ANNUAL REVIEWS

Annual Review of Marine Science

The Science, Engineering, and Validation of Marine Carbon Dioxide Removal and Storage

Scott C. Doney,[1] Wiley H. Wolfe,[1] Darren C. McKee,[1] and Jay G. Fuhrman[2]

[1]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA; email: scd5c@virginia.edu, esz9ds@virginia.edu, dcm2xp@virginia.edu

[2]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Maryland, USA; email: jay.fuhrman@pnnl.gov

Annu. Rev. Mar. Sci. 2025. 17:55–81

First published as a Review in Advance on July 2, 2024

The *Annual Review of Marine Science* is online at marine.annualreviews.org

https://doi.org/10.1146/annurev-marine-040523-014702

Keywords

ocean biogeochemistry, climate mitigation, decarbonization, monitoring, reporting and verification, ocean acidification

Abstract

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

1. RATIONALE FOR CARBON DIOXIDE REMOVAL

CO_2: carbon dioxide, a key greenhouse gas that readily dissolves in seawater

Decarbonization: the reduction of CO_2 and other greenhouse gas emissions from economic sectors, including through energy efficiency, renewable energy, and carbon capture and sequestration

Carbon dioxide removal (CDR): the deliberate removal and sequestration of excess CO_2 away from the atmosphere for long periods of time

Integrated assessment models (IAMs): coupled simulations of the economy, energy systems, and climate–carbon cycle dynamics used to evaluate climate policies and future climate projections

Over the past several centuries, large human perturbations to the global carbon cycle have increased atmospheric carbon dioxide (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 (Bindoff et al. 2019, Cooley et al. 2022).

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, 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 climate stabilization scenarios 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, 2023).

Figure 1 illustrates the scope of the required levels of decarbonization and CDR for a below +1.5°C climate scenario (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 = 1×10^{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) sharply reduce fossil fuel emissions. However, there remain within this scenario economic sectors that are difficult or expensive to decarbonize, such as some heavy industry and maritime shipping, with residual emissions of 2–3 Pg C y^{-1}. The residual emissions are compensated by CDR or negative emissions, resulting in net-zero human CO_2 emissions by midcentury. Even larger amounts of CDR (>3 Pg C y^{-1}) and net-negative CO_2 emissions are required for the latter half of the century to compensate for continued human CH_4 and other greenhouse gas emissions.

Climate scenarios such as those in **Figure 1** are often created using integrated assessment models (IAMs) that couple the global economy, energy systems, and climate–carbon cycle dynamics. Within IAMs, there is an interplay between the projected availability of CDR, residual emissions, and required rate of decarbonization, with lower estimated CDR costs, energy use, and resource demands resulting in higher projected residual emissions and slower decarbonization. While IAMs exhibit a wide range of future decarbonization and CDR pathways, even for the same climate policy target, a majority of the ensemble of IAMs used in the recent Intergovernmental Panel on Climate Change (IPCC) assessments projected substantial use of CDR to meet the +1.5°C goal (IPCC 2018, Fuhrman et al. 2023) (gray mean and standard deviation in **Figure 1**).

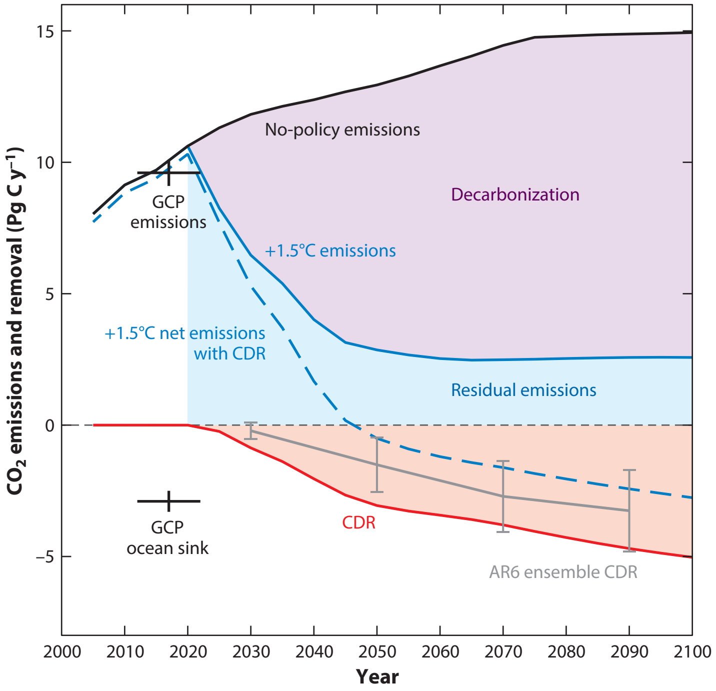

Figure 1

Historical and projected CO_2 emissions (Pg C y^{-1}) for the twenty-first century for a no-policy reference scenario and a climate scenario limiting global surface warming to below +1.5°C relative to a preindustrial baseline by 2100. The solid black line shows fossil fuel gross CO_2 emissions under the no-policy scenario, the solid blue line shows gross emissions under the +1.5°C scenario, the solid red line shows CDR, and the dashed blue line shows net emissions under the +1.5°C scenario with CDR. The scenarios are from GCAM, which simulates the global energy system, economy, and carbon and climate systems; more minor simulated land-use emissions and sinks are excluded for clarity (Fuhrman et al. 2023). The mean and standard deviation of the projected CDR from the ensemble of models compiled for AR6 are shown in gray (Fuhrman et al. 2023). The estimated decadal-mean fossil fuel emissions and ocean sink for 2012–2021 from GCP are shown in black with error estimates (Friedlingstein et al. 2022). Abbreviations: AR6, IPCC Sixth Assessment Report; CDR, carbon dioxide removal; GCAM, Global Change Assessment Model; GCP, Global Carbon Project; IPCC, Intergovernmental Panel on Climate Change.

To date, only a subset of possible CDR approaches have been incorporated into IAMs 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 or ocean-based 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 the 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

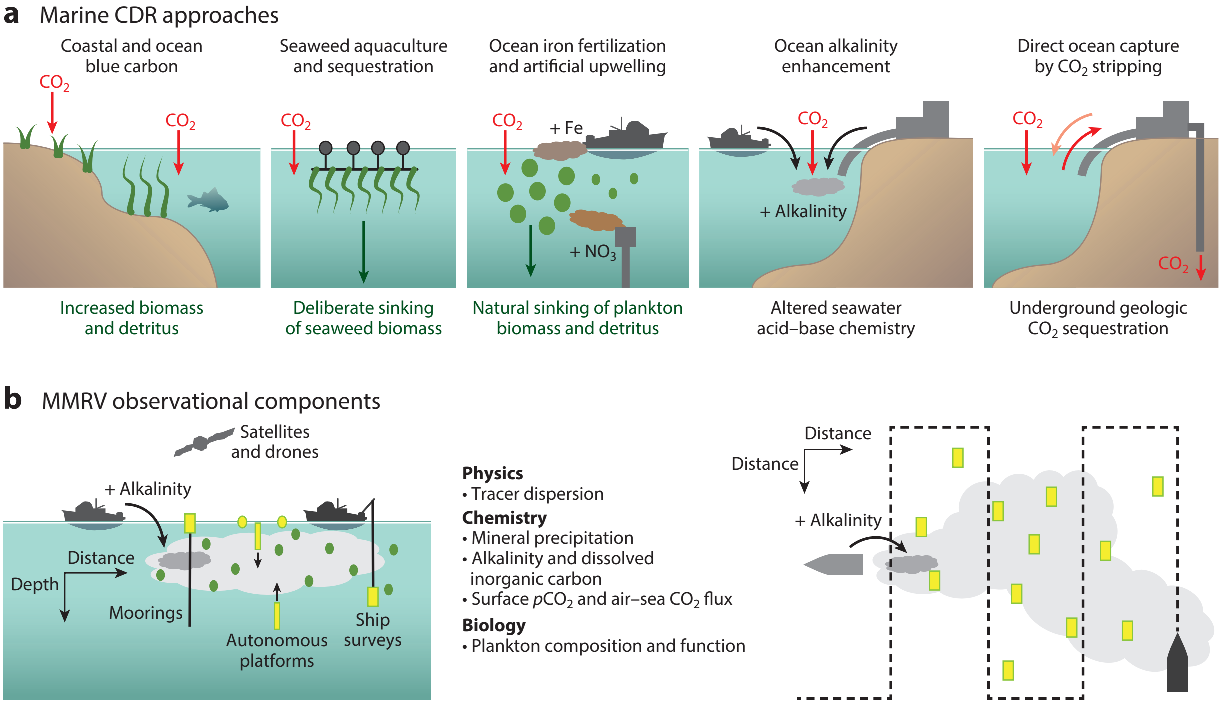

Figure 2

(*a*) Schematic of possible biotic and abiotic marine CDR techniques. The downward red arrows mark 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; MMRV, measurement, monitoring, reporting, and verification.

decades, as shown in **Figure 1**, poses significant scientific, engineering, and societal challenges (IPCC 2018, NASEM 2019).

