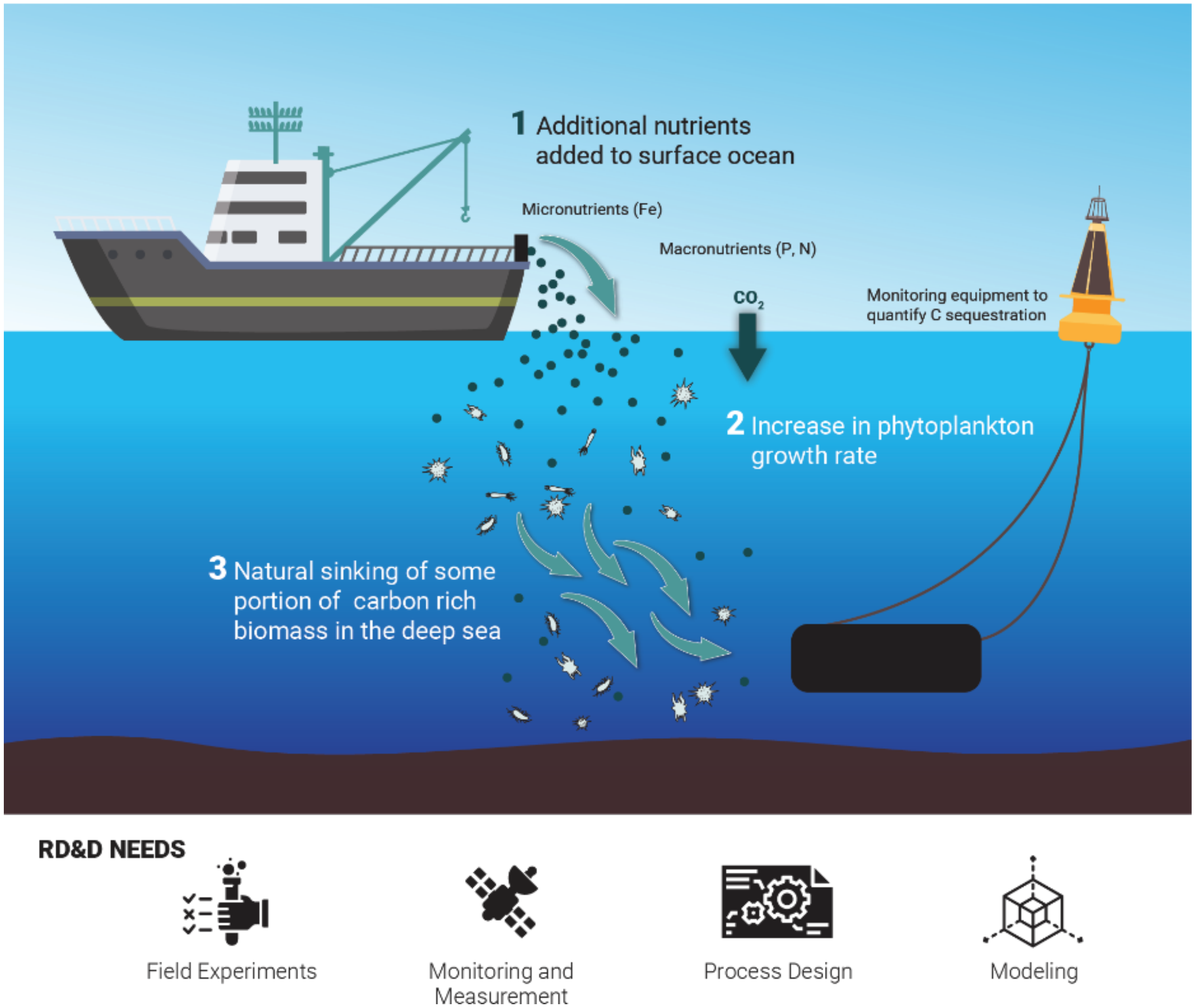
Key RD&D needs:

- → Planning and implementing larger and longer experiments to examine the impacts of scaling
- → Developing autonomous instruments to monitor impacts and quantify carbon sequestration
- → Conducting studies to develop the best delivery methods to maximize impact of fertilization
- → Improving models of ecological and geochemical impacts and to support selection of the most effective sites for large scale CDR experiments and deployments.

b. More extensive reviews of each pathway that were produced for the workshop will be published in forthcoming supporting material on EFI's website.

FIGURE 4

Ocean Fertilization Process and RD&D Needs



Ocean fertilization can help increase phytoplankton productivity, thus increasing organic carbon production and sinking into the deep ocean, where a small fraction is ultimately buried in marine sediments. Additional, well-designed field testing is needed to assess the extent of benefits and issues with scaling up this pathway. Source: EFI, 2020.

Microalgae: Culture

Cultivation of marine microalgae allows a more managed approach to CDR than the in situ fertilization of open-ocean phytoplankton. Marine microalgae aquaculture is an established practice on land for purposes of providing food, fuel, and other products.[12]

Marine cultivation has also been considered, as in the National Aeronautics and Space Administration (NASA)-funded Offshore Membrane Enclosure for Growing Algae (OMEGA) project.[13] Methods of converting the produced biomass into long-lived compounds (plastics, building materials, fiber, etc.) could be employed to provide long-term carbon sequestration (in contrast to food and fuel products, where at least some carbon is returned to the atmosphere).[14,15,16] The potential use of algae products for animal and aquaculture feeds, as well as for direct human consumption, is substantial and could free up agricultural land for other uses (including land-based CDR).

Large-scale (1,000,000 m^2) culturing facilities have been operated for biofuel production, animal feed, and other products. This experience could be translated into CDR with the formation of long-lived/storable products from algal carbon (Figure 5). The cost and resources required, however, may be significant and efficient and safe recycling or disposal of downstream process waste is required.

Key R&D needs:

- Providing sufficient nutrients, especially phosphorus, to facilitate large-scale, dense culturing
- Recycling nutrients to allow sustainability and to avoid downstream pollution/eutrophication;[c]
- Disease and invasive species management;
- Innovations in carbon storage capacity
- Efficient harvesting and processing
- Long-lived product production (e.g., plastics, carbon fiber, biochar)
- Exploration of safe genetic selection or modification to increase efficiency, sustainability, and product generation

Macroalgae Culture

Marine macroalgae (seaweed) ecosystems (e.g., kelp forests and sargassum rafts) far exceed coastal blue carbon systems in terms of potential carbon sequestration capacity.[17] Various methods exist or are proposed to increase CDR by increasing the area covered by macroalgae, and/or by increasing the CDR rate per unit area, through purposefully cultivating this macroalgae and moving/converting the resultant biomass to long-term storage (Figure 6). Such carbon storage could be achieved by:

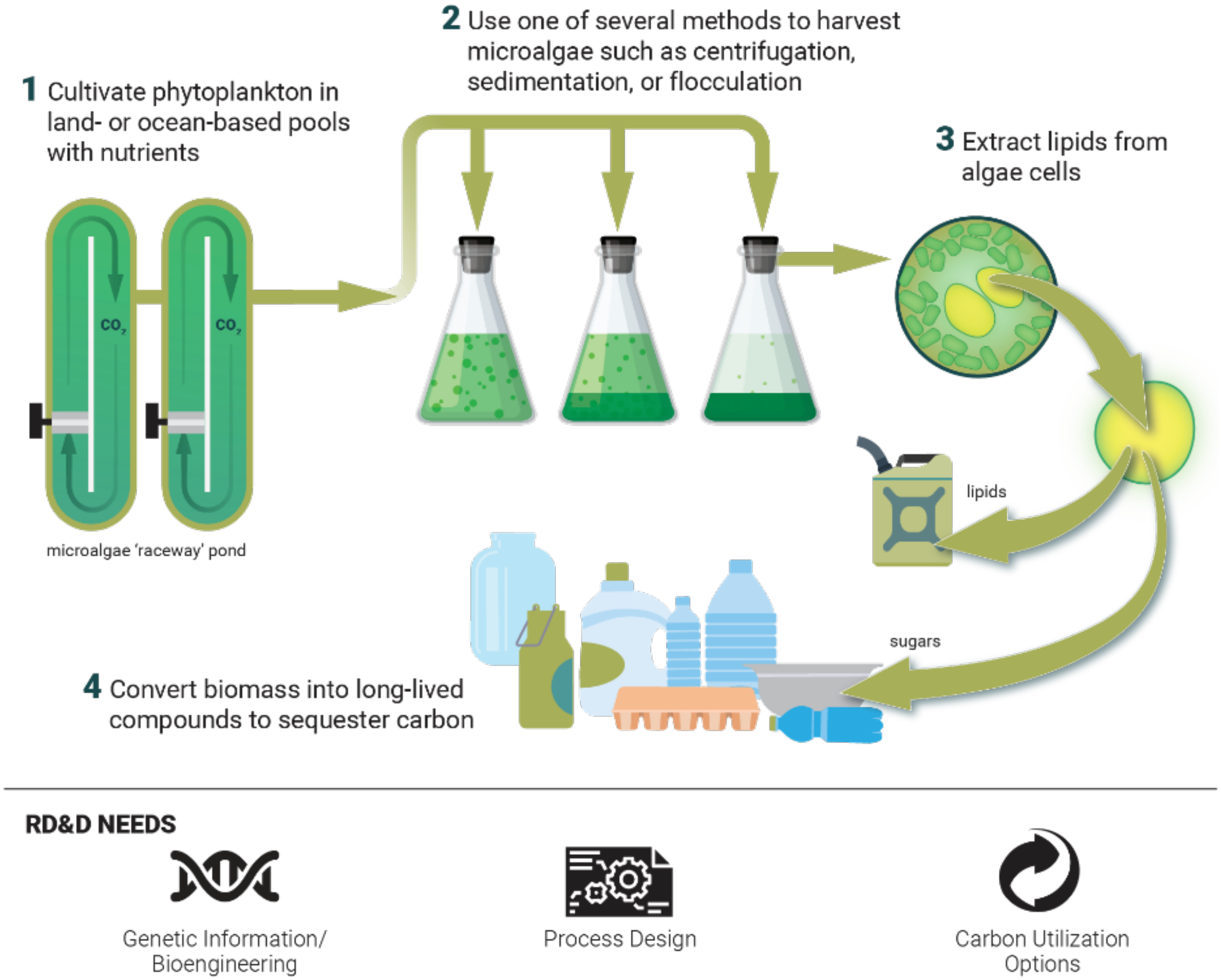
- Harvesting the biomass and converting it to long-lived products (fiber, plastics, biochar);
- Using it as a source of renewable fuel in a BECCS system; or
- Sinking the macroalgal biomass (or residues after extraction of useful products) into the deep ocean.

