WRITTEN TESTIMONY OF
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HEARING ON
NAVIGATING THE BLUE FRONTIER: EVALUATING THE POTENTIAL OF MARINE CARBON DIOXIDE REMOVAL APPROACHES

BEFORE THE
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COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
JOINT ENVIRONMENT AND ENERGY SUBCOMMITTEES

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Introduction

Good morning, Chairmen Miller and Williams, Ranking Members Ross and Bowman, and members of the Environment and Energy Subcommittees. Thank you for the opportunity to speak with you today on marine carbon dioxide removal. My name is Scott Doney, and I am the Kington Professor in Environmental Change at the University of Virginia in Charlottesville, Virginia. My research focuses on interactions among climate, the ocean and global carbon cycles, and coastal and marine ecosystems.

For today's hearing, you asked me to discuss the benefits and risks of marine carbon dioxide removal (mCDR) approaches as they relate to carbon capture and sequestration, as well as ecosystem and community side effects. My testimony touches on the current state of the science along with research opportunities to address critical knowledge gaps. My comments are based on several scientific assessments compiled by the ocean research community (e.g., GESAMP, 2019; Gattuso et al., 2021; NASEM, 2022) as well as a recent review article based on the available scientific literature (Doney et al., 2024a).

Summary

Scenarios to stabilize global climate and meet international climate agreements require rapid reductions in human carbon dioxide (CO_2) emissions, often augmented by substantial carbon dioxide removal (CDR) from the atmosphere. While some ocean-based removal techniques show potential promise as part of a broader CDR and decarbonization portfolio, no marine approach is ready yet for deployment at scale because of gaps in both scientific and engineering knowledge. Marine CDR spans a wide range of biotic and abiotic methods, with both common and technique-specific limitations. Further targeted research is needed on CDR efficacy, permanence, and additionality as well as on robust validation methods—measurement, monitoring, reporting, and verification—that are essential to demonstrate the safe removal and long-term storage of CO_2. Engineering studies are needed on constraints including scalability, costs, resource inputs, energy demands, and technical

[1] The views expressed here are my own and do not necessarily represent those of the University of Virginia

readiness. Research on possible co-benefits, ocean acidification effects, environmental and social impacts, and governance is also required.

Rationale for Carbon Dioxide Removal

Over the past several centuries, large human perturbations to the global carbon cycle have increased atmospheric CO_2 by 50% and methane CH_4 by more than 150% relative to preindustrial levels (IPCC, 2023). Elevated atmospheric levels of CO_2, CH_4, and other minor greenhouse gases absorb infrared radiation and alter planetary radiative forcing; greenhouse gas perturbations are the dominant factor behind the observed global surface warming of +1.1°C (average for 2011–2020) above preindustrial levels (IPCC, 2023). Climate change, ocean warming, and ocean acidification from rising atmospheric CO_2 have widespread ramifications for ocean physical–biogeochemical dynamics, marine ecosystems, and dependent human coastal communities.

Natural processes have limited capacity to remove excess atmospheric CO_2 on human timescales, and therefore the current elevated levels of atmospheric CO_2 and resulting climate change will take decades to centuries or longer to dissipate (Canadell et al., 2021). Continued human emissions of CO_2 will only further exacerbate these problems, and stabilization of global surface temperatures will require human CO_2 emissions to drop sharply to near zero in the coming decades (IPCC, 2018; IPCC, 2023). The international climate Paris Agreement commits to hold global surface warming to below +2.0°C and to pursue a more ambitious target of only +1.5°C warming above preindustrial levels. The +1.5°C and +2.0°C climate thresholds may be reached in only a decade to a few decades, respectively, if human CO_2 emissions continue at current rates (Friedlingstein et al., 2022). Rapid decarbonization of the global energy system and overall economy is needed, therefore, to meet the Paris Agreement climate targets. Many scenarios for climate stabilization augment decarbonization with substantial levels of carbon dioxide removal (CDR), approaches that actively remove and store CO_2 away from the atmosphere for long periods of time (IPCC, 2018; IPCC 2023).