Proposed coastal and ocean-based CDR methods cover a broad mix of nature-based and technological approaches that alter either ocean biotic or abiotic carbon cycles (**Figure 2**). Biotic CDR 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 macroalgae aquaculture); abiotic CDR approaches involve geochemical and electrochemical techniques (e.g., alkalinity enhancement) (GESAMP 2019, Gattuso et al. 2021, NASEM 2022). 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 subseabed 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 ocean-based CDR is thus complicated by the large natural background of ocean carbon storage and cycling (DeVries 2022, Gruber et al. 2023) as well as the substantial contemporary ocean anthropogenic CO_2 sink of 2.9 ± 0.4 Pg C y^{-1} (**Figure 1**) (Friedlingstein

Blue carbon: carbon stored in biomass and sediments in biologically productive, coastal ecosystems (mangroves, salt marshes, and seagrasses)

Ocean blue carbon: conservation-based marine CDR approaches for benthic, pelagic, and offshore ocean ecosystems, including macroalgae and marine animals 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), 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) (**Figure 2**). 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 subseabed geological CO_2 sequestration linked to power- and industry-sector carbon capture (Blackford et al. 2021). 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).

The remainder of the review is partitioned into sections on the context of the contemporary ocean carbon cycle (Section 2), the framing of ocean-based CO_2 removal and storage (Section 3), validation and MMRV (Section 4), and surveys of abiotic and biotic ocean-based removal approaches (Sections 5 and 6), followed by summary points.

Ocean fertilization: the addition of the micronutrient iron or macronutrients to stimulate biological productivity, increase carbon export, and reduce surface-ocean CO_2

Artificial upwelling: enhanced vertical transport of nutrients from the subsurface to the surface ocean to increase biological carbon export and reduce surface-ocean CO_2

Alkalinity: a conserved thermodynamic measure of seawater acid–base chemistry equal to the charge difference between conservative cations and anions

Alkalinity enhancement: geochemical or electrochemical methods to increase CO_2 solubility in seawater by adding alkaline dissolved ions or soluble minerals

Air–sea CO_2 flux: gas exchange of CO_2 across the ocean–atmosphere interface controlled by thermodynamic and kinetic factors

2. THE CONTEMPORARY OCEAN CARBON CYCLE

Ocean-based 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 river, coastal, and ocean biogeochemistry, adding another layer of complexity to the system (**Figure 3**). CO_2 gas dissolves in and reacts with alkaline seawater to create dissolved inorganic carbon (DIC), the sum of the concentrations of aqueous CO_2 ($CO_2(aq)$), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), where $[y]$ refers to the concentration of chemical species y (Millero 2007):

$$\mathrm{DIC} = [\mathrm{CO_2\,(aq)}] + [\mathrm{H_2CO_3}] + [\mathrm{HCO_3}^-] + [\mathrm{CO_3}^{2-}]. \qquad 1.$$

At seawater pH, the concentration of H_2CO_3 is negligible relative to that of aqueous CO_2, and the two are often combined into a single effective term, $H_2CO_3^*$. DIC is the dominant ocean carbon reservoir (preindustrial DIC inventory ~37,100 Pg C; DeVries 2022) followed by a smaller ocean dissolved organic carbon (DOC) pool (~662 Pg C; Hansell et al. 2009), including a semilabile fraction with seasonal to decadal turnover times and a larger refractory fraction with millennial turnover times. 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 preindustrial ocean DIC 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, salinity, and alkalinity, a measure of the acid/base balance and a result of rock weathering (Millero 2007):

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

More CO_2 will partition into a colder, more alkaline ocean, thus lowering the atmosphere mixing ratio on geologic timescales (CO_2^{atm}, ppm) (Ciais et al. 2013). The ocean solubility pump response to rising CO_2^{atm}, modulated by rates of physical circulation between the surface and deep ocean,

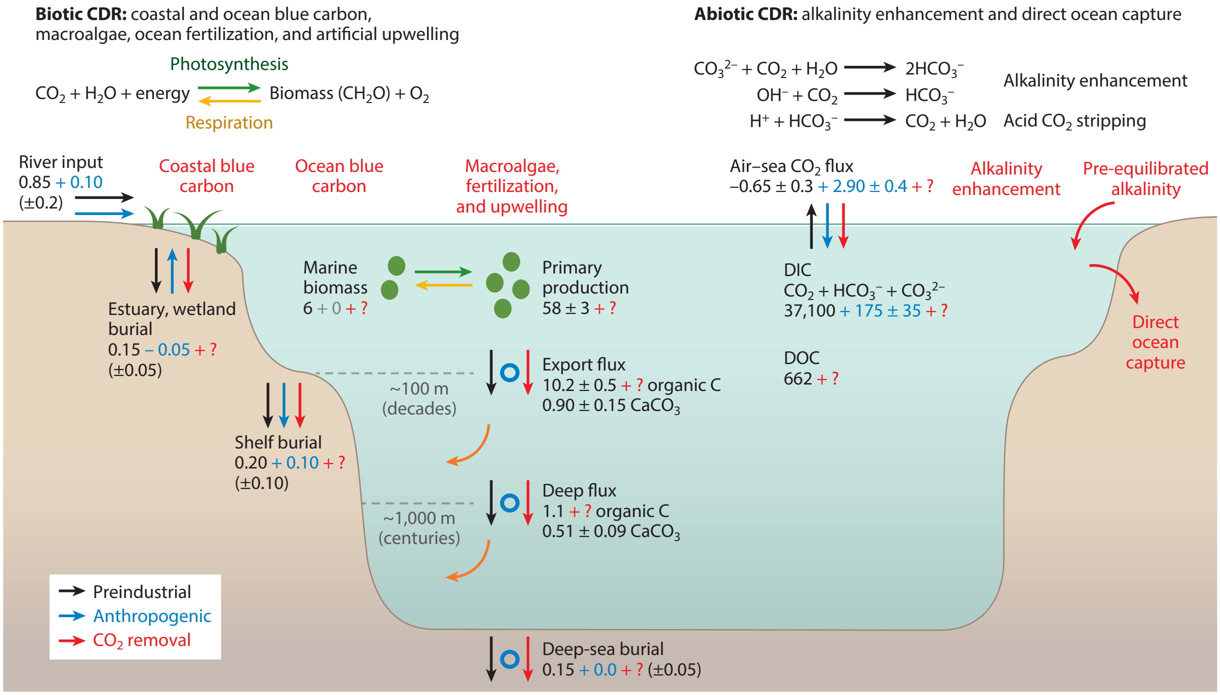

Figure 3

Schematic of the contemporary global ocean carbon system overlaid with perturbations from potential biotic and abiotic marine CDR techniques (*red labels, arrows, and possible inventory changes*). Relevant organic and inorganic carbon reactions are shown along with contemporary fluxes (Pg C y^{-1}) and reservoirs (Pg C), partitioned into preindustrial (*black*) and anthropogenic (*blue*) arrows and numerical values (where the *blue circle* marks a minimal anthropogenic flux perturbation) from illustrative literature estimates: carbon river input and sediment burial (Regnier et al. 2022), water-column primary production and organic carbon export and deep-sea flux (Nowicki et al. 2022), $CaCO_3$ export and deep-sea flux (Battaglia et al. 2016), preindustrial air–sea CO_2 outgassing (Regnier et al. 2022), anthropogenic air–sea CO_2 uptake (mean 2012–2021) (Friedlingstein et al. 2022), preindustrial and anthropogenic DIC inventory (DeVries 2022, Friedlingstein et al. 2022), marine biomass stock (Bar-On et al. 2018), and marine DOC (Hansell et al. 2009). Note that there are a wide range (not shown) of literature estimates for marine biomass (J.R. Collins, R.E. Boenish, M.R. Cape, C.R. Benitez-Nelson, S.C. Doney, et al., manuscript in review) and biological pump fluxes (Doney et al. 2024). The water-column sequestration timescales vary from decades in the main thermocline (100–1,000 m) to centuries in the deep sea (>1,000 m) (Siegel et al. 2021). Abbreviations: CDR, carbon dioxide removal; DIC, dissolved inorganic carbon; DOC, dissolved organic carbon.

also largely explains the ocean uptake of anthropogenic CO_2, increasing the preindustrial DIC inventory by 175 ± 35 Pg C (Friedlingstein et al. 2022).