RD&D on macroalgae cultivation and use is currently underway in multiple parts of the world, though not necessarily directly focused on CDR. In the U.S., a significant funding effort (over $50 million) focused on reducing cost and enabling large-scale macroalgal cultivation was launched by DOE's Advanced Research Project Agency-Energy (ARPA-E) in 2017 and is scheduled to run at least until 2023. International efforts are also arising in support of macroalgae cultivation; The Climate Foundation, as an example, is prototyping Marine Permaculture in the Philippines and Australia, with similar initiatives planned for New Zealand, Indonesia, the Solomon Islands, and various locations in Africa.

c. Eutrophication refers to waters that become flooded with nutrients (often from runoff), leading to algal blooms and hypoxic conditions, harming ecosystems.

FIGURE 5

Microalgae Cultivation Process and RD&D Needs



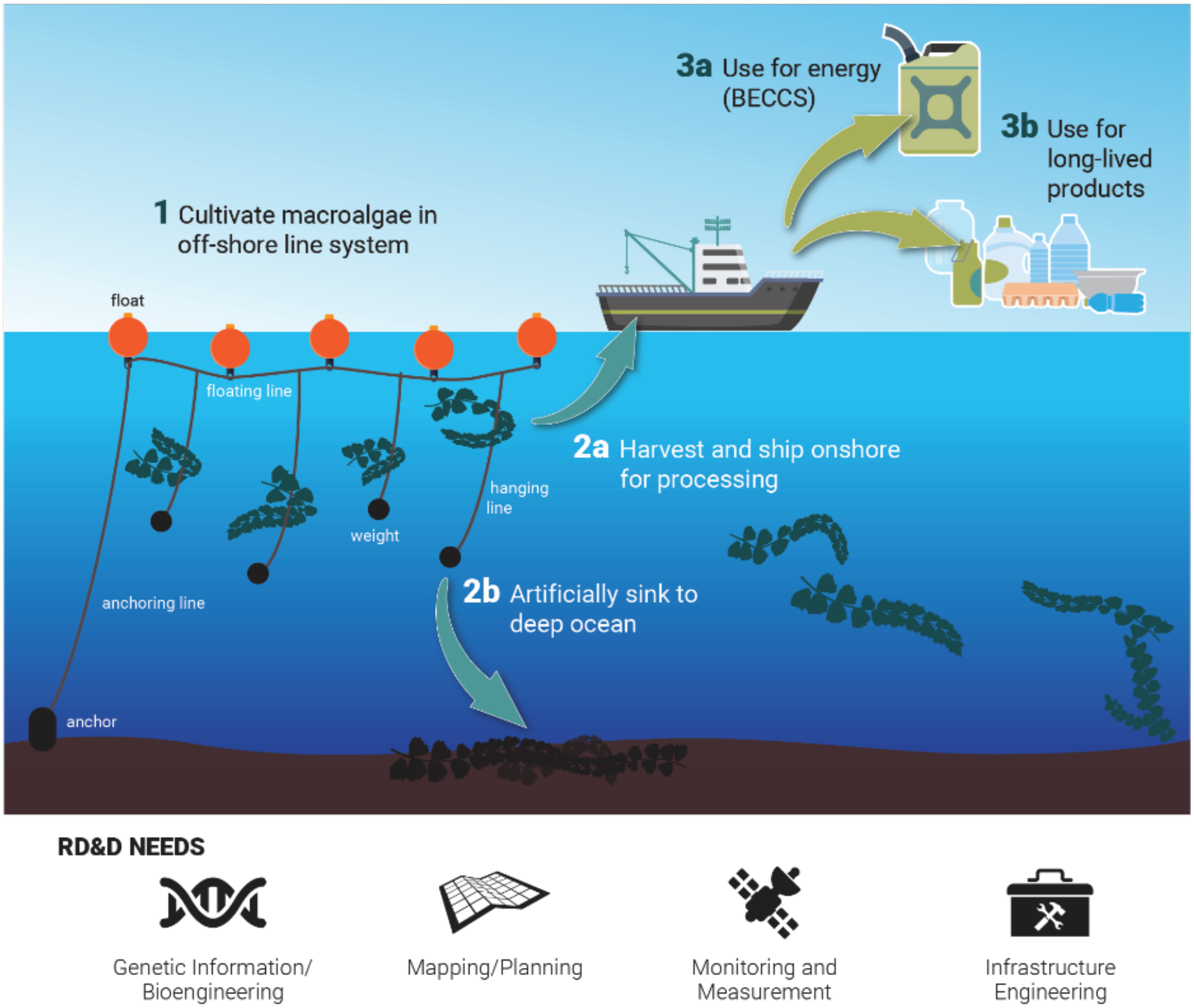
Microalgae cultivation can take place in facilities on land or possibly in open-ocean enclosures. Harvesting microalgae involves separating the biomass from the culture water, followed by drying and processing/refining of the biomass to make products. Source: EFI, 2020.

Key RD&D needs:

- → Enhancing biomass yields through better understanding of the biology and ecology of seaweeds, and use of genomics enhanced breeding strategies
- → Developing more cost-effective designs and materials of construction for large-scale offshore mariculture systems[d]
- → Developing at-sea biorefining techniques
- → Conducting additional research on the impacts of sinking biomass to the deep ocean

d. Mariculture is a subset of aquaculture that involves cultivation of marine organisms in the ocean.

FIGURE 6
Macroalgae Cultivation Process and RD&D Needs



Macroalgae cultivation requires a large network of durable lines, buoys, and anchors, as well as robust monitoring technology. RD&D is needed to ensure these offshore systems are resilient against harsh ocean conditions. Source: EFI, 2020.

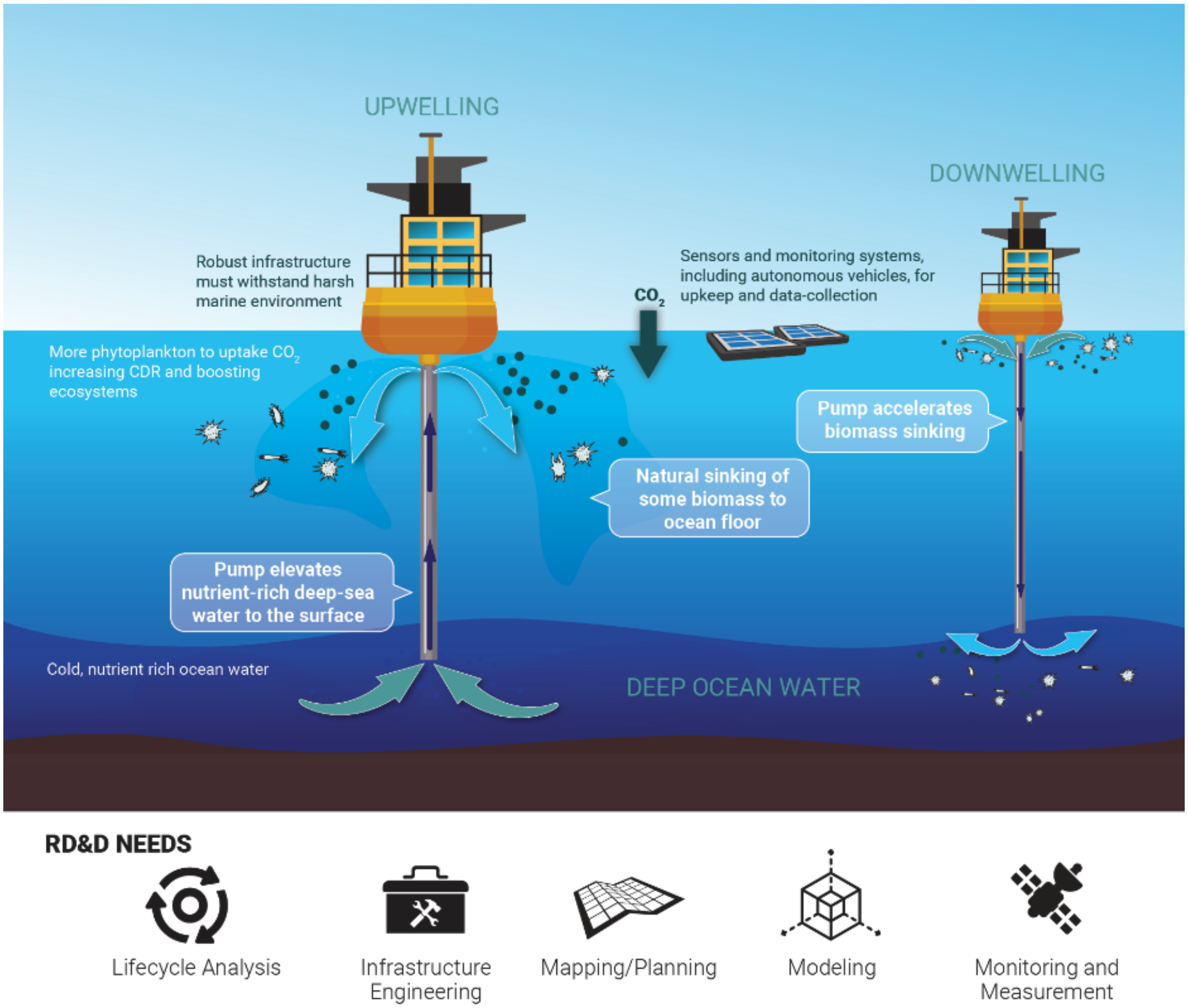
- → Developing marine models and spatial planning tools to optimize and accelerate siting of mariculture operations
- → Developing methods for efficient monitoring and safe management of offshore facilities specific to CDR

Enhanced Upwelling and Downwelling

Artificially enhanced upwelling or downwelling of seawater to move nutrients and dissolved CO_2 can accomplish CDR by physically lifting nutrient-rich water to the surface to enhance photosynthesis (phytoplankton production), or by physically speeding up the sinking of surface ocean carbon to the deep sea, thus increasing the duration of carbon

FIGURE 7

Upwelling and Downwelling Process and RD&D Needs



Moving nutrients from the deep ocean to the surface to stimulate increased organic uptake of carbon, or conversely, hastening carbon transport into the deep sea, will require additional RD&D to understand the full range of effects of these artificial process. Robust Sensing and monitoring is required to validate system effectiveness. Source: EFI, 2020.

sequestration from the atmosphere (Figure 7). Such processes require energy to power the vertical pumping, for example harnessing wave, tidal, ocean thermal (OTEC), or thermohaline energy.[18,19,20]

Nearly all field trials to date have consisted of short-term, single-pipe experiments focused on artificial upwelling.[21] The objective of these field experiments has been to test various pumping mechanisms (wave energy, perpetual salt fountain, etc.) and/or evaluate whether upwelling effectively transports nutrients and results in localized productivity increases.[22] The experience with the European Union Ocean Artificial Upwelling Program could serve as a good starting point for developing a US-based RD&D program.[23]

Key RD&D needs:

- → Gaining a better understanding and quantification of the net effects of enhanced upwelling and downwelling on ocean and atmospheric carbon
- → Developing materials and technologies robust enough to withstand harsh marine environments
- → Developing ocean-based renewable energy sources to power operations
- → Improving the security and reducing maintenance requirements for structures
- → Advancing sensors and monitoring systems, including autonomous and remote vehicles for monitoring CO_2 and environmental benefits/impacts and overall system function
- → Improving analytical techniques for siting and modeling

Blue Carbon

“Blue carbon" refers to carbon management via preservation or restoration of mangroves, tidal wetlands, salt marshes, and seagrasses. These coastally restricted ecosystems contain about 73 $GtCO_2e$ with a CO_2 sequestration rate of about 0.4 Gt/yr. The rate of uptake and storage has been declining due to eutrophication, lack of sediments, accelerating sea level rise (SLR), and coastal development. Options for blue carbon CDR focus almost exclusively on maintaining and/or restoring the extent of these coastal ecosystems.