The scope of the required levels of decarbonization and CDR for a below +1.5°C climate scenario is substantial (Fuhrman et al. 2023). For the decade 2012–2021, fossil fuel CO_2 emissions averaged 9.6 ± 0.5 Pg C y^{-1}, where 1 Pg C = $1x10^{15}$ g C = 1 Gt C (1 billion metric tons) (Friedlingstein et al. 2022), and emissions are projected to be stable or increase under no-climate-policy scenarios; note that some literature and policy documents use mass of CO_2 rather than C, with 1 Pg C = 3.66 Pg CO_2. Dramatic decarbonization transitions across the energy system (e.g., more renewable electricity generation and electrification of transportation and heating) are needed to reduce sharply fossil fuel emissions. However, there likely will remain economic sectors that are difficult or expensive to decarbonize, such as some heavy industry and maritime shipping, with residual emissions of 1–3 Pg C y^{-1}. CDR or negative emissions may be required to compensate for these residual emissions in order to reach net-zero human CO_2 emissions by midcentury. Even larger amounts of CDR (>3 Pg C y^{-1}) and net-negative CO_2 emissions may be required for the latter half of the century to compensate for continued human CH_4 and other greenhouse gas emissions.

To date, only a subset of possible CDR approaches has been incorporated into the climate models and other climate policy tools, with an emphasis on land-based techniques (NASEM, 2019; Fuhrman et al., 2020; IPCC, 2023); there is a notable lack of marine CDR approaches, reflecting, in part, more limited scientific and techno-economic information and lower technical readiness (NASEM, 2022). Even across land-based CDR techniques, generalizations warrant caution because of the different principles used for reducing and storing CO_2 away from atmosphere. Proposals span from restoring and enhancing natural carbon sinks (e.g., afforestation, soil carbon, and enhanced weathering) to more industrial solutions (e.g., direct air capture or bioenergy coupled with geologic carbon sequestration). Each approach comes with distinct constraints associated with scaling potential, costs, energy use, land and resource demand, environmental damage, governance, and interactions with other societal objectives, such as the United Nations Sustainable Development Goals (Fuhrman et al. 2019). Deploying CDR technology or a combination of technologies at a scale of removing 1 Pg C y^{-1} within a few decades poses significant scientific, engineering, and societal challenges (IPCC 2018, NASEM 2019).

Proposed coastal and marine CDR methods cover a broad mix of nature-based and technological approaches that alter either ocean biotic or abiotic carbon cycles (see Figure and Table below) (GESAMP 2019, Gattuso et al. 2021, NASEM 2022). Abiotic marine CDR approaches are mediated by inorganic chemical reactions that alter the ocean CO_2 solubility pump by shifting seawater CO_2 solubility equilibrium and enhancing air–sea CO_2 uptake. Ocean alkalinity enhancement utilizes geochemical or electrochemical methods to add alkalinity to seawater, while direct ocean capture or removal utilizes electrochemical techniques to strip CO_2 from the surface ocean. Prospective biotic marine CDR approaches attempt to increase the marine storage of carbon in biomass and organic detritus or strengthen the marine biological pump, which transfers carbon from the atmosphere–upper-ocean system into the deep sea. Biotic methods include habitat and ecosystem protection and restoration (e.g., coastal and ocean blue carbon) and enhancement of the marine biological carbon pump (e.g., ocean fertilization, artificial upwelling, and macroalgal aquaculture).

Unlike many terrestrial CDR approaches, ocean-based methods typically do not directly remove CO_2 from the atmosphere; rather, they act indirectly by increasing carbon in marine biomass, enhancing biological carbon export from the surface to the deep ocean, elevating seawater CO_2 solubility, or stripping CO_2 from seawater for onshore or sub-seabed geologic sequestration. Most marine CDR methods thus implicitly depend on perturbations internal to the ocean that will result in carbon removal from the atmosphere via enhanced downward air–sea CO_2 flux into the ocean. The validation of marine CDR is thus complicated by the large natural background of ocean carbon storage and cycling as well as the substantial contemporary ocean anthropogenic CO_2 sink that is about 30% of human fossil fuel emissions (Friedlingstein et al. 2022). The coastal domain is a likely site for many marine CDR experiments. However, it is particularly complex and spatially heterogeneous, with regions of both CO_2 uptake and release, large seasonal variability, and competing climate effects from emissions of other greenhouse gases, CH_4 and nitrous oxide (N_2O), that partially compensate for net CO_2 uptake for the global coastal ocean (Resplandy et al., 2024).

Efforts are underway to develop guidelines for marine CDR measurement, monitoring, reporting, and verification (MMRV; see below), which is essential for CDR carbon accounting and will require a combination of field observations and modeling (Fennel et al., 2023; Ho et al., 2023) (see Figure below). There are significant issues related to marine CDR that include potential environmental and social impacts, governance, and ethical concerns (Cooley et al., 2023). These issues have similarities with those faced by land-based CDR and sub-seabed geological CO_2 sequestration linked to power- and industry-sector carbon capture. These concerns suggest the need for careful consideration and management of marine CDR technologies. Assessment of environmental and socioeconomic impacts, public stakeholder engagement, and agreed-upon research codes of conduct should be a component of any marine CDR field testing (NASEM 2022).