Measurement, monitoring, reporting, and verification (MMRV): a systematic, verifiable, and transparent approach for quantifying the efficacy and permanence of marine CDR

The contemporary global air–sea CO_2 flux is the net difference between ingassing of anthropogenic CO_2 and a now smaller preindustrial outgassing from riverine carbon inputs (**Figure 3**). 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 aqueous CO_2 concentrations:

$$F_{CO_2} = k_w\left([CO_2^{atm}\,(aq)] - [CO_2\,(aq)]\right). \tag{3}$$

Equation 3 is often recast as partial pressure of CO_2 (pCO_2) by including a solubility term. The equilibration time of surface-ocean CO_2 relative to air–sea flux is long, O(1 year), because of the large DIC pool and shifts in seawater acid–base chemistry (Emerson & Hamme 2022).

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

$$CO_2 + H_2O \rightarrow HCO_3^{-} + H^{+},\quad CO_3^{2-} + H^{+} \rightarrow HCO_3^{-}, \qquad 4.$$

$$\mathrm{pH} = -\log_{10}\left[H^{+}\right]. \qquad 5.$$

Seawater alkalinity is not affected by adding CO_2. Alkalinity is enhanced by adding 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.

Because marine CDR approaches can alter seawater acid–base chemistry, CDR is often linked to discussions of ocean acidification, the changes in chemistry associated with ocean uptake of anthropogenic CO_2. Ocean acidification has the potential to harm many types of marine organisms, particularly for those that create shells and skeletons from $CaCO_3$ minerals (Doney et al. 2020):

$$CaCO_3\ (s) \leftrightarrow CO_3^{2-} + Ca^{2+}. \qquad 6.$$

Carbonate mineral precipitation and dissolution can be expressed with a geochemical saturation state (Ω) that varies with alkalinity and CO_3^{2-} concentration:

$$\Omega = \frac{[CO_3^{2-}][Ca^{2+}]}{K_{sp}}, \qquad 7.$$

where the apparent solubility product (K_{sp}) depends on temperature, salinity, pressure, and carbonate mineral form. $\Omega > 1$ marks supersaturated conditions, though abiotic carbonate precipitation is kinetically limited except for strong supersaturation ($\Omega \gg 1$), which can be caused by local excess alkalinity additions.

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 CO_2^{atm} (Marinov et al. 2008). Surface-ocean photosynthesis and inorganic CO_2 uptake, $O(50\ \mathrm{Pg\ C\ y^{-1}})$, is nearly balanced by respiration (forward and backward reactions in Equation 8):

$$CO_2 + H_2O + \text{energy} \leftrightarrow CH_2O + O_2. \qquad 8.$$

The net imbalance of $O(10\ \mathrm{Pg\ C\ y^{-1}})$ is exported as organic matter to the subsurface ocean, with an accompanying $CaCO_3$ inorganic carbon export of $O(1\ \mathrm{Pg\ C})$ that mostly dissolves in the water column or at the deep-sea sediment surface. Only a small fraction of the organic carbon export, $O(1\ \mathrm{Pg\ C\ y^{-1}})$, is transferred to depths greater than 1,000 m, and an even smaller fraction, $O(0.1\ \mathrm{Pg\ C\ y^{-1}})$, is buried in deep-ocean sediments. Comparable carbon burials occur in the much smaller areas of estuaries and coastal wetlands and on the continental shelf.

3. 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 (Section 4). Scientific assessment centers on efficacy, permanence, additionality, and scalability (GESAMP 2019; NASEM 2019, 2022; Gattuso et al. 2021). 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 DIC (Section 2) 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

Dissolved inorganic carbon (DIC): the total concentration of dissolved CO_2, carbonic acid, and bicarbonate and carbonate ions, with speciation controlled by seawater acid–base chemistry

pCO_2: the partial pressure of aqueous CO_2 gas dissolved in seawater and a thermodynamic driver of air–sea CO_2 flux

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 a CDR method at climate policy–relevant scales physical circulation, turbulence, and mixing and the O(1 year) 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 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.

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 (Malhorta & Schmidt 2020). 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 (Grubler et al. 2016).

These issues have been raised with respect to CO_2 storage in the (relatively static) subsurface (Lane et al. 2021); they 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 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).

Technical and techno-economic assessments are being developed for marine CDR techniques (La Plante et al. 2021, Eisaman et al. 2023). To add context to CDR life cycle and techno-economic studies, marine CDR can be included in IAMs that dynamically couple energy and land-use sectors with the atmospheric and ocean systems (Hartin et al. 2015). However, the usefulness of IAM results will be subject to the input parameters, reflecting the scaling considerations discussed above, as well as improved representation of the complex spatiotemporal dynamics inherent to most if not all marine CDR approaches.

4. MEASUREMENT, MONITORING, REPORTING, AND VERIFICATION

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 accounting and incorporation into carbon markets (Arcusa & Sprenkle-Hyppolite 2022). Abiotic CDR approaches (Section 5) 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 (Section 6).

One challenge facing MMRV for marine CDR strategies is that natural variability in the marine carbon cycle is large. For example, the natural seasonal cycle of upper-ocean $p\mathrm{CO}_2$ is approximately 49 ± 23 µatm in the open ocean and 210 ± 76 µatm in the coastal ocean (Torres et al. 2021). In comparison, the biological drawdowns of surface DIC and $p\mathrm{CO}_2$ associated with past mesoscale iron fertilization experiments were $O(15\ \mu\mathrm{mol\ kg}^{-1})$ and $O(30\ \mu\mathrm{atm})$, respectively (Yoon et al. 2018), and a similar $p\mathrm{CO}_2$ decline would result from an alkalinity addition of $O(15\ \mu\mathrm{mol\ kg}^{-1})$ (Ho et al. 2023). While such CDR signals are well resolved with ship- and shore-based analysis at climate-level measurement uncertainties (DIC and alkalinity 2 $\mu\mathrm{mol\ kg}^{-1}$, $p\mathrm{CO}_2$ 2 µatm), the signal-to-noise ratio is more challenging for distributed observing systems and autonomous platforms with more weather-level measurement uncertainties (DIC and alkalinity 10 $\mu\mathrm{mol\ kg}^{-1}$, $p\mathrm{CO}_2$ 10 µatm) (Tilbrook et al. 2019).

Climate-level measurement uncertainties: the measurement precision and/or accuracy needed to track long-term anthropogenic CO_2, climate change, and CDR trends

Weather-level measurement uncertainties: the measurement precision and/or accuracy needed to track short-term CDR perturbations and natural variability

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, DIC, or $p\mathrm{CO}_2$ are effectively stirred into filaments that can be difficult to observationally resolve and can be transported far from the deployment site. These points are illustrated in **Figure 4**, where a patch with enhanced alkalinity is stirred by surface-ocean currents and quickly deformed, stretched, and transported laterally. The initial alkalinity perturbation of $+100\ \mu\mathrm{mol\ kg}^{-1}$, set as an illustrative upper bound on a perturbation level that would avoid secondary alkalinity precipitation in most ocean regions without substantial CO_2 pre-equilibration (Hartmann et al. 2023, Schulz et al. 2023), is rapidly diluted over a few weeks over large portions of the patch to near the weather-level uncertainty limit (10 $\mu\mathrm{mol\ kg}^{-1}$).

Ocean circulation at the mesoscale, O(10–100 km), is largely horizontal and well described by quasi-balanced flows with a steep energy spectrum and flat tracer variance spectrum. The stirring of tracer by mesoscale eddies is nonlocal, with the largest eddies dominating the stirring and effectively straining and stretching tracer into thin filaments (**Figure 4**). The circulation in between the mesoscales and the dissipation scales—the submesoscales—is more complicated, is less well understood, and can have strong impacts on MMRV efforts. At these smaller length scales, force balances break down and motions across ocean fronts become important. These motions include additional stirring by smaller mixed-layer eddies, strong velocity shears that can further disperse tracer by shear dispersion, and episodic vertical velocities that can conspire with a vertical tracer distribution to yield a net removal of tracer from the mixed layer by subduction (Mahadevan 2016, McWilliams 2016). This latter point is especially important as perturbations to the carbon system designed to reduce upper-ocean $p\mathrm{CO}_2$ 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. While there is some debate as to whether stirring at submesoscales is local or nonlocal (Balwada et al. 2021), lateral dispersion is in general associated with a scale-dependent diffusivity, which must be taken into consideration when designing observational arrays for MMRV.