Pathways for enhancing coastal CDR (see Figure 8) include conservation-oriented management of wetlands (such as controlling shoreline erosion and coastal nitrogen runoff), restoring lost or degraded wetlands, converting hardened shorelines to instead use natural features (e.g. living shorelines), and managing wetland migration into uplands as sea levels rise.[24] Techniques to enhance soil carbon storage (e.g., organic matter/biochar amendments and plant bioengineering) could be harnessed to boost carbon storage.

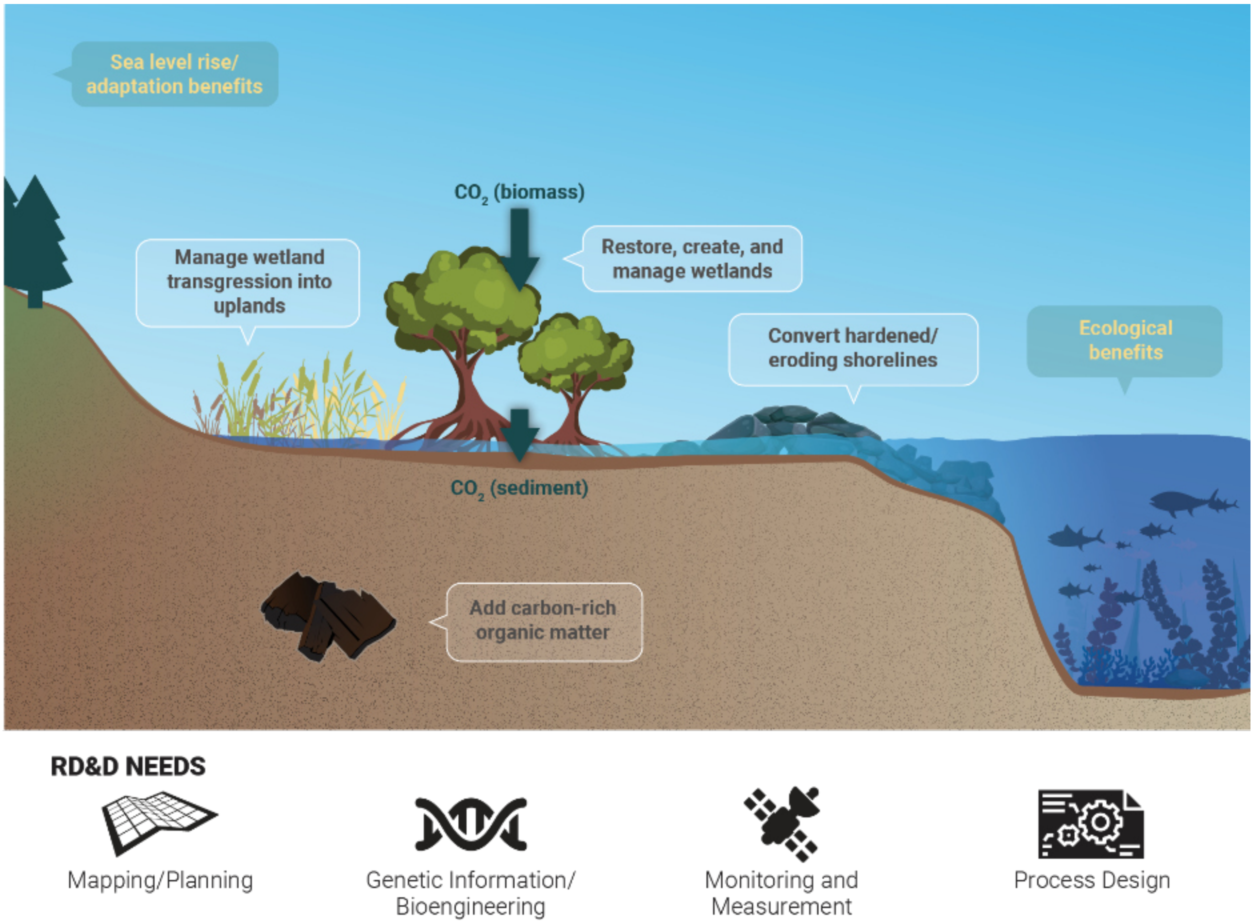
Blue carbon ecosystems are relatively well understood, mapped, and increasingly prioritized in national climate plans and coastal resilience plans; it is one of the most mature options for marine CDR today. Consequently RD&D needs are less extensive than with other less mature marine CDR pathways. The principal challenge to blue carbon is scale of deployment. Expansion of blue carbon systems often must compete with other coastal land uses. Additional limitations include very small additional global CDR potential and loss of capacity with rapid sea level rise.

Key RD&D needs:

- → Developing better inventories of existing blue carbon, and identification of additional sites for potential restoration or expansion
- → Improving restoration techniques, including genetic selection/ manipulation
- → Improving methods of validating blue carbon CDR performance and costs.

FIGURE 8

Blue Carbon Approaches and RD&D Needs



Managing and restoring blue carbon ecosystems is a well understood practice, which can further improve with more practice (i.e. learning by doing), and with better mapping and monitoring to quantify and ensure net CO_2 removal and ecosystem benefits. Source: EFI, 2020.

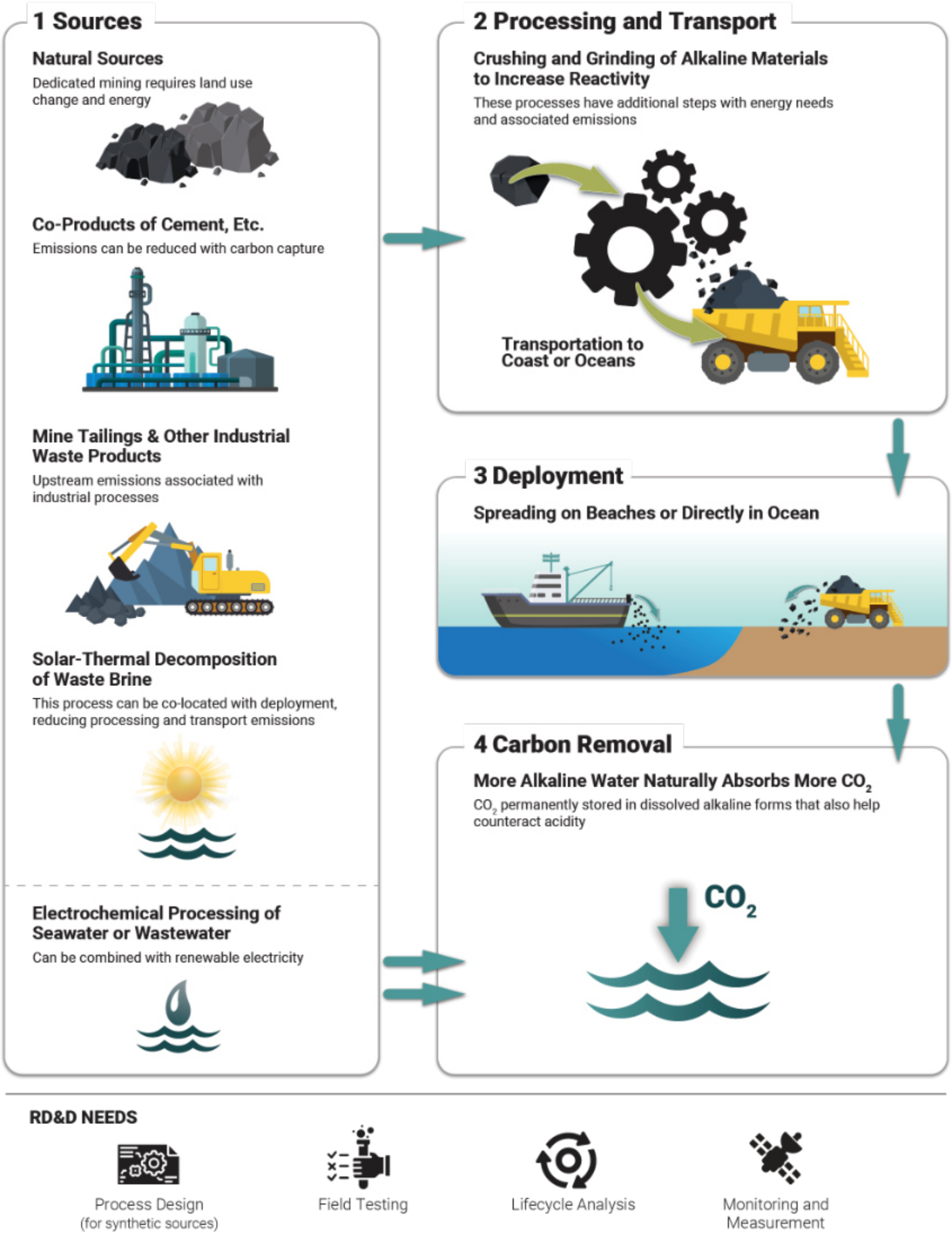
Non-biological Marine CDR Pathways

Ocean Alkalization: Natural Sources

By far the most abundant form of carbon on the Earth's surface consists of dissolved bicarbonate and carbonate ions in seawater. The formation and maintenance of this carbon reservoir occurs via reactions between rocks, CO_2, and water on the Earth's surface. Proposals to accelerate this process include grinding alkaline minerals to increase their reactive surface area and exposing the minerals to more reactive environments. For example, the reactivity of silicate minerals could be increased by spreading finely ground alkaline rocks over the open ocean or on beaches. These techniques are analogous and complementary to efforts to enhance mineral weathering on land (see EFI's report on mineralization in this series, *Rock Solid*). Research on this approach so far has been mostly confined to modeling and lab studies; field work has been limited. Key unknowns include chemical and biological impacts of rock addition to the ocean, especially the

FIGURE 9

Ocean Alkalinity Enhancement Approaches and RD&D Needs



There are several viable sources of alkaline material to utilize for synthetic alkalization of ocean water. Most supply-chains of ocean alkalization involve some form of transporting materials, though this not necessarily always the case as shown by the electrochemical processing of seawater. Source: EFI, 2020.

effects of trace metals and silica on marine ecosystems that can accompany such addition.