Contemporary Ocean Carbon Cycle

Marine CDR experiments and any potential future large-scale CDR deployments would perturb an already dynamic and complex ocean carbon cycle. The ocean has large and evolving carbon reservoirs, and significant fluxes occur among internal organic and inorganic carbon pools, sediments, and the atmosphere. Additionally, human activities have altered rivers, coasts, and oceans, adding another layer of complexity to the system.

Carbon dioxide gas dissolves in and reacts with alkaline seawater to create dissolved inorganic carbon (DIC), the sum of the concentrations [ ] of aqueous CO_2, carbonic acid H_2CO_3, bicarbonate HCO_3^-, and carbonate CO_3^{2-} concentrations (Millero, 2007):

$$DIC = [CO_2(aq)] + [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]$$

At seawater pH, the concentration of H_2CO_3 is negligible relative to that of CO_2(aq), and the two are often combined into a single effective term. Dissolved inorganic carbon is the dominant ocean carbon reservoir (pre-industrial DIC inventory ~37,100 Pg C; DeVries, 2022) followed by a smaller ocean dissolved organic carbon pool (~662 Pg C). The marine biomass stock is quite small (~6 Pg C; Bar-On et al., 2018), with mostly rapid turnover times. Coastal, shelf, and deep-ocean sediments contain substantial carbon reservoirs with widely varying timescales for water-column exchange.

The pre-industrial dissolved inventory reflects, to a great extent, CO_2 solubility equilibrium between the vast deep-ocean and atmosphere CO_2 reservoirs. CO_2 solubility is dependent on temperature and alkalinity, a measure of the acid/base balance and a result of rock weathering (Millero, 2007):

$$Alkalinity = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+] + minor\ species$$

More CO_2 will partition into a colder, more alkaline ocean, thus lowering the atmosphere CO_2 mixing ratio on geologic time scales. The ocean solubility pump response to rising atmosphere CO_2 mixing ratio, modulated by rates of surface-deep ocean physical circulation, also largely explains the ocean uptake of anthropogenic CO_2, increasing the pre-industrial DIC inventory by 175 ± 35 Pg C (Friedlingstein et al., 2022).

The contemporary global air-sea CO_2 flux is the net difference between ingassing of anthropogenic CO_2 and a now smaller pre-industrial outgassing from riverine carbon

inputs. Air-sea CO_2 flux can be computed from an empirical gas transfer velocity k_w and the difference between surface ocean and atmosphere equilibrium CO_2(aq) concentrations:

$$F_{CO2} = k_w([CO_2^{atm}(aq)] - [CO_2(aq)])$$

The flux equation is often recast as partial pressures pCO_2 by including a solubility term. The equilibration time of surface ocean CO_2 relative to air-sea flux is long, order months to a year, because of the large DIC pool and shifts in seawater acid-base chemistry.

Carbon dioxide can be added to seawater either directly by gas injection or by the respiration of organic matter. The additional CO_2(aq) elevates pCO_2 and thus net CO_2 outgassing, increases seawater dissolved inorganic in a 1:1 mole ratio, and enhances HCO_3^- and hydrogen ion H^+ concentration, shifting pH lower towards more acidic conditions.

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \qquad CO_3^{2-} + H^+ \rightarrow HCO_3^-$$

$$pH = -log_{10}[H^+]$$

Seawater alkalinity is not affected by adding CO_2. Alkalinity is enhanced by adding carbonate ion, CO_3^{2-}, through the dissolution of mineral calcium carbonate $CaCO_3$, for example, or through the addition of hydroxide ions, OH^- or soluble mineral oxides such as brucite $Mg(OH)_2$. Alkalinity enhancement increases seawater pH, lowers pCO_2, and causes net CO_2 ingassing.

The marine biological pump transfers DIC from the surface to the deep ocean, substantially enhancing the vertical DIC gradient, elevating the preindustrial DIC inventory by ~2,800 Pg C (DeVries, 2022) and reducing atmosphere CO_2. Surface ocean photosynthesis and inorganic CO_2 uptake, ~50 Pg C y^{-1}, is nearly balanced by respiration (forward and backward reactions):

$$CO_2 + H_2O + energy \leftrightarrow CH_2O + O_2$$

The net imbalance of ~10 Pg C y^{-1} is exported as organic matter to the subsurface ocean, with only a small fraction of the organic C export is transferred to depths greater than 1000 m with an even smaller fraction buried in deep ocean sediments (Doney et al., 2024b). Comparable carbon burials occur in the much smaller areas of estuaries, coastal wetlands, and on the continental shelf.