Field observations from emerging biogeochemical autonomous platform technologies, augmented by numerical modeling and remote sensing where applicable, will provide valuable insights

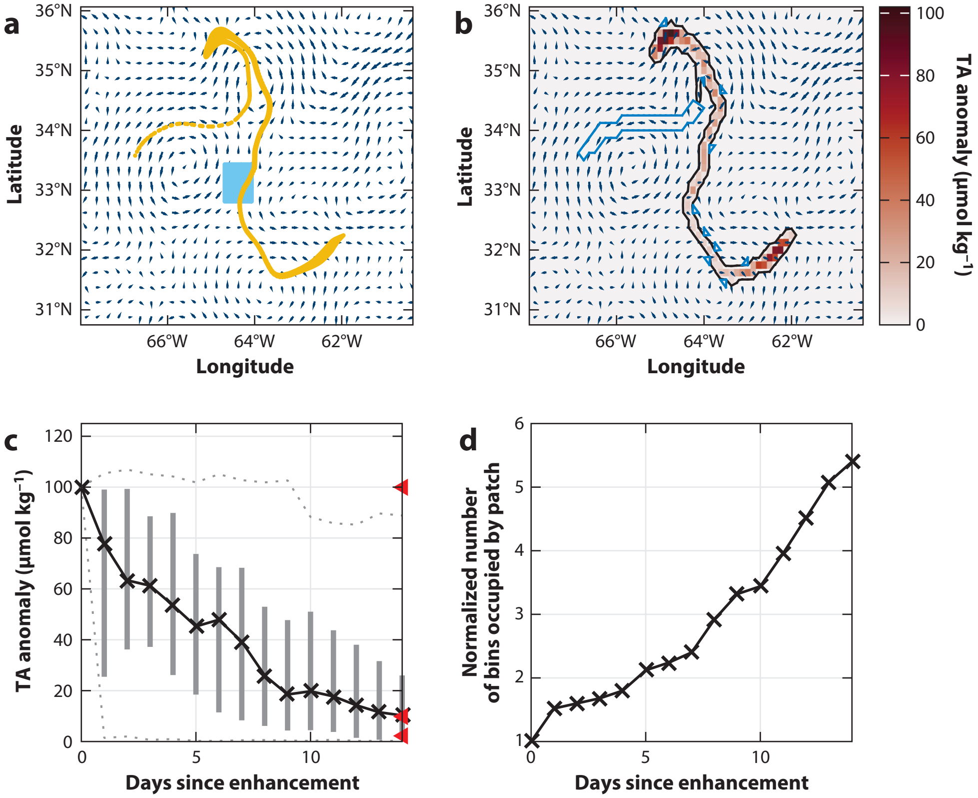

Figure 4

Example of the horizontal dispersion of a hypothetical TA addition by the mesoscale geostrophic (balanced) flow using a particle tracking method described by McKee et al. (2022). A tracer perturbation is applied to a 0.625° × 0.625° patch in a moderate straining region in the subtropical North Atlantic. The initial patch is uniformly seeded on a latitude–longitude grid with 10,000 particles that are then advected forward in time by the surface geostrophic currents from satellite altimetry (Copernic. Mar. Environ. Serv. 2022) with a fourth-order Runge–Kutta scheme at an hourly time step for 14 days. Particles are then collected into 0.125° × 0.125° pixels and converted to a scalar TA concentration field using an initial patch TA_{max} perturbation of 100 μmol kg^{-1}. The representation is approximate as particles are collected in evenly spaced latitude–longitude pixels, not evenly spaced Cartesian pixels. (*a*) Initial (*light blue*) and final (*gold*) particle locations with initial current vectors. (*b*) Final TA concentrations (*colors*). The black and blue contours enclose pixels with a nonzero TA perturbation above and below climate-level uncertainties (TA_{meas} = 2 μmol kg^{-1}), respectively. (*c*) Time series (subsampled once per day) of the time evolution of the patch. The thick black line indicates the median TA of all nonzero pixels containing particles within the stretched patch, the vertical lines bound the 25th and 75th percentiles, and the thin dotted lines indicate the 2.5th and 97.5th percentiles. The red wedges on the right indicate TA_{max} and the climate- and weather-level uncertainties TA_{meas} (2 and 10 μmol kg^{-1}). (*d*) Time series (subsampled once per day) of the total number of pixels occupied by the patch divided by the value at the initial time step. Abbreviation: TA, total alkalinity.

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 (**Figure 4**), 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 (DIC, alkalinity, pH, and $p\text{CO}_2$). Standardized CO_2-system methods at climate-level uncertainty are available for discrete samples, surface underway sampling, and mooring pH and $p\text{CO}_2$ (Sloyan et al. 2019, Wanninkhof et al. 2019). Substantial advances have also occurred for CO_2-system and biogeochemical sensors on autonomous platforms, including profiling Argo floats and surface saildrones (Bushinsky et al. 2019a,b; Hauck et al. 2023).

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 $p\text{CO}_2$ data, wind speed, and empirical gas transfer parameterizations (Equation 3) for open-ocean (Ho et al. 2011) and coastal (Dobashi & Ho 2023) conditions. 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 ($^3\text{He}/\text{SF}_6$) should be considered for validating gas transfer parameterizations for different systems.

Simultaneous release of dye-like tracers (e.g., 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).

Adequate representation of simulated ocean dynamics is also important, though often difficult to determine. While ocean model CO_2 biases may be inevitable at some level (DeVries et al. 2023), emerging physical–biogeochemical skill assessment and data assimilation methods can help identify and sometimes minimize biases (Fennel et al. 2022). To effectively study ocean turbulence, it is necessary to use models of varying physical resolutions. The same principle applies to geo- and biogeochemical models. For detailed analysis, it is recommended to employ high-resolution hydrodynamic models that directly simulate smaller submesoscales, rather than relying on parameterizations (Fennel et al. 2023). 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.

Direct ocean capture: electrochemical techniques that acidify seawater, stripping out CO_2 for sequestration in land or subseabed geological reservoirs

5. ABIOTIC CARBON DIOXIDE REMOVAL APPROACHES

Abiotic 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 (Section 5.1) utilizes geochemical or electrochemical methods to add alkalinity to seawater, while direct ocean capture (Section 5.2) utilizes electrochemical techniques to strip CO_2 from the surface ocean (Kheshgi 1995). Scientific and engineering characteristics, validation and MMRV challenges, and social–environmental impacts for the two broad categories of abiotic ocean CDR are summarized in **Table 1** based on the available literature (NASEM 2022).

5.1. Alkalinity Enhancement

On geological timescales of hundreds of thousands of years and longer, atmospheric CO_2 is partially modulated by a stabilizing feedback between chemical weathering of continental silicate and carbonate minerals and the marine formation and burial of carbonate minerals (Berner 1991). A transient increase in ocean alkalinity from enhanced continental weathering causes a drawdown in seawater aqueous CO_2 approximated by

$$CO_3{}^{2-} + CO_2 + H_2O \rightarrow 2HCO_3{}^{-}. \qquad 9.$$

Ocean alkalinity enhancement seeks to accelerate this natural weathering process and for this reason may also be termed enhanced or accelerated weathering (Kheshgi 1995, Rau et al. 2007, Archer et al. 2009, Goll et al. 2021). 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 $HCO_3{}^-$ and $CO_3{}^{2-}$ concentrations and lower aqueous CO_2 concentration (Schuiling & Krijgsman 2006, Wolf-Gladrow et al. 2007). 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. 2009, 2020; Hartmann et al. 2013; Albright et al. 2016).

While ocean alkalinity enhancement generally refers to the direct application of alkalinity to the marine environment, terrestrial application of alkaline materials will also eventually increase ocean alkalinity due to runoff (Taylor et al. 2016). Terrestrial alkalinity application may have additional co-benefits, including improved soil health and crop yields (Beerling 2017, 2018; Kantola et al. 2017; Strefler et al. 2018; Kantzas et al. 2022). However, the CDR efficiency of terrestrial alkalinity applications may be substantially reduced if the dissolved alkalinity passes, even temporarily, through regions of lower pH (<5–6) along the land–aquatic–ocean continuum, resulting in offgassing of CO_2 (Bertagni & Porporato 2022). Because IAMs already include economy–energy–land linkages and owing to the more uncertain legal status of direct ocean alkalinity application (Webb 2021), terrestrial weathering approaches have received somewhat more attention in the IAM literature than ocean alkalinity enhancement (Holz et al. 2018, Strefler et al. 2021, Fuhrman et al. 2023).