Key RD&D needs include (many of these are also applicable to the synthetic approaches pathway):

- Initiating small-scale proof of concept field testing of ocean alkalization to better quantify CDR potentials as well as ecosystem impacts
- Developing protocols for monitoring and accounting
- Developing models and observational tools capable of monitoring ocean alkalinization efforts and verifying carbon dioxide storage
- Improving models to help identify suitable locations for various ocean alkalinity enrichments, potential co-benefits and disbenefits to marine ecosystems impacts
- Investigating of upstream and downstream environmental effects (including the impacts of rock extraction, processing, and transportation) and CO_2 lifecycle accounting
- Development of ROVs and autonomous platforms for monitoring and verification

Ocean Alkalization: Synthetic Sources

To overcome the slow reaction rates inherent in naturally occurring minerals, use of synthetic/industrial materials are being contemplated for ocean alkalization (see Figure 9 for a summary of alkalization approaches with both natural and synthetic sources). These include, for example, highly CO_2-reactive, alkaline calcium oxide (quicklime) or calcium hydroxide (slaked lime) materials that are currently in commercial use in steel, concrete, and certain food products industries The production of these materials, however, is emissions-intensive, so carbon-free methods of production (e.g., carbon capture and storage of emissions from process heating) or alternative, "green" production routes would be required to achieve net negative emissions.[26,27]

Another way to reduce the carbon emissions would be to use emissions-free electricity from renewable or nuclear energy sources in electrochemical processes that split water and salt, forming alkaline hydroxide and hydrogen gas.[28,29] The solar-thermal decomposition of salt brine, e.g. from desalination, to form CO_2-reactive alkalinity has also been considered,[30] as have linkages to wastewater treatment.[31]

These approaches are still in the early stages of RD&D, with modeling and lab-scale experimentation.

Key RD&D needs:

- Optimizing technology performance and cost reflecting systems analysis
- Improved modeling and validation of data on the spatial and temporal dynamics of ocean pH, dissolved inorganic carbon and alkalinity, and other critical ocean parameters resulting from implementation of these processes
- Understanding downstream environmental impacts and benefits

BOX 2

Sub-seabed Carbon Sequestration

Both marine- and land-based CDR pathways (BECCS, DAC, seawater CO_2 extraction) that capture and concentrate CO_2 require methods for sequestering that carbon. One alternative involves injection of CO_2 into deep-sea basalt formations that offer high CO_2 storage potential. Here, CO_2 and seawater could be injected and subsequently reacted with the basalt, forming stable carbonates and bicarbonates that prevent the return of CO_2 to the atmosphere.[25]

While the alkalizing function of deep-sea basalt is analogous to ocean CDR alkalization, the subsurface mineralization effected by the former is distinct from ocean alkalization's ultimate formation of bicarbonate/carbonate dissolved in seawater. Another report in the EFI Frontiers of CDR series, *Rock Solid: Harnessing Mineralization for Large-Scale Carbon Management*, discusses subsurface mineralization activities in greater detail.

Seawater CO_2 Extraction

CO_2 gas can be extracted from seawater by applying a vacuum to the air space in contact with the seawater, or by purging with a gas that is undersaturated in CO_2 relative to that in seawater.[32] The seawater can also be acidified with a mineral acid so that dissolved inorganic carbon, which is mostly in the form of bicarbonate ions (HCO_3-) in natural seawater, is converted to dissolved CO_2 gas. Both electrodialysis and electrolysis have been explored as ways of acidifying seawater for subsequent CO_2 stripping.[33,34,35] The removal of CO_2 from the ocean surface leads to undersaturation in the water, thus forcing CO_2 to move from the atmosphere into the ocean to restore equilibrium. This is a purely technological CDR pathway, analogous to direct air capture (Figure 10); as a result, the CO_2 removed from seawater must be sequestered through techniques such as underground storage in saline formations, or converted into long-lived products (cement, plastics, etc.) or fuels.

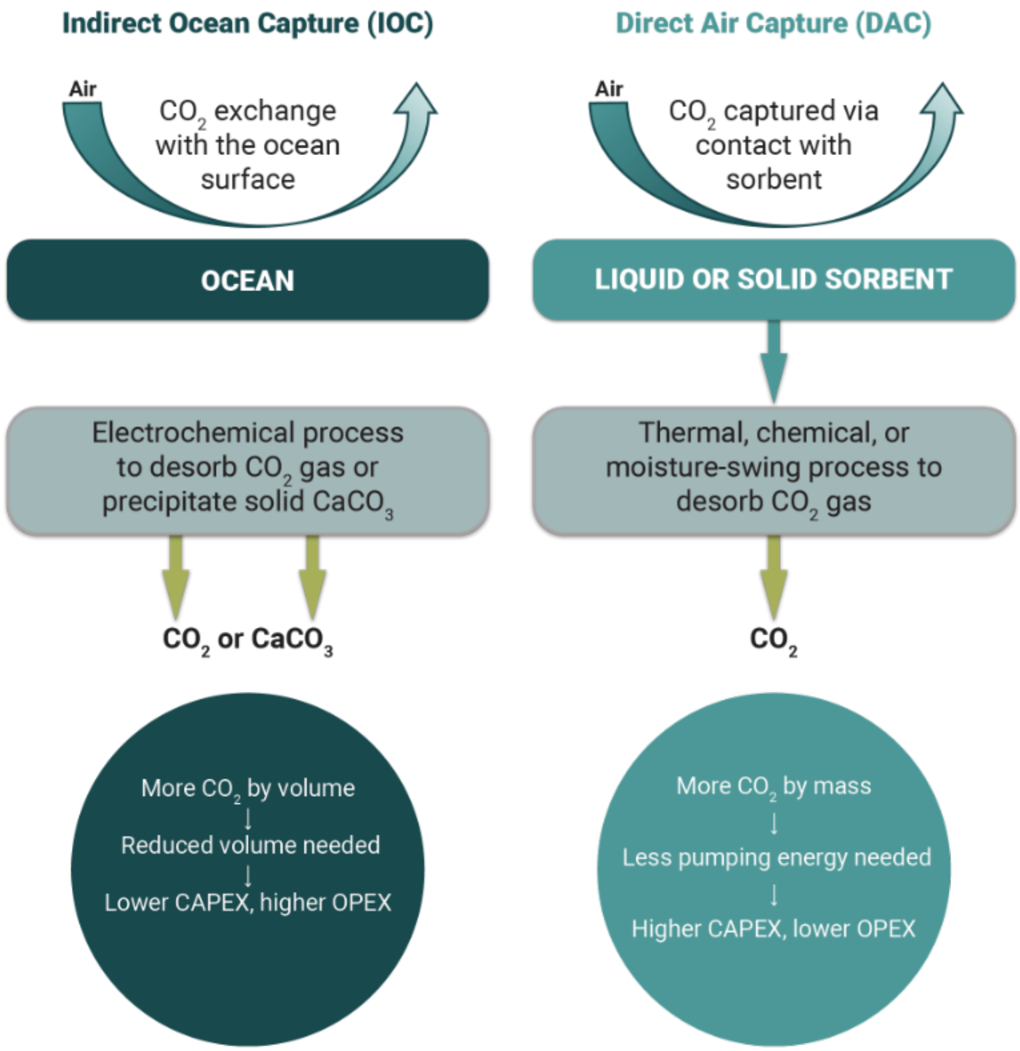
Electrochemical seawater CO_2 extraction has been modeled, prototyped, and analyzed from a techno-economic perspective.[36,37,38,39,40] One particular process design is shown in Figure 11. A particular focus has been on fuels production from the extracted CO_2. One approach to reducing the cost of CO_2 conversion to fuels is to integrate the extraction process with other processes already pumping vast quantities of seawater (e.g., coastal power plant cooling, desalination, etc.).[41,42,43]

Key RD&D needs:

- → Optimizing electrochemical and process designs and locations for minimizing resource requirements (e.g., seawater pumping requirements, energy consumption)
- → Investigating the downstream chemical and biological effects of CO_2-undersaturated (i.e., elevated pH) seawater, including the air-to-ocean CO_2 uptake rates and storage in downstream (i.e., processed) seawater following CO_2 extraction)
- → Developing High-resolution oceanographic models that can simulate the physics, chemistry, and biology of the local environment to properly design electrochemical

FIGURE 10

Comparison of Seawater CO_2 Extraction and Direct Air Capture



Seawater CO_2 extraction can be analogized to DAC, in that seawater itself serves as the equivalent of the solvent or sorbent in the latter. Due to the differences between CO_2 in water and air, seawater extraction would require less fluid throughput than DAC, but more energy spent on pumping. Source: Adapted from Eisaman, 2020

conversion systems and understand marine ecosystem feedback effects;

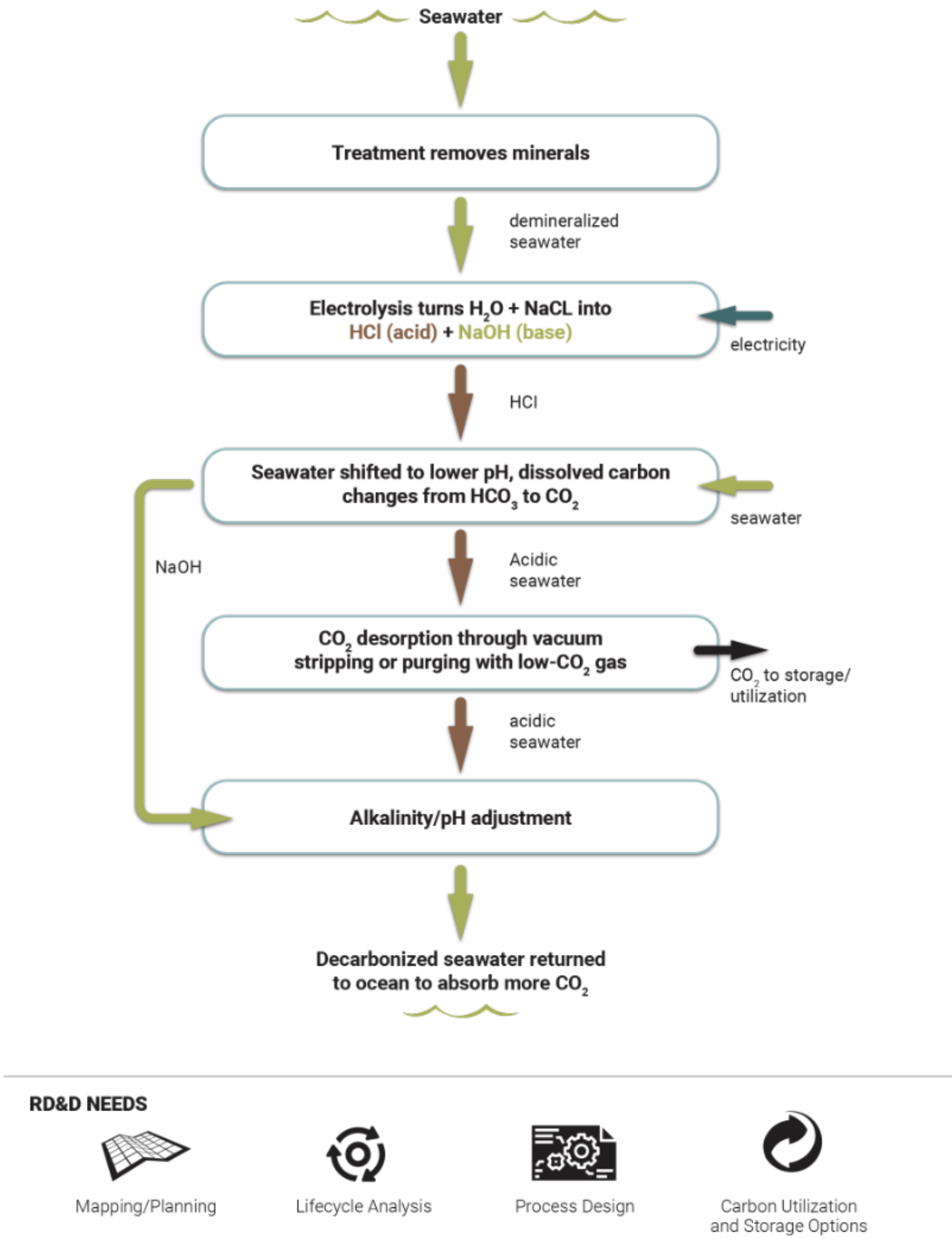
- Identifying cost-effective and verifiable CO_2 storage/utilization methods.