Framing Ocean-Based Carbon Dioxide Removal

To serve as safe and effective climate mitigation options, marine CDR approaches must meet a combination of scientific and engineering criteria, address environmental and social concerns, and be amenable to validation through transparent MMRV. Scientific assessment centers on efficacy, permanence, additionality, and scalability (GESAMP 2019; NASEM 2019 and 2022; Gattuso et al. 2021) where:

- Efficacy: the removal of CO_2 from the atmosphere, as opposed to the simple redistribution of carbon pools within the ocean
- Permanence: the sequestration of CO_2 away from the atmosphere for climate policy–relevant time periods of decades to centuries; also called durability
- Additionality: CO_2 removal that is due to deliberate human actions and not natural processes or background oceanic uptake of anthropogenic CO_2

- Scalability: an assessment of biophysical, geochemical, engineering, environmental, and social constraints for potential deployment of CDR method at climate policy–relevant scales

Efficacy requires an approach that removes CO_2 from the atmosphere rather than simply redistributing carbon within ocean pools. This can be difficult to demonstrate directly because of the large natural concentrations and time/space variability in ocean dissolved inorganic carbon and the substantial upper-ocean concentrations and ongoing ocean uptake of anthropogenic CO_2 that is independent of CDR efforts. Evaluation of CDR efficacy is also challenging because of physical circulation, turbulence, and mixing and the long timescale or order a year for CO_2 gas exchange equilibration timescale, all of which combine to transport, disperse, and delay CDR perturbation signals in CO_2 air–sea flux and storage.

The permanence (or durability) of CDR-induced changes in ocean CO_2 storage requires sequestration away from the atmosphere for time periods sufficiently long enough to contribute to climate policy goals, typically multiple decades to centuries. While MMRV observations and modeling are essential for quantifying near-term changes in ocean biogeochemistry and net ocean CO_2 uptake from the atmosphere (Palter et al. 2023), ocean biogeochemical models likely provide the only viable, though imperfect, measure of long-term marine CDR permanence (Siegel et al. 2021). Additionality for CDR requires demonstrating that any observed CO_2 removal is due to deliberate human actions rather than natural processes and would not have occurred naturally or from the ongoing oceanic uptake of anthropogenic CO_2. Assessments of CDR efficacy, permanence, and additionality should also include the CO_2 and other greenhouse gases emitted in carrying out the ocean-based CDR project (e.g., emissions from energy use during deployment, material production, and transportation), highlighting the importance of full life cycle analysis for any marine CDR approach.

All marine CDR approaches require the allocation of energy, capital, and/or other resources for pumping, chemical/material processing, aquaculture, and/or (re)distribution of materials in the ocean. Returns on public and private investment in marine CDR, like its terrestrial counterpart, will therefore hinge upon (correctly) understanding how costs, impacts, and efficacy vary with the scale of deployment. Despite the large cumulative capacity for ocean uptake of CO_2 from the atmosphere on geologic timescales, the usefulness of marine CDR in addressing climate change on decadal to centennial timescales will be constrained, in practice, by removal rates achievable at a reasonable cost, as well as the pace at which supporting infrastructure and institutions can be scaled to realize those rates. These issues could be exacerbated in the case of marine CDR given the tendency of ocean water to circulate globally, requiring more sophisticated MMRV, and the often far higher costs required to operate in marine environments. Corrosion control and severe weather protection for pumping systems and offshore structures over the full life cycle of marine CDR projects will be critical considerations when moving from the lab and demonstration scale to the required large-scale deployments (tens to hundreds of teragrams of CO_2 per year, where 1 Tg = 1 Mt, or 1 million tons) implied by climate model results. Reallocation of a substantial portion of bulk materials shipping capacity to

alkalinity enhancement and/or ocean iron fertilization could serve as another technical barrier to scaling up these marine CDR approaches, irrespective of policy, legal, and social concerns (NASEM, 2022).

Marine Carbon Dioxide Removal Approaches

Scientific and engineering characteristics, validation and MMRV challenges, and social–environmental impacts for the broad abiotic and biotic categories marine CDR are summarized here and also in a Table (see below).

Ocean alkalinity enhancement seeks to accelerate rock natural weathering processes and for this reason may also be termed enhanced or accelerated weathering (Renforth and Henderson, 2017; Eisaman et al., 2023). Under ocean alkalinity enhancement, alkaline materials would be mined and then pulverized into small particles to increase their reactive surface area and accelerate their dissolution into proton acceptors, resulting in higher seawater bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ion concentrations and lower aqueous CO_2 concentration. The alkalinity could be added to the ocean in solution or in soluble mineral particle form; some methods would pre-equilibrate alkaline solutions with elevated CO_2 gas streams prior to ocean release, thus linking CDR with carbon capture and sequestration. The resulting pH increase would also directly counteract anthropogenic CO_2–induced ocean acidification that is negatively impacting marine ecosystems (Doney et al. 2020).