Table 1 Summary of marine CDR approaches

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 at effluent discharge points; need to treat and safely dispose of any waste products)	Mitigation of ocean acidification; potential to colocate with desalinated water; H_2 and Cl_2 co-production

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

Silicate-bearing minerals (e.g., olivine and basalt), limestone in raw (i.e., $CaCO_3$) and calcined forms (CaO and $Ca(OH)_2$), and various alkaline waste materials are all under consideration to enhance alkalinity in seawater (Rau & Caldeira 1999, Xi et al. 2016, Renforth 2019). The molar CDR efficiency of silicates is higher (∼1.5) than that of carbonates (∼0.5), where any secondary carbonate precipitation from local supersaturation would sharply reduce the removal efficiency from stoichiometric ratios (Renforth & Henderson 2017). Due to the low solubility constants of silicate minerals, very small (1–100 μm) particle sizes are required to induce their dissolution on relevant timescales (GESAMP 2019). If applied directly to the open ocean (i.e., in situ), small particle sizes are also required to avoid rapid sinking out of the surface layer, where they would be unable to enhance CO_2 uptake from the atmosphere (Meysman & Montserrat 2017). Such fine rock comminution could result in a substantial energy burden and correspondingly reduce the removal efficiency if this energy is provided by fossil fuels (Hangx & Spiers 2009, Foteinis et al. 2023). Dissolving alkalinity in a land-based or shipboard reactor prior to dispersion (i.e., ex situ) may help address particle sinking, but secondary precipitation would remain a concern (Caserini et al. 2021). Discrepancies between laboratory and field observations and a lack of unifying analytical equations on dissolution kinetics imply that numerical modeling validated by field experimentation will be required to constrain uncertainty and optimize deployment locations (Brantley et al. 2008, Harvey 2008, Rimstidt et al. 2012, Jiang et al. 2015).

Secondary precipitation: the formation of mineral solids when seawater alkalinity is in great excess; the resulting removal of alkalinity lowers the effectiveness of alkalinity enhancement CDR

Coastal ecosystems (e.g., coral reefs) vulnerable to ocean acidification and upwelling zones could be good candidates for initial trials of ocean alkalinity enhancement, with wastewater treatment effluent as a potential delivery mechanism (Feng et al. 2016, Cai & Jiao 2022). Ocean alkalinity enhancement deployment at scale on the open ocean will require up to 1,000 repurposed commercial or dedicated vessels for dispersion (Caserini et al. 2021). This could introduce additional environmental challenges, including increases in ambient noise, invasive species transfer, and criteria air pollutant emissions from shipping (Dalsøren et al. 2013, Muirhead et al. 2015, Kaplan & Solomon 2016).

The extraction and processing of minerals for alkalinity enhancements on a scale sufficient to meaningfully contribute to climate mitigation (i.e., hundreds to thousands of teragrams of carbon per year) could require dedicated rock extraction of similar or larger magnitude to that of the global cement industry (Renforth & Henderson 2017, USGS 2021). While such expansion could provide local employment at the mine sites, it could also exacerbate negative socioenvironmental effects associated with the expansion of resource extractive activities (Buck et al. 2020). Due to the inherent need for very small particle sizes—especially of silicates, which can penetrate deep into the lungs—controlling fine particulate emissions to the air is of particular concern (Daly & Zannetti 2007). Controls are also needed on CO_2 emissions associated with processing (e.g., quicklime production and electricity for rock crushing). While alkalinity addition would directly counteract ocean acidification, both the potential impacts of excess alkalinity, trace metal, and nutrient releases on marine biota and, conversely, the impacts of the marine biota themselves on the removal efficacy of ocean alkalinity enhancement remain unknown (NASEM 2022). Current sensor technologies and practices could be modified to measure and monitor the performance of ocean alkalinity enhancement. However, they may have limitations due to the poor spatiotemporal resolution associated with ship- or buoy-based measurements in many ocean regions. The emergence of profiling biogeochemical float and other autonomous technologies may offer invaluable supplements to ship-based observations (Bushinsky et al. 2019a,b; Hauck et al. 2023).

5.2. Electrochemical and Direct Ocean Capture

Electrochemical CDR approaches utilize acid–base chemistry to either decrease pH and force CO_2 offgassing (Willauer et al. 2011, Eisaman et al. 2018) or increase pH to induce carbonate precipitation (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 (Patterson et al. 2019, Digdaya et al. 2020). Electrochemical processes can also be used to increase seawater alkalinity directly and are thus a special case of ocean alkalinity enhancement (Section 5.1). Such direct ocean capture processes are analogous to direct air capture processes that capture CO_2 from the atmosphere. Ocean capture may be less energy intensive due to the higher effective CO_2 concentration in ocean water, which exceeds atmospheric concentrations by approximately 120-fold (Khatiwala et al. 2013, DeVries 2014, DeVries et al. 2017). However, the cost and energy associated with seawater pumping are many times those of the electrochemical process, making it a prohibitively expensive stand-alone process. Colocation of direct ocean capture with desalination plants could substantially reduce this cost (Davies et al. 2018, Digdaya et al. 2020). This colocation approach could offer a mechanism for a prospective carbon valuation scheme that allows arid regions to provide for their freshwater needs and reduce pressure on surface and groundwater resources. However, the carbon removal potential of colocated desalinated and direct ocean capture technologies will be limited by demand for desalinated water (Eke et al. 2020, Fuhrman et al. 2023).

Environmental considerations for electrochemical carbon removal approaches include the management of excess chlorine gas, for which approximately 1 ton of chlorine could be produced per ton of CO_2 removed. This implies that removals of 100 Tg CO_2 y^{-1} would generate chlorine exceeding the scale of the current global market for chlorine (60–70 Tg y^{-1}). Low DIC concentrations at effluent discharge points could also negatively affect aquatic organisms (Hansen et al. 2007). Considerations for low-carbon electricity procurement are also like those of direct air capture and ocean alkalinity enhancement. Potential co-benefits of direct ocean capture include the co-production of H_2 and/or brines resulting from acid neutralization that contain high concentrations of silica, aluminum, and iron (NASEM 2022). CO_2 captured from seawater would need to be compressed and stored in geologic formations, stored as a liquid in the deep ocean, or stabilized into either aqueous or solid carbonates, presenting similar mass-handling challenges as ocean alkalinity enhancement or any other prospective source of captured carbon (Lane et al. 2021).

5.3. Connections to Other Technologies

As discussed above, both ocean alkalinity enhancement and electrochemical processes have potential connections with existing infrastructure and technologies (e.g., wastewater treatment and desalination). Integrated assessment modeling scenarios could help explore these connections and inform estimates of realistic scaling potential under different policy environments. While not carbon removal per se, electrochemical and ocean alkalinity enhancement approaches could also be used as onboard exhaust gas treatment to mitigate CO_2 emissions from international shipping (DaJose 2023).

6. BIOTIC CARBON DIOXIDE REMOVAL APPROACHES

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. Scientific characteristics, validation and MMRV challenges, and social–environmental impacts for broad classifications of biotic marine CDR are summarized in **Table 1** based on the available literature (NASEM 2022).

6.1. Coastal Blue Carbon

Nature-based climate mitigation solutions encompass approaches to repair or prevent further human degradation of ecosystems and thereby enhance carbon storage. Coastal blue-carbon ecosystems—mangroves, salt marshes, and seagrasses—are often prioritized because of their high biological productivity, large carbon storage in living biomass (leaves, stems, and roots), and detrital organic carbon in underlying sediments, as well as their numerous environmental co-benefits, including shore protection and biodiversity (NASEM 2019, May et al. 2023, Schindler Murray et al. 2023).

Despite their small spatial extent, high blue-carbon burial rates—roughly an order of magnitude higher than those of many terrestrial ecosystems on a per-area basis—translate into globally significant total carbon burial, reported by McLeod et al. (2011) at 31–34, 5–87, and 48–112 Tg C y^{-1} for mangroves, salt marshes, and seagrass beds, respectively. MMRV protocols are under development or already in use to quantify carbon storage and greenhouse gas emissions for coastal habitats for carbon accounting and national emissions inventory reporting (Crooks et al. 2018, Oreska et al. 2020), though with substantial uncertainties (Holmquist et al. 2018). Macreadie et al. (2021) estimated that conservation could potentially avoid emissions of 141–466 Tg CO_2 equivalent (CO_2-eq) y^{-1}, with an additional 621–1,064 Tg CO_2-eq y^{-1} coming from restoration. Coastal carbon storage is under threat from ongoing habitat destruction, and coastal CO_2, CH_4, and N_2O emissions are impacted by complex interactions with climate change, sea-level rise, and salinization (Kirwan et al. 2023). The extent to which blue-carbon restoration can serve as a cost-effective climate mitigation option is also open to debate (Williamson & Gattuso 2022).

6.2. Marine Ecosystem Protection, Recovery, and Restoration

Recent research expands beyond coastal blue carbon to the potential of conservation-based CDR approaches for benthic, pelagic, and offshore ocean ecosystems, including macroalgae and marine animals (Christianson et al. 2022). Reversing the rapid decline in coastal macroalgae kelp and rockweed forests (Feehan et al. 2021) could generate a large potential for carbon sequestration, mostly via detritus export, of up to 173 Tg C y^{-1} (Duarte et al. 2013, Krause-Jensen & Duarte 2016). Restoration methods include macroalgae seeding, protections for sea otters and other predators, and sea urchin reduction (Sharma et al. 2021). Challenges for coastal and open-ocean macroalgae approaches include quantifying carbon storage from particulate organic carbon export, as well as the extent to which biogeochemical feedbacks, nutrient reallocation, and calcification reduce CDR efficacy (Queirós et al. 2019). Similar knowledge gaps exist regarding the CDR potential and reversibility of calcifying algal systems (e.g., coral reefs) (van der Heijden & Kamenos 2015).