New and Emerging Methods

It is important at this early stage of marine CDR RD&D to not only to support current frontrunner pathways, such as those described above, but to encourage emergence and testing of new and potentially better concepts. Any RD&D portfolio for marine CDR

FIGURE 11

Proposed Process for Seawater CO_2 Extraction With Acidic pH Shift



CO_2 can be extract from seawater through electrochemical means, and the resulting CO_2-undersaturated seawater returned to the ocean to absorb and store additional CO_2 from air. Several utilization or storage options are available for the extracted CO_2, including use in making long-lived products or injection into geologic formations. Further RD&D can clarify the extent of those co-benefits as technologies are scaled up.
Source: Adapted from Eisaman et al., 2018.

should set aside a small portion of funding to encourage and support new, innovative concepts.[44,45]

Co-benefits of Marine CDR

While ocean CDR offers a means to combat climate change at scale, its value extends far beyond mitigating GHG emissions (Figure 12).

Ecosystem Benefits

Elevated CO_2 concentrations in the air and the ocean have disproportionately impacted the marine environment through three main processes—ocean warming, deoxygenation, and ocean acidification—all of which have had and continue to have deleterious effects on the ocean's living resources. By removing CO_2 from the atmosphere, ocean CDR can help stabilize and restore key ecological functions by helping remove thermal and chemical stress. Such stress removal **cannot be achieved** solely by conventional marine conservation pathways such as establishing protected areas or reducing fishing pressure. New methods of marine management that include CDR are now required to effectively conserve and restore marine ecosystems.[46]

Marine CDR pathways bring localized benefits for marine conservation. Biotic pathways can help restore critical oceanic species, communities, and habitats (e.g., phytoplankton, kelp forests, sea grasses). Upwelling and downwelling may help cool surface water, countering the impacts of warming on local ecosystems, combating natural or human-caused hypoxic conditions in subsurface environments, and potentially boosting fish stocks. Several pathways (e.g., macroalgae growth, ocean alkalinization, and seawater CO_2 removal) can help ameliorate surface ocean acidification.

The benefits of marine CDR pathways to marine conservation can also bring economic benefits. For example, more robust blue carbon ecosystems can increase coastal resilience to sea level rise and storm surges. Similar benefits are derived for coastal reefs when ocean acidity is neutralized. The value of mariculture activity will also be enhanced by thriving, biodiverse ocean ecosystems. In addition, methods of ocean alkalinization and CO_2 removal can provide co-benefits to the aquaculture industry via pH control.

Valuable Products and Downstream Emissions Reductions Benefits

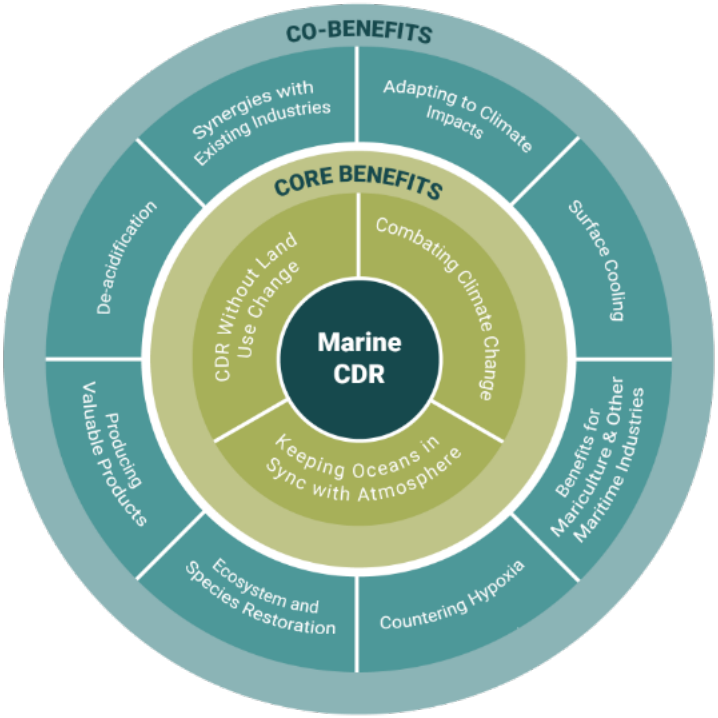
Some marine CDR pathways discussed here produce useful products that can boost the economic viability of those methods. Mariculture of micro- or macroalgae can produce food, fuel, or durable products. Electrochemical separation of CO_2 from seawater can co-produce hydrogen for use as a negative-emissions fuel when the electrolysis powered by carbon-free electricity. Electrochemistry can also produce acids for seawater CO_2 stripping and enhanced mineral weathering processes.[47,48]

Marine CDR can be a valuable complement to land-based CDR, reducing demand for the use of arable land that otherwise might be used for agricultural production. The higher productivity of marine CDR pathways results in a smaller footprint; the area needed for marine CDR may be as little as one-tenth of the land area needed for an equivalent level of CDR using land plants.[49,50]

Synergies with Existing Ocean Industries

Many ocean CDR pathways can coexist with and complement conventional marine activities and platforms. These include marine renewable energy, aquaculture, fisheries, marine tourism shipping, ports, desalination,

FIGURE 12
Co-benefits of Marine CDR



While combating climate change is the primary role of marine CDR, such methods can also provide significant co-benefits. Further RD&D can clarify the extent of those co-benefits and thus potentially provide additional justification for accelerating scale up and widespread deployment. Source: EFI, 2020.

and sewage treatment. Coupling CDR with these activities could provide economic and environmental benefits and entry points for safe, low-cost methods of marine CO_2 management. Micro- or macroalgae mariculture can also be a gateway to a plethora of employment opportunities for coastal communities including the cultivation as well as the processing and creation of valuable products such as animal feeds and fertilizers.

Cross-Cutting Marine CDR Priorities

Establishing baselines is essential to support effective monitoring and verification. One issue facing marine CDR is a lack of understanding of how much and by what mechanisms carbon is removed through natural processes at any given location. For example, unless harvested, the end products of CDR (e.g., dissolved/solid organic and inorganic materials) may be difficult to quantify relative to the natural carbon cycle, and easily dispersed away from the immediate site of CDR. More R&D at the basic science level, as well as much more rigorous monitoring and modeling tools, are necessary to establish a better baseline for natural carbon cycling against which ocean carbon removal can be compared.

Lifecycle impact analysis will need to be incorporated into marine CDR research plans. Marine CDR pathways will have environmental challenges that will require additional measures to mitigate potential lifecycle impacts, such as:

- Energy use and associated emissions, from CDR processes, e.g., as used in seawater CO_2 extraction, by ships and other platforms used, and in the production of materials such as the generation of synthetic alkalinity;
- Potential for reversal of CDR benefits, such as sea level rise compromising coastal blue ecosystem CDR; and
- Issues with recycling or disposal of downstream process waste, such as from micro- and macroalgae culture.

The potential side effects of marine CDR measures need to be carefully considered in research planning and in monitoring of experiments. The unintended collateral and downstream consequences of the CDR may be subtle, widespread, long-lasting, and method-specific. Every CDR method described above still carries some level of uncertainty in terms of ecological effects. These potential effects vary with each CDR approach. Potential side effects that should be considered in the design of marine CDR experiments could include increases in toxic algae blooms arising from ocean fertilization, macroalgae culture structures entangling marine animals, release of trace or byproduct chemicals from ocean alkalization, or unintended organism response to particulate or dissolved alkalinity addition. These uncertainties can present issues to conventional oceanographic measurement methods involving ship deployments over significant areas potentially for long periods of time.

Monitoring, reporting and verification (MRV) will need to be developed. In addition to technological RD&D, researchers and policymakers have to collaborate on innovation for monitoring, reporting, and verification standards and regulations. To further ensure objectivity, transparency, and safety, measurement and validation by third parties should be considered for large-scale projects. In these efforts, expanded development and use of remote sensing, advanced sensors, and autonomous ocean vehicles will play a key role in cost-effectively testing, monitoring, and verifying marine CDR methods.

Expanded field testing will be a critical step in scaling up marine CDR. To date, field testing has been limited in scope, size, or duration—or in some cases, completely nonexistent. Expanded, but still small-scale (about 1 km^2) field tests can verify the functionality of designs, determine impacts and test out systems for monitoring and verification. Field tests are also a critical steppingstone for learning about the environmental impacts of marine CDR, as well as identifying and assessing other challenges that may arise with scale-up. Field tests are largely reversible and can be stopped if adverse impacts are discovered.

New modeling and planning tools will be needed. The ability to accurately model and predict outcomes of marine CDR activities is also vital, so as to better identify locations that provide the most cost-effective testing and deployment of specific CDR methods. In turn, the results of such testing can be used to iteratively improve the models and provide better information for decision- and policymakers.

Consideration for Large-Scale Deployment of for Marine CDR

Creating an Effective Governance Framework

For purposes of governance, the ocean areas typically classified into three maritime zones:

the Territorial Sea (extending 12 sea miles from a baseline shore), the Exclusive Economic Zone (extending a maximum of 200 sea miles), and the "high seas" (or international waters) outside the jurisdiction of any one nation (the latter comprising half or more of the entire extent of the oceans). There are a wide number of local, regional, national, and international laws, regulations, and institutions that govern activities in the various maritime zones (Figure 13). For example, activities in international waters can fall within a number of treaties and protocols, including the United Nations (U.N.) Convention on the Law of the Sea (UNCLOS); the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and its successor agreement, the London Protocol; and the U.N. Convention on Biological Diversity (CBD).