Electrochemical marine CDR approaches utilize acid–base chemistry to either decrease pH and force CO_2 offgassing or increase pH to induce carbonate precipitation (Eisaman et al., 2018; La Plante et al., 2021). When the aqueous CO_2 is removed, the discharged seawater can take up more gaseous CO_2 from the atmosphere to restore equilibrium. Electrochemical processes can also be used to increase seawater alkalinity directly and thus can be a special case of ocean alkalinity enhancement. Pre-equilibration of alkaline water generated from alkalinity enhancement with excess CO_2 prior to discharge to the ocean may alleviate some of local environmental impacts and the MMRV challenges associated with tracking changes in air-sea CO_2 fluxes.

Marine conservation efforts have the potential co-benefit of carbon dioxide removal through the protection, recovery and restoration of benthic, pelagic, and offshore ocean ecosystems, including macroalgae and marine animals (Christianson et al. 2022). Potential CDR benefits extend beyond direct biomass carbon storage because marine flora and fauna generate a substantial fraction of surface biological carbon export, though there are substantial challenges including quantifying net changes in ocean carbon storage as well as the extent to which biogeochemical feedbacks and nutrient reallocation may reduce CDR efficacy. Although likely smaller in scale than other CDR approaches, marine conservation- and restoration-based methods are likely to enjoy more widespread public support owing to the real and perceived environmental co-benefits.

Macroalgal aquaculture can also be pursued coupling seaweed farming with deliberate sinking or pumping of macroalgae biomass into deep ocean. Many questions remain about methods for large-scale farming, harvesting, and conveying biomass carbon

to depth, particularly if offshore sites are required to avoid local coastal environmental damage and competition for coastal space with fisheries or other ocean activities. Biological constraints on scalability include natural or artificial substrate, light, and nutrient growth requirements, where large-scale aquaculture will feed back on local and downstream nutrient concentrations (Berger et al. 2023). Detrimental environmental impacts could include local ecological modification as well as deoxygenation and acidification for the deep-ocean ecosystems where biomass is ultimately sequestered (Ross et al. 2022).

Artificial upwelling that enhances nutrient input and phytoplankton productivity could serve as a form of marine CDR (Dutreuil et al. 2009). An important caveat is that respiration and nutrient remineralization are typically closely linked, and artificial upwelling will be effective for CDR only in locations where the ratio of nutrients to excess or metabolic dissolved inorganic carbon in upwelled water is greater than the elemental stoichiometry of plankton organic matter production. Open-ocean field testing of artificial upwelling devices has been limited by costs and technological barriers (White et al. 2010). Theoretical and modeling studies suggest a global scalability of artificial upwelling CDR of only order 10 Tg C y^{-1} (Koweek, 2022).

Ocean fertilization could act as a potential marine CDR pathway by enhancing the marine biological carbon pump that transports carbon from the surface to deep ocean, effectively removing the carbon from contact with the atmosphere for some period of time. Multiple open-ocean fertilization field experiments conducted over the past several decades demonstrated that phytoplankton primary production can be stimulated in situ at mesoscale (10–100 km) in specific regions through the addition of the micronutrient iron or macronutrients (Boyd et al. 2007). Studies have also indicated, to varying extents, shifts in plankton community structure to larger cells (such as diatoms), increases in sinking particulate organic carbon flux, and biological drawdown in surface pCO_2 and dissolved inorganic carbon. Ocean iron fertilization at scale would purposefully alter the structure and function of plankton ecosystems over large ocean regions, with a variety of possible, often poorly characterized environmental risks, including harmful algal blooms and impacts on fisheries and higher trophic levels, with substantial disagreements within the scientific community (Buesseler et al. 2008, Strong et al. 2009, Buesseler et al., 2024).

Measurement, Monitoring, Reporting, and Verification (MMRV)

Demonstrating effective ocean CDR requires robust MMRV methods for detecting and attributing the causes behind changes in ocean inorganic carbon inventories and surface-ocean pCO_2 for air–sea CO_2 gas fluxes. Transparent MMRV is also a crucial step in the development of standard marine CDR protocols and certification processes needed for carbon account and incorporation into carbon markets. Abiotic CDR approaches will require additional measurements of seawater chemistry, in particular alkalinity as well as trace constituents. Biotic approaches will require information on organic carbon biomass and detrital stocks as it enters the various export pathways of the marine biological carbon pump. One challenge facing MMRV for marine CDR strategies is that natural variability in the marine carbon cycle is large. While initial signals following CDR perturbations to the ocean likely will be well resolved with ship- and shore-based analysis with high

precision/accuracy, climate-level measurement uncertainties, the signal-to-noise ratio may be more challenging for distributed observing systems and autonomous platforms with lower precision/accuracy, more weather-level measurement uncertainties (Tilbrook et al. 2019).