Marine CDR opportunities arise from recovery of exploited invertebrate, fish, and marine mammal species and limits on further expansion of industrial-scale fishing, such as the harvesting of poorly characterized mesopelagic stocks (NASEM 2022; J.R. Collins, R.E. Boenish, M.R. Cape, C.R. Benitez-Nelson, S.C. Doney, et al., manuscript in review). Potential CDR benefits extend beyond direct biomass carbon storage because marine fauna generate a substantial fraction of surface biological carbon export (Bianchi et al. 2021) and nutrient recycling (Schmitz et al. 2018).

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 (Wolske et al. 2019). Coastal and open-ocean conservation could be facilitated through targeted implementation of marine protected areas that recognizes multiple ocean co-uses with other economic activities (e.g., shipping, fishing, and recreation) and leverages existing policy frameworks and infrastructure for ecosystem-based CDR monitoring and enforcement (Grorud-Colvert et al. 2021).

6.3. Macroalgae Aquaculture

Large-scale seaweed aquaculture has been proposed as a climate mitigation option to offset higher-greenhouse-gas-emitting land-based agriculture (Froehlich et al. 2019) and as a potential marine

CDR approach when farming is coupled with deliberate sinking or downward pumping of the produced macroalgal biomass into the deep ocean (NASEM 2022). Macroalgal CDR would build on a rapidly growing global aquaculture industry for human and animal feed, coastal remediation, and biofuels (Buschmann et al. 2017, Sharmila et al. 2021). However, 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).

Macroalgal CDR: an approach coupling seaweed farming (aquaculture) with deliberate sinking or pumping of macroalgae biomass into deep ocean

6.4. Artificial Upwelling and Downwelling

In many surface-ocean regions, biological carbon export is limited by the supply of new nutrients or micronutrients such as iron. A primary supply pathway is via physical upwelling and upward vertical mixing from nutrient-rich subsurface thermocline waters. 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 DIC in upwelled water is greater than the elemental stoichiometry of plankton organic matter production.

Artificial upwelling seeks to fertilize otherwise nutrient-limited waters using air bubbling, salt fountains, or hydraulic pumps (Pan et al. 2016), while artificial downwelling has been suggested as a means of enhancing the export of DOC and particulate organic carbon and could be paired with artificial upwelling to limit degassing of CO_2-rich subsurface waters. Small-scale artificial upwelling experiments conducted in enclosed waters successfully increased phytoplankton growth, though no measurements were taken of net carbon fluxes (McClimans et al. 2010), and 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 $O(10\ \mathrm{Tg\ C\ y^{-1}})$ (Koweek 2022), with larger, more uncertain effects on surface-ocean temperature and the marine CO_2 solubility pump (Jürchott et al. 2023).

6.5. Nutrient and Iron Fertilization

Multiple open-ocean nutrient fertilization field experiments conducted over the past several decades have 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 $p\mathrm{CO_2}$ and DIC. 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).

The focus on upper-ocean biology and the relatively short duration of most perturbation experiments (only a few weeks) have precluded tracking the longer-term alteration of air–sea CO_2 flux and the fate of the added iron and generated excess organic carbon (Yoon et al. 2018, Jiang et al.

2024), though numerous ocean biogeochemical modeling studies have provided useful context for evaluating the efficiency of iron addition to ocean CDR and downstream effects on nutrients and productivity (Aumont & Bopp 2006, Jin et al. 2008). Most fertilization-based proposals for marine CDR focus on adding the micronutrient iron to otherwise macronutrient-replete surface waters in the Southern Ocean, North Pacific, and equatorial Pacific because of the much larger potential CDR per mass of iron, though nitrogen or phosphorus fertilization has been examined for some other, more nutrient-poor ecosystems (Boyd et al. 2007).

7. 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 (**Table 1**), 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 petagrams of carbon 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.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

S.C.D., W.H.W., and D.C.M. were supported by the US National Science Foundation through the Center for Chemical Currencies of a Microbial Planet (**https://ccomp-stc.org**; NSF award OCE-2019589) and the Palmer Long-Term Ecological Research project (National Science Foundation award OPP-2224611). J.G.F. was supported by the Pacific Northwest National Laboratory.

LITERATURE CITED

Albright R, Caldeira L, Hosfelt J, Kwiatkowski L, Maclaren JK, et al. 2016. Reversal of ocean acidification enhances net coral reef calcification. *Nature* 531:362–65. **https://doi.org/10.1038/nature17155**

Archer D, Eby M, Brovkin V, Ridgwell A, Cao L, et al. 2009. Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* 37:117–34. **https://doi.org/10.1146/annurev.earth.031208.100206**

Arcusa S, Sprenkle-Hyppolite S. 2022. Snapshot of the carbon dioxide removal certification and standards ecosystem (2021–2022). *Clim. Policy* 22:1319–32. **https://doi.org/10.1080/14693062.2022.2094308**

Aumont O, Bopp L. 2006. Globalizing results from ocean in situ iron fertilization studies. *Glob. Biogeochem. Cycles* 20:GB2017. **https://doi.org/10.1029/2005GB002591**

Bach LT, Ho DT, Boyd PW, Tyka MD. 2023. Toward a consensus framework to evaluate air-sea CO_2 equilibration for marine CO_2 removal. *Limnol. Oceanogr. Lett.* 8:685–91. **https://doi.org/10.1002/lol2.10330**

Balwada D, LaCasce JH, Speer KG, Ferrari R. 2021. Relative dispersion in the Antarctic Circumpolar Current. *J. Phys. Oceanogr.* 51:553–74. **https://doi.org/10.1175/JPO-D-19-0243.1**

Bar-On YM, Phillips R, Milo R. 2018. The biomass distribution on Earth. *PNAS* 115:6506–11. **https://doi.org/10.1073/pnas.1711842115**

Battaglia G, Steinacher M, Joos F. 2016. A probabilistic assessment of calcium carbonate export and dissolution in the modern ocean. *Biogeosciences* 13(9):2823–48. **https://doi.org/10.5194/bg-13-2823-2016**

Beerling DJ. 2017. Enhanced rock weathering: biological climate change mitigation with co-benefits for food security? *Biol. Lett.* 13:20170149. **https://doi.org/10.1098/rsbl.2017.0149**

Beerling DJ, Leake JR, Long SP, Scholes JD, Ton J, et al. 2018. Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* 4:138–47. **https://doi.org/10.1038/s41477-018-0108-y**

Berger M, Kwiatkowski L, Ho DT, Bopp L. 2023. Ocean dynamics and biological feedbacks limit the potential of macroalgae carbon dioxide removal. *Environ. Res. Lett.* 18:024039. **https://doi.org/10.1088/1748-9326/acb06e**

Berner RA. 1991. A model for atmospheric CO_2 over Phanerozoic time. *Am. J. Sci.* 291:339–76. **https://doi.org/10.2475/ajs.291.4.339**

Bertagni MB, Porporato A. 2022. The carbon-capture efficiency of natural water alkalinization: implications for enhanced weathering. *Sci. Total Environ.* 838:156524. **https://doi.org/10.1016/j.scitotenv.2022.156524**

Bianchi D, Carozza DA, Galbraith ED, Guiet J, DeVries T. 2021. Estimating global biomass and biogeochemical cycling of marine fish with and without fishing. *Sci. Adv.* 7:eabd7554. **https://doi.org/10.1126/sciadv.abd7554**

Bindoff NL, Cheung WWL, Kairo JG, Arístegui J, Guinder VA, et al. 2019. Changing ocean, marine ecosystems, and dependent communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, ed. H-O Pörtner, DC Roberts, V Masson-Delmotte, P Zhai, M Tignor, et al., pp. 447–587. Cambridge, UK: Cambridge Univ. Press. **https://doi.org/10.1017/9781009157964.007**

Blackford J, Romanak K, Huvenne VAI, Lichtschlag A, Strong JA, et al. 2021. Efficient marine environmental characterisation to support monitoring of geological CO_2 storage. *Int. J. Greenh. Gas Control* 109:103388. **https://doi.org/10.1016/j.ijggc.2021.103388**

Boyd PW, Jickells T, Law CS, Blain S, Boyle EA, et al. 2007. Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions. *Science* 315:612–17. **https://doi.org/10.1126/science.1131669**