A key challenge is the clarification of an enabling policy and governance framework for marine CDR that can work effectively in the jurisdictional complexity and fragmentation of present ocean governance. Because the current frameworks were created without CDR in mind, regulators and researchers will need to collaborate to determine how these existing governing frameworks should be adapted to marine CDR. An additional challenge is to determine how international governance frameworks should be applied to U.S.-based marine CDR. While the U.S. is a party to the London Convention, the U.S. has signed but not ratified the London Protocol, the UNCLOS, and the CBD. The U.S. marine CDR scientific community may need to adopt interim procedures, reflecting the international requirements, in order to implement marine CDR activities in open ocean waters pending the resolution of whether the U.S. will formally ratify these agreements.

Current International Requirements Affecting Marine CDR

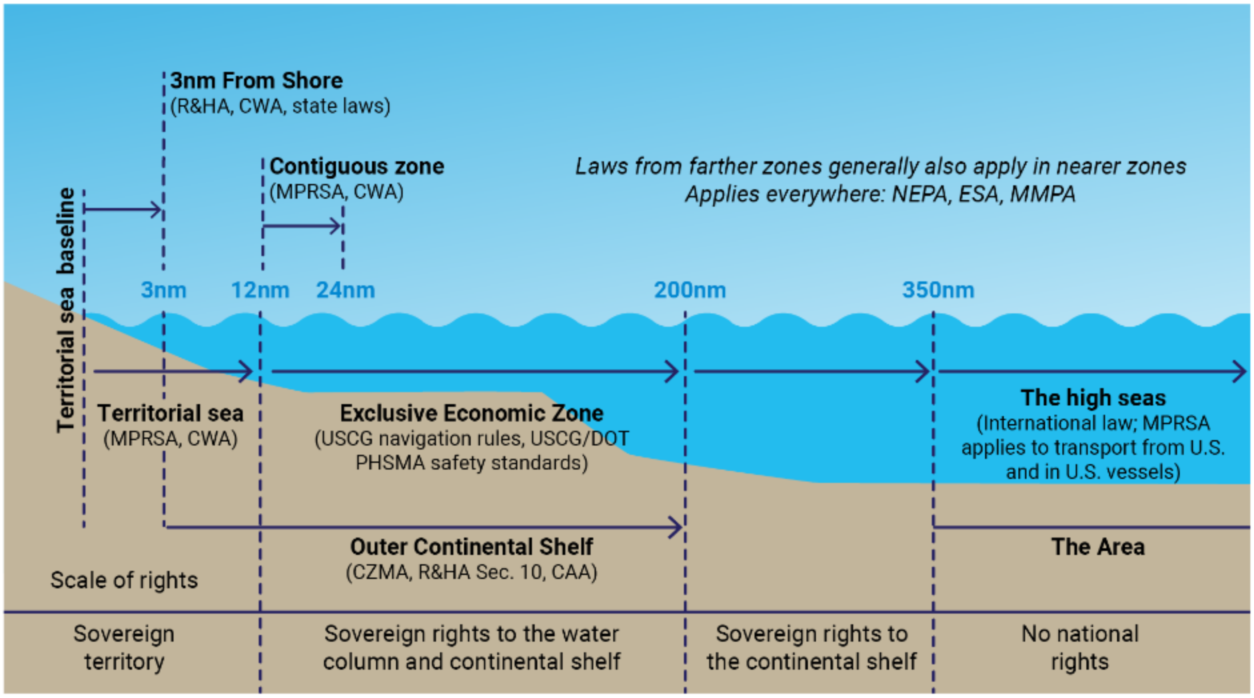
Activities in the seabed generally fall under the UNCLOS. Currently, storing CO_2 in geological formations under the seabed is permitted under UNCLOS, the London Convention, and the London Protocol, and it is currently in commercial practice at several sites including two in the North Sea (Sleipner and Snohvit). CO_2 pipelines on the seafloor and CO_2 injection for enhanced oil recovery from hydrocarbon formations under the seabed are permissible.

The experience with ocean iron fertilization (OIF) experiments have led to more restrictive international requirements. OIF, as well as other CDR methods that add materials to ocean waters, fall within the applicability of the London Convention and London Protocol. In 2008, the parties to the London Convention and Protocol adopted a non-binding resolution permitting fertilization under certain conditions. They also formulated an assessment framework for scientific research on ocean fertilization, which included provisions for exposure and effects assessment, risk characterization and management, and monitoring.[51] In 2013, the parties to the London Protocol went further, approving an amendment that would require them to conform to an assessment framework that limited ocean fertilization to only "legitimate scientific research."[52] The amendment also lays the groundwork for assessment frameworks for other marine CDR approaches. It has not, however, been adopted by the requisite number of parties to enter into force.

The CBD, to which the U.S. is not a party, passed a similar non-binding resolution limiting fertilization to "small-scale research" that is "subject to thorough prior assessment."[53] Marine CDR may also be subject to the UNCLOS, under which the right to research is subject to other provisions of the agreement, including environmental

FIGURE 13

Jurisdictional Zones of the U.S. Coast and Laws and Regulations with Relevance to CDR



This figure show the different laws and agency jurisdictions that may apply to marine CDR at different distances from shore in nautical miles (nm). Most jurisdictional categories apply to other nations' waters as well. CAA = Clean Air Act; CWA = Clean Water Act; CZMA = Coastal Zone Management Act; DOT PHMSA = Department of Transportation Pipeline and Hazardous Materials Safety Administration; ESA = Endangered Species Act; MMPA = Marine Mammal Protection Act; MPRSA = Marine Protection, Research and Sanctuaries Act; NEPA = National Environmental Policy Act; R&HA = Rivers and Harbors Act; USCG = U.S. Coast Guard;
Source: EFI, 2020. Adapted from the Royal Society, 2017.

protections. This could create liability for countries if marine CDR research creates "pollution"—which is defined broadly—that has harmful effects. Other potentially relevant laws include global and regional fisheries agreements; regional marine pollution regimes; and transboundary environmental impact assessment requirements.

The eligibility of large-scale deployment of marine CDR as part of a country's Nationally Determined Contribution (NDC) under the Paris Agreement is uncertain. Article IV of the Agreement defines domestic mitigation measures to include initiatives to protect and enhance sinks. This could be interpreted to allow credits for marine CDR projects within a county's territorial sea zone and perhaps exclusive economic zone. The lack of clarity on the application of the Paris Agreement, and any future international agreement on climate change, could act as a disincentive for countries to invest in needed marine CDR RD&D.

U.S. Laws and Regulations Potentially Affecting Marine CDR Deployment

Current U.S. laws do not explicitly recognize marine CDR as a specific class of activities subject to regulation, though several laws govern relevant activity. Marine CDR pathways could fall under regulations that cover activities such as ocean dumping, bulk transport of materials by ship, fixed or anchored structures in the ocean, pollutants released from vessels, and the safety of endangered species or marine mammals. The legal and regulatory framework is more extensive within the zone of the U.S. territorial sea but some extend to the Exclusive Economic Zone as well. The federal agencies and regulatory authorities that may be applicable to deployment of marine CDR measures include:

- The Environmental Protection Agency (Clean Air Act; Clean Water Act; Marine Protection, Research and Sanctuaries Act; National Environmental Policy Act);
- The U.S. Fish and Wildlife Service (Endangered Species Act, Marine Mammal Protection Act);
- The Army Corps of Engineers (Rivers and Harbors Act);
- The Department of Transportation; and
- The Coast Guard.

In addition, various state laws might apply in certain circumstances.

Considerations for New Governance Frameworks

A key tension to be addressed in creating enabling an effective and efficient governance framework for the deployment of marine CDR is the dynamic between the urgent need to find new, effective ways to combat climate effects that are already having an outsized impact to the ocean and to restore and preserve marine ecosystems, while avoiding further adverse collateral impacts on ocean ecosystems. While this effort seeks to ensure that marine CDR measures can be deployed safely and effectively, and potential adverse side effects must be compared directly to the damage currently being caused by elevated levels of atmospheric and oceanic CO_2. Further, impact analysis must also compare any potential damage from CDR with the potential marine ecosystem benefits to be gained by CDR both directly in ocean health, and indirectly by countering the effects climate change.

An effective governance framework should reflect several core principles:

- It must be capable of ensuring access to the best available scientific information regarding all aspects and potential impacts of a given marine CDR activity;
- It must enable stage-gated, science-based decisionmaking;
- The design and execution of marine CDR experiments must take into consideration of all potential direct and indirect impacts, be carefully controlled and fully monitored, with fully transparent results; and
- It must provide opportunities for input from all points of view from all relevant stakeholders.

Adhering to these principles will help build greater confidence in marine CDR pathways while minimizing potential for undesirable outcomes. This is critical in building the public and stakeholder engagement that will be needed to move marine CDR out of the labs and into the ocean. Where conclusive information is lacking or in question, as is the case in much of the ocean CDR field, governance cannot be so strict as to prohibit information gathering from well-controlled and monitored, small-scale experiments.

Whether or when the U.S. ratifies the UNCLOS, the CBD, or the London Protocol is uncertain; the issues are well beyond the scope of marine CDR. As an interim step, however, the federal government and the U.S. scientific community could seek to develop interim guidelines, modeled after the requirements in the various international agreements, to govern federal funding of marine CDR RD&D activities. These interim U.S. guidelines can become fully harmonized with international standards as part of the process of achieving final resolution of these agreements. The key aspect of this strategy is for the U.S. marine CDR community (government, industry, and academia) to be proactive and not become deterred by the international negotiation process.

For marine CDR RD&D, and eventual deployment, in ocean waters under U.S. jurisdiction, clear direction from the federal government will be needed, either from the executive branch, Congress or (preferably) both. Clarifying the authorities of the federal agencies or establishment of an interagency coordinating body would be helpful in setting the framework for ultimate commercial deployment of marine CDR pathways. Special flexible interim arrangements could be put into place to govern RD&D activities as the scientific information base is developed to enable durable requirements and procedures.

Addressing Social and Public Acceptance Concerns

Perhaps the biggest challenge facing marine CDR is not technical but rather social. Societal concern for the health and use of the oceans is very high and has been a factor in slowing and even stopping similar research in the past. If marine CDR is to advance, public education and outreach is required to build public acceptance. As part of such efforts, the potential risks and consequences of deployment must be clearly and quantifiably weighed against the risks and consequences of taking no action.