Compared with terrestrial CDR strategies, MMRV of strategies in marine environments is inherently more difficult because the ocean is a turbulent fluid that stirs and mixes scalars. This creates challenges for two main reasons: (a) a concentrated signal will eventually be diluted to a level that is below measurement limits, and (b) perturbations to tracers such as added alkalinity, dissolved inorganic carbon, and the partial pressure of CO_2 gas (pCO_2) are effectively stirred into filaments that can be difficult to observationally resolve and can be transported far from the deployment site. For example, a patch with a plausible enhanced alkalinity will be stirred by surface-ocean currents and quickly deformed, stretched, and transported laterally, resulting in rapid dilution over a few weeks over large portions of the patch to near the uncertainty limit for autonomous sensor measurements. Ocean turbulence at the scales of kilometers to tens of kilometers can also act to remove tracers from the mixed layer into the ocean subsurface. This latter point is especially important as perturbations to the carbon system designed to reduce upper-ocean pCO_2 cannot enhance air–sea fluxes if the perturbation is transported to depth, an issue exacerbated by the long air–sea CO_2 equilibration timescales compared with surface-ocean dynamics.

Field observations from emerging biogeochemical autonomous platform technologies, augmented by numerical modeling and remote sensing where applicable, will provide valuable insights for marine CDR MMRV in a turbulent sea. A long-duration observational backbone can be created by using arrays of gliders, profiling floats and drifters, and moorings. However, due to operational constraints and costs, the observational array density may be relatively sparse and suboptimal without sufficient modeling support. For pulse-release experiments, denser autonomous arrays backed by ship sampling could be deployed for relatively short time periods. After release and before perturbed tracers are dispersed and diluted below detectable limits, it is advisable to leave a reduced number of autonomous observational assets in place to track longer-term responses to ocean carbon storage, air–sea CO_2 flux, and biological variables that may have response time lags. Observations are required inside and outside the perturbed patch to characterize baseline values and natural variability. For continuous-release experiments where tracer perturbation levels could be maintained for an extended period and growing patch size, experimental design and asset allocation will differ somewhat.

Measurement suites will vary depending on the CDR approach, with at a minimum the inclusion of the perturbation tracer (e.g., alkalinity, iron, upwelled nutrients, and macroalgal biomass), technique-specific responses (e.g., alkalinity loss from secondary mineralization, phytoplankton productivity, and export flux), and sufficient observations to constrain changes in ocean inorganic carbon storage and air–sea CO_2 gas exchange. Requirements include a minimum of temperature, salinity, pressure, and two of four inorganic CO_2-system variables (dissolved inorganic carbon, alkalinity, pH, and pCO_2). Standardized CO_2-system methods at climate-level uncertainty are available for discrete

samples, surface underway sampling, and mooring pH and pCO2 (Sloyan et al., 2019; Wanninkhof et al., 2019). Substantial advances have also occurred for CO2-system and biogeochemical sensors on autonomous platforms, including profiling Argo floats and surface saildrones (Bushinsky et al. 2019).

While air–sea CO_2 flux is critically important for CDR MMRV (Bach et al. 2023), most studies will likely estimate rather than directly measure flux perturbations using air–sea pCO_2 data, wind speed, and empirical gas transfer parameterizations. Where feasible, air–sea flux estimates should be generated prior to the CDR perturbation and inside and outside the patch over a spatial region large enough to account for expected patch dispersion. Pilot studies using dual-tracer release experiments (e.g., $^3He/SF_6$) should be considered for validating gas transfer parameterizations for different systems. Simultaneous release of dye-like tracers (e.g., rhodamine, SF_6) can also be used to track water parcel motion and visualize three-dimensional patch dispersion. Surface-water horizontal motion can be diagnosed through satellite-tracked Lagrangian drifters, ideally deployed in strategic patterns to track evolution of pairs or triplets, and for coastal applications, high-resolution surface velocities can be measured by coastal high-frequency radar arrays that can be used to generate simulated parcel trajectories and locate areas of convergence or divergence where vertical motions might be important.