Brantley SL, Kubicki JD, White AF, eds. 2008. *Kinetics of Water-Rock Interaction*. New York: Springer. **https://doi.org/10.1007/978-0-387-73563-4**

Buck HJ, Fuhrman JG, Morrow DR, Sanchez DL, Wang FM. 2020. Adaptation and carbon removal. *One Earth* 3:425–35. **https://doi.org/10.1016/j.oneear.2020.09.008**

Buesseler KO, Doney SC, Karl DM, Boyd PM, Caldeira K, et al. 2008. Ocean iron fertilization: moving forward in a sea of uncertainty. *Science* 319:162. **https://doi.org/10.1126/science.1154305**

Buschmann AH, Camus C, Infante J, Neori A, Israel Á, et al. 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *Eur. J. Phycol.* 52:391–406. **https://doi.org/10.1080/09670262.2017.1365175**

Bushinsky SM, Landschützer P, Rödenbeck C, Gray AR, Baker D, et al. 2019a. Reassessing Southern Ocean air-sea CO_2 flux estimates with the addition of biogeochemical float observations. *Glob. Biogeochem. Cycles* 33:1370–88. **https://doi.org/10.1029/2019GB006176**

Bushinsky SM, Takeshita Y, Williams NL. 2019b. Observing changes in ocean carbonate chemistry: our autonomous future. *Curr. Clim. Change Rep.* 5:207–20. **https://doi.org/10.1007/s40641-019-00129-8**

Cai W-J, Jiao N. 2022. Wastewater alkalinity addition as a novel approach for ocean negative carbon emissions. *Innovation* 3:100272. **https://doi.org/10.1016/j.xinn.2022.100272**

Canadell JG, Monteiro PMS, Costa MH, Cotrim da Cunha L, Cox PM, et al. 2021. Global carbon and other biogeochemical cycles and feedbacks. In *Climate Change 2021: The Physical Science Basis; Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. V Masson-Delmotte, P Zhai, A Pirani, SL Connors, C Péan, et al., pp. 673–816. Cambridge, UK: Cambridge Univ. Press. **https://doi.org/10.1017/9781009157896.007**

Caserini S, Pagano D, Campo F, Abbà A, De Marco S, et al. 2021. Potential of maritime transport for ocean liming and atmospheric CO_2 removal. *Front. Clim.* 3:575900. **https://www.frontiersin.org/articles/10.3389/fclim.2021.575900**

Christianson A, Cabre A, Bernal B, Baez SK, Leung S, et al. 2022. The promise of blue carbon climate solutions: where the science supports ocean-climate policy. *Front. Mar. Sci.* 9:851448. **https://doi.org/10.3389/fmars.2022.851448**

Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, et al. 2013. Carbon and other biogeochemical cycles. In *Climate Change 2013: The Physical Science Basis; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, et al., pp. 465–570. Cambridge, UK: Cambridge Univ. Press. **https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf**

Cooley SR, Klinsky S, Morrow DR, Satterfield T. 2023. Sociotechnical considerations about ocean carbon dioxide removal. *Annu. Rev. Mar. Sci.* 15:41–66. **https://doi.org/10.1146/annurev-marine-032122-113850**

Cooley SR, Schoeman D, Bopp L, Boyd P, Donner S, et al. 2022. Oceans and coastal ecosystems and their services. In *Climate Change 2022: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. H-O Pörtner, DC Roberts, M Tignor, ES Poloczanska, K Mintenbeck, et al., pp. 379–550. Cambridge, UK: Cambridge Univ. Press. **https://doi.org/10.1017/9781009325844.005**

Copernic. Mar. Environ. Monit. Serv. 2022. Global ocean gridded L4 sea surface heights and derived variables reprocessed 1993 ongoing. *Copernicus Marine Environment Monitoring Service*. **https://doi.org/10.48670/moi-00148**

Cornwall W. 2023. An alkaline solution. *Science* 382:988–92. **https://doi.org/10.1126/science.zn8487l**

Crooks S, Sutton-Grier AE, Troxler TG, Herold N, Bernal B, et al. 2018. Coastal wetland management as a contribution to the US National Greenhouse Gas Inventory. *Nat. Clim. Change* 8:1109–12. **https://doi.org/10.1038/s41558-018-0345-0**

DaJose L. 2023. Caltech start-ups capture CO_2 at sea. *Caltech Magazine*, May 15. **https://magazine.caltech.edu/post/carbon-capture-ocean-caltech-startups-calcarea-captura**

Dalsøren SB, Samset BH, Myhre G, Corbett JJ, Minjares R, et al. 2013. Environmental impacts of shipping in 2030 with a particular focus on the Arctic region. *Atmos. Chem. Phys.* 13:1941–55. **https://doi.org/10.5194/acp-13-1941-2013**

Daly A, Zannetti P. 2007. Air pollution modeling—an overview. In *Ambient Air Pollution*, ed. P Zannetti, D Al-Ajmi, S Al-Rashied, pp. 15–28. Damascus, Syria, and Reno, NV: Arab Sch. Sci. Technol. and EnviroComp Inst. **http://home.iitk.ac.in/~anubha/Modeling.pdf**

Davies PA, Yuan Q, De Richter R. 2018. Desalination as a negative emissions technology. *Environ. Sci. Water Res. Technol.* 4:839–50. **https://doi.org/10.1039/c7ew00502d**

DeVries T. 2014. The oceanic anthropogenic CO_2 sink: storage, air-sea fluxes, and transports over the industrial era. *Glob. Biogeochem. Cycles* 28:631–47. **https://doi.org/10.1002/2013GB004739**

DeVries T. 2022. The ocean carbon cycle. *Annu. Rev. Environ. Resour.* 47:317–41. **https://doi.org/10.1146/annurev-environ-120920-111307**

DeVries T, Holzer M, Primeau F. 2017. Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature* 542:215–18. **https://doi.org/10.1038/nature21068**

DeVries T, Yamamoto K, Wanninkhof R, Gruber N, Hauck J, et al. 2023. Magnitude, trends, and variability of the global ocean carbon sink from 1985–2018. *Glob. Biogeochem. Cycles* 37:e2023GB007780. **https://doi.org/10.1029/2023GB007780**

Digdaya IA, Sullivan I, Lin M, Han L, Cheng WH, et al. 2020. A direct coupled electrochemical system for capture and conversion of CO_2 from oceanwater. *Nat. Commun.* 11:4412. **https://doi.org/10.1038/s41467-020-18232-y**

Dobashi R, Ho DT. 2023. Air-sea gas exchange in a seagrass ecosystem—results from a $^3He/SF_6$ tracer release experiment. *Biogeosciences* 20:1075–87. **https://doi.org/10.5194/bg-20-1075-2023**

Doney SC, Busch DS, Cooley SR, Kroeker KJ. 2020. The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annu. Rev. Environ. Resour.* 45:83–112. **https://doi.org/10.1146/annurev-environ-012320-083019**

Doney SC, Fabry VJ, Feely RA, Kleypas JA. 2009. Ocean acidification: the other CO_2 problem. *Annu. Rev. Mar. Sci.* 1:169–92. **https://doi.org/10.1146/annurev.marine.010908.163834**

Doney SC, Mitchell KA, Henson SA, Cavan E, DeVries T, et al. 2024. Observational and numerical modeling constraints on the global ocean biological carbon pump. *Glob. Biogeochem. Cycles* 38:e2024GB008156. **https://doi.org/10.1029/2024GB008156**

Duarte CM, Losada IJ, Hendriks IE, Mazarrasa I, Marbà N. 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* 3:961–68. **https://doi.org/10.1038/nclimate1970**

Dutreuil S, Bopp L, Tagliabue A. 2009. Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability. *Biogeosciences* 6:901–12. **https://doi.org/10.5194/bg-6-901-2009**

Eisaman MD, Geilert S, Renforth P, Bastianini L, Campbell J, et al. 2023. Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In *Guide to Best Practices in Ocean Alkalinity Enhancement Research*, ed. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, et al., chap. 3. Göttingen, Ger.: Copernicus. **https://doi.org/10.5194/sp-2-oae2023-3-2023**

Eisaman MD, Rivest JLB, Karnitz SD, de Lannoy CF, Jose A, et al. 2018. Indirect ocean capture of atmospheric CO_2: part II. Understanding the cost of negative emissions. *Int. J. Greenh. Gas Control* 70:254–61. **https://doi.org/10.1016/j.ijggc.2018.02.020**

Eke J, Yusuf A, Giwa A, Sodiq A. 2020. The global status of desalination: an assessment of current desalination technologies, plants and capacity. *Desalination* 495:114633. **https://doi.org/10.1016/j.desal.2020.114633**