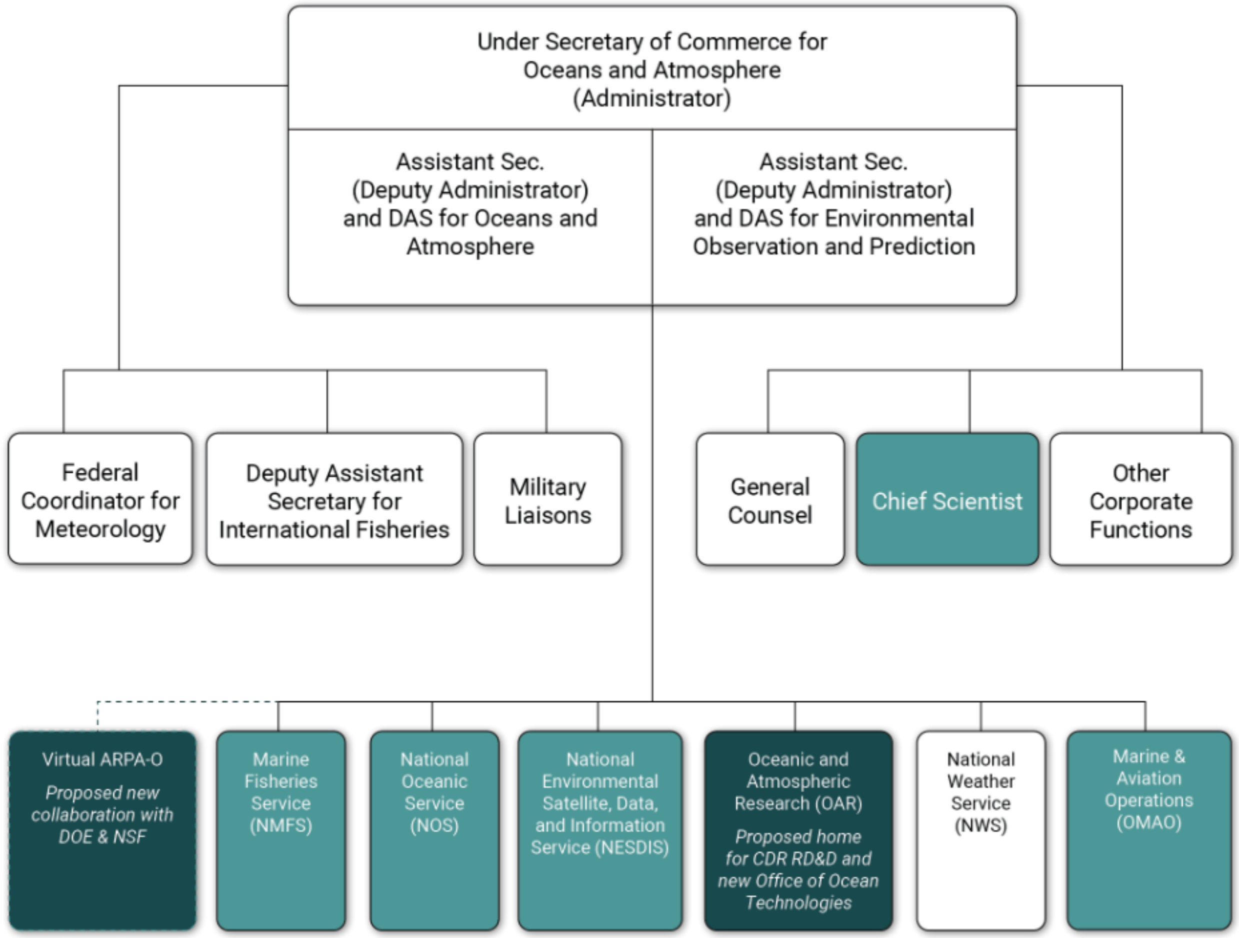
This dialogue needs to include the marine science, management, and conservation communities, where there currently can be a relatively low level of awareness and understanding of the issues and opportunities surrounding ocean CDR. Venues for stakeholder engagement on this topic can include workshops, roadmapping exercises, and publications. Working with local communities where CDR will be implemented—and making sure that co-benefits accrue to those communities—will also be crucial. Building the public profile of ocean CDR will be required if it is to play a role in climate and ocean management in the 21st century.

Beyond public and stakeholder outreach, it is necessary for marine CDR RD&D to address some of these pathways' inherent uncertainties, including the potential ecosystem and lifecycle effects described above. This creates a possible "chicken-and-egg" problem, with field testing necessary to address uncertainties, but greater public acceptance needed for field testing to proceed. It is important for a federal RD&D program to establish processes that increase confidence in needed experiments. To this end, it is also critical that addressing ethical and social concerns be an explicit part of any RD&D agenda at the federal level.

Integration of Carbon Credits from Marine CDR into Carbon Markets

Another key area of need across marine CDR pathways is the creation of markets for both CDR itself and for the co-products produced. State governments and voluntary carbon offset markets in the U.S. have established

FIGURE 11
NOAA Offices with Relevance to CDR



NOAA is headed by the Under Secretary for Oceans and Atmosphere, alongside several corporate offices that are involved in high level decision-making. The subsidiary Line Offices are distributed by research area, several of which may be able to incorporate marine CDR research into their agenda. OAR, NESDIS, NOS, NMSF, and the proposed Virtual ARPA-O all are compatible with marine CDR RD&D priorities.
Source: EFI, 2020.

means for certain technological (e.g., DAC) or natural (e.g., reforestation) CDR methods to participate in carbon markets. There has been some action internationally to include blue carbon pathways in protocols for carbon markets, but in general avenues are limited for marine CDR to participate in these systems. Methods for confirming additionality, monitoring, reporting, verification, and risk mitigation will need to be developed for that to happen, and policymakers, regulators, and RD&D performers must work together to move those methods along.

In addition, creating carbon markets for the products of micro- and macroalgae culture practices (be they food, fuel, plastics, building materials, etc.) or hydrogen fuel from seawater electrolysis can exert market "pull" on marine CDR RD&D and make them more cost-effective.

Implementation: Organization, Management and Funding

Currently, there is no designated agency in the U.S. federal government specifically authorized or enabled to develop marine CDR. Nor have any specific administrative or congressional designations have been made to develop research, policy, or regulation around marine CDR. Accordingly, there has not been significant investment in this area. A previous analysis by EFI and the Bipartisan Policy Center of federal investments in CDR RD&D found a total expenditure of just $44.3 million on marine pathways across 115 projects from 2005 to 2018.[54]

The growing need for CDR, the significant role the ocean CDR naturally plays, and the significant potential marine methods offer require that marine CDR be included in the evaluation and development of atmospheric CO_2 mitigation and management options going forward.

Management Recommendations

The September 2019 EFI *Clearing the Air* report recommended that the Department of Commerce's NOAA be one of the three lead agencies of a federal interagency effort on CDR (along with the Departments of Energy and Agriculture), and be designated the lead agency for marine pathways. In 2020, bipartisan groups in both houses of Congress introduced the Carbon Removal, Efficient Agencies, Technology Expertise (CREATE) Act, which followed the recommendation from *Clearing the Air* that the National Science and Technology Council (NSTC) establish a new Committee on Large-Scale Carbon Management. The CREATE Act proposes that NOAA representatives would sit on the executive committee and co-chair the oceans working group, along with the National Science Foundation (NSF).

The report also made specific management recommendations for NOAA (relevant offices are shown in Figure 11), including that it should:

- → Add CDR to the NOAA mission through incorporation of programs and projects into the NOAA R&D Plan;
- → Establish of a new Office of Ocean Technologies, reporting to the Assistant Administrator for Oceanic and Atmospheric Research, with responsibility for CDR RD&D;
- → Use this new office to harness ocean research assets at NOAA (Cooperative Institutes, Research Laboratories, and Sea-Grant Colleges and Universities), NSF, and the U.S. Coast Guard;
- → Integrate existing ocean acidification monitoring and data collection programs into this new office's research portfolio; and
- → Add, where appropriate, RD&D to existing NOAA programs on regional coastal and open-ocean ecosystems.

The participants in the expert workshops identified a number of additional actions to further the RD&D priorities outlined in this report. The major themes, discussed throughout this report, include:

- → Adding CDR RD&D to a broad suite of NOAA coastal, ocean ecosystem, and ocean chemistry programs, expanding the focus beyond blue carbon;
- → Recommending specific funding for pathways that build on existing

TABLE 2
Marine CDR Portfolio ($millions)

	Year 1	5-Year Total	10-Year Total	Previous EFI 2019 Allocation
1. Biological Methods	**$34**	**$465**	**$950**	**$1282**
a. Microalgae Fertilization	$2	$40	$100	$328
b. Microalgae Cultivation	$10	$100	$200	$38
c. Macroalgae Cultivation	$10	$100	$200	$40
d. Biomass Utilization RD&D	$5	$100	$200	$107
e.Upwelling/Downwelling	$2	$25	$50	$0
f. Blue Carbon	$5	$100	$200	$769
2. Non-biological Methods	**$100**	**$325**	**$800**	**$374**
a. Seawater Alkalinity Addition	$50	$200	$500	$374
b. Seawater CO_2 extraction, utilization, and storage	50	$125	$300	$0
3. New/Emerging Marine CDR Methods	**$5**	**$50**	**$100**	**$0**
4. Modeling, Measuring and Planning Tools	**$20**	**$105**	**$125**	**$94**
5. Governance, and Stakeholder and Public Engagement	**$5**	**$50**	**$100**	**$0**
TOTAL	**$164**	**$995**	**$2075**	**$1750**

Source: EFI, 2020.

knowledge bases and can be scaled up quickly, such as blue carbon and mariculture practices;

- → Developing a U.S. protocol for field experimentation that would start to bring the U.S. in line with standards in other countries;
- → Expanding international coordination, such as starting with a formal collaborative relationship with the European Union's OceanNETs initiative;
- → Establishing a cutting-edge research focus, such as an Advanced Research Projects Agency for Oceans (ARPA-O)[e] integrating the combined expertise and agency capacities of NOAA, DOE and NSF to accelerate RD&D on cutting-edge ocean technology

e. Modeled on the Defense Advanced Research Projects Agency (DARPA) and ARPA-E solutions including (but not limited to) marine CDR. Such an initiative might not be a new brick-and-mortar institution, but perhaps a virtual partnership with strong linkages among agency programs;

- Expanding NOAA's partnership with the academic and private sectors, as well as partnering with NASA, to advance both in situ and remote sensing tools; and
- Establishing a new initiative with an adequate dedicated funding mechanism for NOAA to engage in outreach to stakeholders and local communities to promote engagement, education, and awareness around marine CDR.

Federal Funding

Previously recommended marine CDR RD&D funding levels from EFI's Clearing the Air can be found in Appendix A. Those suggested allocations reflected NASEM's emphasis on blue carbon as the primary pathway for marine CDR, based on best available information at that time. The report also proposed a $2 billion demonstration project fund that also could be used to support large-scale demonstrations of carbon mineralization selected on a competitive basis.