Numerical ocean models at different scales and levels of physical–biogeochemical complexity will be essential tools for marine CDR MMRV (Fennel et al. 2023). Model comparisons between control (no-perturbation) and perturbation scenarios can assess CDR efficacy and additionality for field experiments when combined with observational, statistical, and climatological baseline and natural variability estimates. Simulations also provide utility on longer timescales as patches disperse more widely and are subducted into the ocean thermocline. They can be used to track biological and biogeochemical interactions and feedbacks that occur far away from the CDR site. In addition, simulations can quantify deep-ocean perturbations where autonomous sampling capability is more limited and weaker CDR signals may be spread over a larger vertical water column. Models further help address the permanence or durability of uncompensated CO_2 released at depth, where sequestration timescales—the time before water parcels and excess CO_2 are returned to the ocean surface and contact with the atmosphere—are on the order of decades (thermocline) to centuries (deep sea) (Siegel et al. 2021). Coupling with regional mesoscale coastal and open-ocean models provides an avenue for assessing larger time/space aspects of CDR efficacy and additionality, and large-scale scalability and permanence questions will likely rely on global models already used for reconstructing past and projecting future ocean climate change, anthropogenic CO_2 uptake, and acidification.

Concluding Thoughts

While some aspects of marine CDR are relatively well understood, grounded in decades of basic ocean science, left unresolved are many applied questions on the science, engineering, and validation needed to determine whether some form of marine CDR can serve as a safe, effective, and scalable climate solution. Trade-offs exist for all CDR techniques across different evaluation criteria, but further research investment is likely warranted to support future deployment decisions if the studies are rigorous, independent,

and transparent and include adequate support for in-depth MMRV and environmental impact assessment. Even though marine CDR is a fast-moving scientific field, rapid technology development (Cornwall, 2023; Service, 2024) and pressure to address mounting climate change damages may outpace our scientific understanding without a substantial ramp-up in marine CDR research.

Summary Points

1. Rapid decarbonization of the global economy, as well as potential carbon dioxide (CO_2) removal (CDR) deployment at a scale of billions of tons of CO_2 per year, is crucial for reaching net-zero human greenhouse gas emission targets and stabilizing global climate change.
2. Numerous abiotic and biotic marine CDR approaches have been put forward to enhance CO_2 removal and storage in the ocean, which already acts as a large sink of excess anthropogenic CO_2 from the atmosphere.
3. While some techniques may show promise, no marine CDR approach is ready yet for deployment at scale because of knowledge gaps on the science, engineering, validation, and environmental and social impacts of CO_2 removal and long-term storage.
4. Demonstration of safe and effective marine CDR requires targeted research on efficacy, additionality, and permanence as well as on engineering constraints such as scalability, costs, resource inputs, energy demands, and technical readiness.
5. Marine CDR methods typically do not directly remove CO_2 from the atmosphere; instead, they depend implicitly on the fact that perturbations internal to the ocean will enhance downward air–sea CO_2 gas flux into the ocean.
6. Progress on marine CDR depends on robust and transparent validation methods—measurement, monitoring, reporting, and verification—that incorporate field observations, autonomous platforms, remote sensing, and numerical modeling.
7. Assessment of environmental and socioeconomic impacts, public stakeholder engagement, and agreed-upon research codes of conduct should be a component of any marine CDR field testing.
8. Research and development efforts should emphasize bidirectional information sharing between experimental and demonstration-scale marine CDR projects and modeling frameworks, including regional and global ocean biogeochemical models and integrated assessment models.

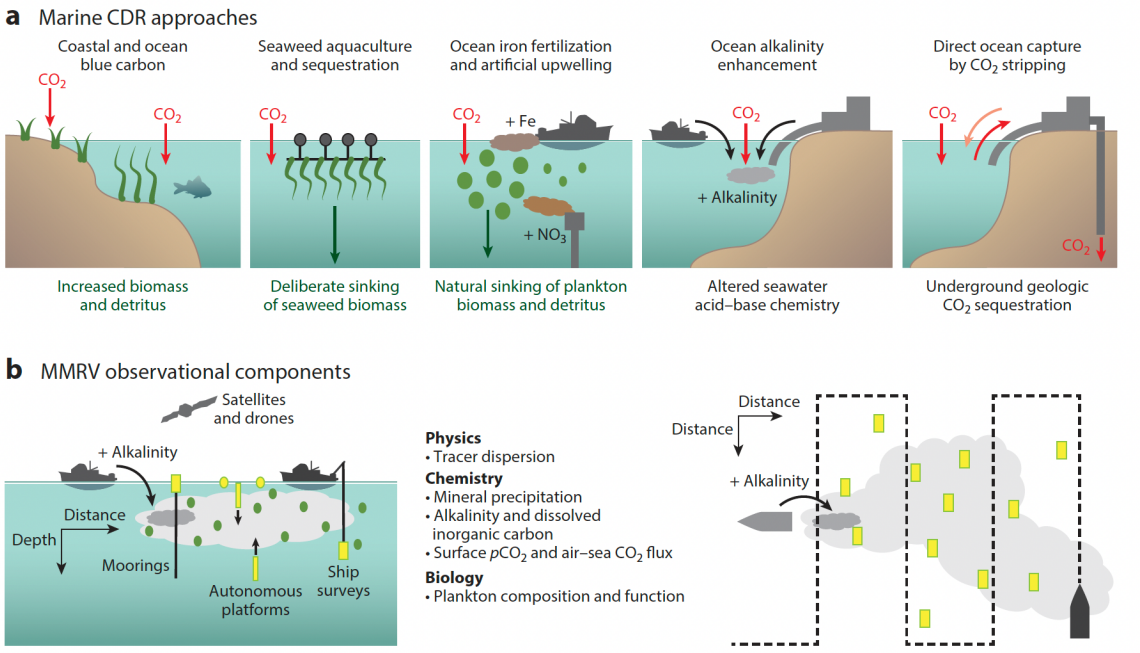

Figure: (a) Schematic of possible biotic and abiotic marine carbon dioxide removal CDR techniques. The downward red arrows mark carbon dioxide (CO_2) removal from the atmosphere into the ocean; depending on the method, carbon storage can occur in inorganic or organic carbon form and in the water column, sediments, or deeper geologic reservoirs. (b) Schematic of observational components for MMRV for an illustrative ocean alkalinity enhancement CDR field experiment. The two subpanels present a depth section (left) and horizontal plan view (right), with moorings and autonomous platforms such as biogeochemical profiling floats denoted as yellow symbols in the plan view. Abbreviations: CDR, carbon dioxide removal; nutrients, Fe for iron and NO_3 for nitrate; MMRV, measurement, monitoring, reporting, and verification. From Doney et al. (2024a).

Approach	Sequestration potential (Pg CO_2 y^{-1})	Cost ($ t CO_2^{-1})	Efficacy	Durability	MMRV challenges	Social considerations	Environmental risk	Co-benefits
Biotic CDR								
Nutrient fertilization	0.1–1	<$50	Medium–high confidence	Medium	Medium–high	Potential conflicts with international treaties on ocean dumping and protection of biodiversity	Medium–high (intended effect is to change surface-ocean biology; potential for undesirable geochemical and ecological consequences)	Potential enhancements to fisheries; surface-ocean decreases in acidity
Artificial upwelling and downwelling	<0.1	$100–150	Low confidence	Low–medium	High	Potential conflicts with other uses	Medium–high (changes in ocean surface temperature and nutrient balances)	Localized enhancement of aquaculture and fisheries
Seaweed cultivation	0.1–1	$100	Medium confidence	Medium–high	Low–medium	Potential for jobs in seaweed cultivation; conflicts with other marine uses	Medium–high (increases in acidification, hypoxia, and eutrophication in areas where seaweed is sequestered)	Colocation with aquaculture could alleviate environmental impacts; biofuels production
Ecosystem conservation	<0.1	<$50	Low–medium confidence	Medium	High	Competition with other uses of coastal ecosystems	Low (generally positive impacts associated with increased biodiversity and ecosystem restoration)	Biodiversity and ecosystem services
Abiotic CDR								
Ocean alkalinity enhancement, including geochemical and electrochemical approaches	>1	$100–150	High confidence	Medium–high	Low–medium	Expansion of mining; potential conflicts with international treaties on ocean dumping	Medium (unknown impacts of elevated alkalinity; potential for toxic effects of trace metals and reduced seawater clarity; mining impacts on land)	Direct amelioration of ocean acidification
Electrochemical ocean capture	0.1–1	>$150	High confidence	Medium–high	Low–medium	Similar to alkalinity enhancement and other industry	Medium–high (local impacts associated with high salinity and pH at effluent discharge points; need to treat and safely dispose of excess acid)	Mitigation of ocean acidification; potential to colocate with desalinated water; H_2 and Cl_2 co-production

Table: Summary of marine CDR approaches. The CDR scalability reflects biophysical, geochemical, engineering, environmental, and social constraints for the potential deployment of a CDR method at climate policy–relevant scales. Note that the protection and restoration of coastal blue-carbon systems are not included in the ecosystem conservation row (NASEM 2019). Abbreviations: CDR, carbon dioxide removal; MMRV, measurement, monitoring, reporting, and verification. Table adapted by Doney et al. (2024a) with permission from NASEM (2022).

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