Based on the panel's reviewing and comparing the relative strengths and weaknesses of the various pathways, their current technological readiness and their relative potential to ultimately contribute significant CDR outcomes, it is recommended that the total funding level for marine CDR RD&D be increased and that allocations among pathways be revised, relative the EFI's previous recommendations. The workshop co-chairs then further evaluated the findings and proposed funding allocations as follows in Table 2. This should be viewed as preliminary and subject to further scrutiny and discussion. For example, NASEM recently convened a new panel to independently evaluate marine CDR opportunities and to recommend RD&D priorities.[55]

Implementation of the marine CDR RD&D initiative could be initiated by Presidential Executive Order. Congressional authorizing legislation would ultimately be desirable; historically, such as in the case of the U.S. Global Change Research Program, Congress has acted on authorizing legislation for new interagency science and technology initiatives promptly in response to executive branch-proposed initiatives. Legislation also could provide multi-year authorizations to guide future appropriations. Congress may wish to consider additional options for implementation, such as establishment of a quasi-governmental entity to manage a broad CDR initiative and establishment of a dedicated funding source.

The federal government should also include a dedicated focus on high-risk, high-reward research support through existing entities such as ARPA-E or new initiatives such as the ARPA-O concept to initiate research that could prove highly impactful for marine CDR but may be too high risk for non-public entities to pursue. In this regard, ARPA-E's inclusion of seawater CO_2 removal in their recent $76 million funding opportunity announcement for new program areas is encouraging but at only $2 million falls far short of the need. To the extent possible, establishing funding continuity in appropriations would help minimize workflow disruptions and give greater confidence to researchers that experiments could be executed without interruption across multiple years.

Appendix A

Clearing the Air Funding Levels for Marine-Based CDR R&D Portfolio

TABLE 3

Marine-Based CDR R&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Organization or Office	Year 1	5-Year Total	10-Year Total
5.10 Coastal Systems (Blue Carbon)					
5.11 Fundamental Research	DOC	NOAA (OAR)	$3	$15	$30
	NSF	GEO	$2	$14	$29
5.12 Resource Assessment	DOC	NOAA (OAR)	$1	$5	$10
	NASA	ESD	$1	$5	$10
5.13 Regional Field Trials	DOC	NOAA (Fisheries)	$10	$185	$435
	DOD	USACE	$10	$110	$235
5.14 National Coastal Wetland Data Center	DOC	NOAA (OAR)	$2	$10	$20
5.15 Coastal Blue Carbon Project Deployment	N/A	N/A	$0	$0	$0
5.10 Subtotal, Coastal Systems (Blue Carbon)			**$29**	**$344**	**$769**
5.20 Marine Biomass Capture and Storage					
5.21 Aquatic Biomass Cultivation	DOC	NOAA (OAR)	$1	$19	$40
	DOE	EERE (BETO)	$1	$19	$38
5.22 Aquatic Biomass Energy Conversion	DOE	EERE (BETO)	$2	$47	$107
5.20 Subtotal, Marine Biomass Capture and Storage			**$4**	**$85**	**$185**
5.30 Alkalinity Modification					
5.31 Fundamental Research	NSF	GEO	$2	$31	$71
	DOE	SC (BER)	$2	$28	$63

5.32 Applied Alkalinity Modification Techniques	DOC	NOAA (OAR)	$0	$65	$175
	NSF	GEO	$0	$25	$65
5.30 Subtotal, Alkalinity Modification			**$4**	**$149**	**$374**
5.40 Ocean Fertilization					
5.41 Fundamental Research	NSF	GEO	$2	$32	$72
	DOC	NOAA (OAR)	$2	$14	$34
	DOE	SC (BER)	$0	$12	$27
5.42 Artificial Ocean Iron Fertilization	DOC	NOAA (OAR)	$0	$25	$75
	NSF	GEO	$0	$15	$40
5.43 Artificial Ocean Macronutrient Fertilization	DOC	NOAA (OAR)	$0	$15	$40
	NSF	GEO	$0	$15	$40
5.40 Subtotal, Ocean Fertilization			**$4**	**$128**	**$328**
5.50 Ocean Environmental Assessments					
5.51 CO2 Impacts and Fate in the Cceans	DOC	NOAA (OAR)	$2	$22	$47
	DOE	SC (BER)	$2	$22	$47
5.50 Subtotal, Ocean Environmental Assessments			**$4**	**$44**	**$94**
TOTAL, Coastal and Oceans			**$45**	**$750**	**$1,750**

OAR = Office of Oceanic and Atmospheric Research. Fisheries = National Marine Fisheries Service. GEO = Directorate for Geosciences. ESD = Earth Sciences Division. USACE = U.S. Army Corps of Engineers. EERE = Office of Energy Efficiency and Renewable Energy. BETO = Bioenergy Technologies Office. SC = Office of Science. BER = Biological and Environmental Research Program. Source: EFI, 2019.

Appendix B

Current RD&D Initiatives in Ocean-Based CDR

Efforts in the United States

→ DOE/ARPA-E MARINER[f] Program: Under this $50 million, five-year research program,[56] DOE is funding a series of research and development efforts focused on macroalgae cultivation at scale for biomass energy. While not explicitly focused on CO_2 capture and storage, this program is helping develop and test the technologies and systems that could be applied to CDR. ARPA-E is supporting the development of innovative cultivation & harvest systems able to produce macroalgae biomass that is cost competitive with terrestrial biomass at energy-relevant scale.

→ DOE/ARPA-E Direct Ocean CO_2 Capture Program: ARPA-E recently announced a new request for proposals (due July 2020) that seeks to "establish robust, energy efficient, and low-cost strategies for direct removal of carbon dioxide from oceanwater."[57] Systems should have the potential to scale to gigaton-levels of CO_2 capture. Approximately $2m is dedicated for this research. It specifically excludes iron fertilization but is open to most of the other pathways described herein.

→ NOAA/Blue Carbon: NOAA's coastal blue carbon activities are a collaborative effort across NOAA, including the National Marine Fisheries Service, National Ocean Service, and Oceanic and Atmospheric Research offices.

→ NOAA/Ocean Acidification Program: Focused on monitoring and predicting ocean acidification (absorption of excess atmospheric CO_2) and impacts on marine ecosystems, but with no mandate for mitigating those impacts. One notable exception is research funding for the use of seagrass and eelgrass to consume and counter ocean acidification.

→ Other NOAA programs: NOAA also operates a "Carbon Cycle Greenhouse Gases" (CCGG) research area that operates a global atmospheric CO_2 and GHG monitoring program. The Pacific Marine Environmental Laboratory's Carbon Program (also a part of NOAA) is aimed at advancing "our scientific understanding of the ocean carbon cycle and how it is changing over time. However, CDR RD&D is absent from this program.

International Efforts

→ OceanNETs:[g] Just launched in July 2020 with partners from 14 institutions in six different countries, this 4-year research project will investigate the potentials and

f. Macroalgae Research Inspiring Novel Energy Resources

g. This project received funding from the European Union's Horizon 2020 research and innovation program under grant agreement #869357.

h. NETS stands for "Negative Emissions Technologies" risks of Marine CDR.[h] The focus is not only on scientific evaluation of these technologies, but also on the politics, economics and societal issues that will determine the ability to deploy Ocean CDR. The European Community is funding this effort with a total of 7.2 million euros over four years. Importantly, this project includes two field trials off Gran Canaria (Spain) and Bergen (Norway) to test for marine organism and ecosystem responses to Ocean Alkalinity Enhancement.

- UK Greenhouse Gas Removal Program: Funded with £8.6m, this research program seeks to address questions around cost, scalability, and environmental and societal consequences of CDR (negative emissions). They are examining one pathway in the ocean: assessing the use of waste materials from mining for enhanced weathering. The program will investigate among other things, mechanisms for accelerating carbon dioxide uptake, implications for the ocean, and societal implications.

- European Research Council Ocean Artificial Upwelling Program: Aims to study the feasibility, effectiveness, associated risks and potential side effects of artificial upwelling in increasing ocean productivity, raising fish production, and enhancing oceanic CO2 sequestration. This €2.5 million (about $2.9 million) program is conducting a combination of experiments at different scales and trophic complexities, field observations of eddy-induced upwelling in oligotrophic waters, and ecosystem-biogeochemical modeling of pelagic systems fertilized by nutrient-rich deep waters. If technically feasible, ecologically acceptable, and economically viable, the use of artificial upwelling for ecosystem-based fish farming could make an important contribution to an ecologically sustainable marine aquaculture.

- A Chinese modeling study (Chinese Iron and Phosphorus Modeling Study [CHIPMOS]) is simulating the addition of iron and phosphorus in the North Pacific subtropical gyre to stimulate nitrogen fixation and lead to carbon export. There have been cruises to this region with onboard incubation with adding iron and/or phosphorus. The group plans to conduct high resolution physical-biological model simulations of the effect of adding iron and/or phosphorus in the different regions and during different times of the year, etc. Prof. Nianzhi Jiao (Xiamen University, People's Republic of China) is heading a project that is investigating microbial carbon pump (MCP). The idea is to enhance the refractory dissolved organic carbon (RDOC) production, which can stay in the water column for hundreds to thousands of years to effect long-term carbon sequestration in the ocean. Experimental studies have shown high efficiency of production of RDOC by the MCP, indicating a potential approach for enhancement of carbon sink in the ocean.

Abbreviations

˚C	Celsius
ARPA-E	Advanced Research Projects Agency-E
ARPA-O	Advanced Research Projects Agency for Oceans
BECCS	Bioenergy with Carbon Capture and Storage
C	Carbon
C2G2	Carnegie Climate Governance Initiative
CBD	Convention on Biological Diversity
CCGG	Carbon Cycle Greenhouse Gases
CDR	Carbon Dioxide Removal
CHIPMOS	Chinese Iron and Phosphorus Modeling Study
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide (GHG warming) equivalent
COP	Conference of Parties
CWA	Clean Water Act
DAC	Direct Air Capture
DAS	Deputy Assistant Secretary
DIC	Dissolved Inorganic Carbon
DOA	Department of Agriculture
DOC	Department of Commerce
DOC	Dissolved Organic Carbon
DOE	Department of Energy
EFI	Energy Futures Initiative
EU	European Union
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse Gases
Gt	Gigaton (1,000,000,000 metric tons)
IPCC	International Panel on Climate Change
m^2	Meters Squared
MARINER	Macroalgae Research Inspiring Novel Energy Resources
MiCP	Microbial Carbon Pump
MPRSA	Macroalgae Research Inspiring Novel Energy Resources
NASA	National Aeronautics and Space Administration
NASEM	National Academy of Sciences, Engineering, and Medicine
NDC	National Determined Contribution
NESDIS	National Environmental Satellite, Data and Information Service
NETS	Negative Emissions Technology
NMFS	National Marine Fisheries Service
NOAA	National Atmospheric and Oceanic Administration
NOS	National Oceanic Service
NSF	National Science Foundation
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OIF	Ocean Iron Fertilization
OMAO	Marine and Aviation Operations
OMEGA	Offshore Membrane Enclosure for Growing Algae
OP	Office of the Presidency
OTEC	Ocean Energy Thermal Conversion
RD&D	Research, Development, and Demonstration
RDOC	Refractory Dissolved Organic Carbon
SLR	Sea Level Rise
SR1.5	Special Report on Global Warming of 1.5°C
U.S.	United States
UN	United Nations

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