Emerson SR, Hamme RC. 2022. *Chemical Oceanography: Element Fluxes in the Sea*. Cambridge, UK: Cambridge Univ. Press

Feehan CJ, Filbee-Dexter K, Wernberg T. 2021. Embrace kelp forests in the coming decade. *Science* 373:863. **https://doi.org/10.1126/science.abl3984**

Feng EY, Keller DP, Koeve W, Oschlies A. 2016. Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification? *Environ. Res. Lett.* 11:074008. **https://doi.org/10.1088/1748-9326/11/7/074008**

Fennel K, Long MC, Algar C, Carter B, Keller D, et al. 2023. Modelling considerations for research on ocean alkalinity enhancement (OAE). In *Guide to Best Practices in Ocean Alkalinity Enhancement Research*, ed. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, et al., chap. 9. Göttingen, Ger.: Copernicus. **https://doi.org/10.5194/sp-2-oae2023-9-2023**

Fennel K, Mattern JP, Doney SC, Bopp L, Moore AM, et al. 2022. Ocean biogeochemical modelling. *Nat. Rev. Methods Primers.* 2:76. **https://doi.org/10.1038/s43586-022-00154-2**

Foteinis S, Campbell JS, Renforth P. 2023. Life cycle assessment of coastal enhanced weathering for carbon dioxide removal from air. *Environ. Sci. Technol.* 57:6169–78. **https://doi.org/10.1021/acs.est.2c08633**

Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Gregor L, et al. 2022. Global carbon budget 2022. *Earth Syst. Sci. Data* 14:4811–900. **https://doi.org/10.5194/essd-14-4811-2022**

Froehlich HE, Afflerbach JC, Frazier M, Halpern BS. 2019. Blue growth potential to mitigate climate change through seaweed offsetting. *Curr. Biol.* 29:3087–93. **https://doi.org/10.1016/j.cub.2019.07.041**

Fuhrman JG, Bergero C, Weber M, Monteith S, Wang FM, et al. 2023. Diverse carbon dioxide removal approaches could reduce impacts on the energy-water-land system. *Nat. Clim. Change* 13:341–50. **https://doi.org/10.1038/s41558-023-01604-9**

Fuhrman JG, McJeon H, Doney SC, Shobe W, Clarens AF. 2019. From zero to hero? Why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim.* 1:11. **https://doi.org/10.3389/fclim.2019.00011**

Fuhrman JG, McJeon H, Patel P, Doney SC, Shobe WM, Clarens AF. 2020. Food-energy-water implications of negative emission technologies in a +1.5°C future. *Nat. Clim. Change* 10:920–27. **https://doi.org/10.1038/s41558-020-0876-z**

Gattuso J-P, Williamson P, Duarte CM, Magnan AK. 2021. The potential for ocean-based climate action: negative emissions technologies and beyond. *Front. Clim.* 2:37. **https://doi.org/10.3389/fclim.2020.575716**

GESAMP (Joint Group Experts Sci. Asp. Mar. Environ. Prot.). 2019. *High level review of a wide range of proposed marine geoengineering techniques*. Rep. Stud. 98, *Int. Marit. Organ.*, London. **http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques**

Goll DS, Ciais P, Amann T, Buermann W, Chang J, et al. 2021. Potential CO_2 removal from enhanced weathering by ecosystem responses to powdered rock. *Nat. Geosci.* 14:545–49. **https://doi.org/10.1038/s41561-021-00798-x**

Grorud-Colvert K, Sullivan-Stack J, Roberts C, Constant V, Lubchenco J, et al. 2021. The MPA Guide: a framework to achieve global goals for the ocean. *Science* 373:eabf0861. **https://www.science.org/doi/10.1126/science.abf0861**

Gruber N, Bakker DCE, DeVries T, Gregor L, Hauck J, et al. 2023. Trends and variability in the ocean carbon sink. *Nat. Rev. Earth Environ.* 4:119–34. **https://doi.org/10.1038/s43017-022-00381-x**

Grubler A, Wilson C, Nemet G. 2016. Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions. *Energy Res. Soc. Sci.* 22:18–25. **https://doi.org/10.1016/j.erss.2016.08.015**

Hangx SJT, Spiers CJ. 2009. Coastal spreading of olivine to control atmospheric CO_2 concentrations: a critical analysis of viability. *Int. J. Greenh. Gas Control* 3:757–67. **https://doi.org/10.1016/j.ijggc.2009.07.001**

Hansell DA, Carlson CA, Repeta DJ, Schlitzer R. 2009. Dissolved organic matter in the ocean: new insights stimulated by a controversy. *Oceanography* 22(4):52–61. **https://doi.org/10.5670/oceanog.2009.109**

Hansen PJ, Lundholm N, Rost B. 2007. Growth limitation in marine red-tide dinoflagellates: effects of pH versus inorganic carbon availability. *Mar. Ecol. Prog. Ser.* 334:63–71. **https://doi.org/10.3354/meps334063**

Hartin CA, Patel P, Schwarber A, Link RP, Bond-Lamberty BP. 2015. A simple object-oriented and open-source model for scientific and policy analyses of the global climate system—Hector v1.0. *Geosci. Model Dev.* 8:939–55. **https://doi.org/10.5194/gmd-8-939-2015**

Hartmann J, Suitner N, Lim C, Schneider J, Marín-Samper L, et al. 2023. Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches—consequences for durability of CO_2 storage. *Biogeosciences* 20:781–802. **https://doi.org/10.5194/bg-20-781-2023**

Hartmann J, West AJ, Renforth P, Köhler P, De La Rocha CL, et al. 2013. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* 51:113–49. **https://doi.org/10.1002/ROG.20004**

Harvey LDD. 2008. Mitigating the atmospheric CO_2 increase and ocean acidification by adding limestone powder to upwelling regions. *J. Geophys. Res. Oceans* 113:C04028. **https://doi.org/10.1029/2007JC004373**

Hauck J, Gregor L, Nissen C, Patara L, Hague M, et al. 2023. The Southern Ocean carbon cycle 1985–2018: mean, seasonal cycle, trends, and storage. *Glob. Biogeochem. Cycles* 37:e2023GB007848. **https://doi.org/10.1029/2023GB007848**

Ho DT, Bopp L, Palter JB, Long MC, Boyd PW, et al. 2023. Monitoring, reporting, and verification for ocean alkalinity enhancement. In *Guide to Best Practices in Ocean Alkalinity Enhancement Research*, ed. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, et al., chap. 12. Göttingen, Ger.: Copernicus. **https://doi.org/10.5194/sp-2-oae2023-12-2023**

Ho DT, Wanninkhof R, Schlosser P, Ullman DS, Hebert D, Sullivan KF. 2011. Toward a universal relationship between wind speed and gas exchange: gas transfer velocities measured with $^3He/SF_6$ during the Southern Ocean Gas Exchange Experiment. *J. Geophys. Res.* 116:C00F04. **https://doi.org/10.1029/2010JC006854**

Holmquist JR, Windham-Myers L, Bliss N, Crooks S, Morris JT, et al. 2018. Accuracy and precision of tidal wetland soil carbon mapping in the conterminous United States. *Sci. Rep.* 8:9478. **https://doi.org/10.1038/s41598-018-26948-7**

Holz C, Siegel LS, Johnston E, Jones AP, Sterman J. 2018. Ratcheting ambition to limit warming to 1.5°C-trade-offs between emission reductions and carbon dioxide removal. *Environ. Res. Lett.* 13:064028. **https://doi.org/10.1088/1748-9326/aac0c1**

IPCC (Intergov. Panel Clim. Change). 2018. Summary for policymakers. In *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, ed. V Masson-Delmotte, P Zhai, H-O Pörtner, D Roberts, J Skea, et al., pp. 3–24. Cambridge, UK: Cambridge Univ. Press. **https://doi.org/10.1017/9781009157940.001**

IPCC (Intergov. Panel Clim. Change). 2023. Summary for policymakers. In *Climate Change 2023: Synthesis Report; Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. H Lee, J Romero, pp. 1–34. Geneva: IPCC. **https://doi.org/10.59327/IPCC/AR6-9789291691647.001**

Jiang HB, Hutchins DA, Zhang HR, Feng YY, Zhang RF, et al. 2024. Complexities of regulating climate by promoting marine primary production with ocean iron fertilization. *Earth-Sci. Rev.* 249:104675. **https://doi.org/10.1016/j.earscirev.2024.104675**

Jiang L-Q, Feely RA, Carter BR, Greeley DJ, Gledhill DK, Arzayus KM. 2015. Climatological distribution of aragonite saturation state in the global oceans. *Glob. Biogeochem. Cycles* 29:1656–73. **https://doi.org/10.1002/2015GB005198**

Jin X, Gruber N, Frenzel H, Doney SC, McWilliams JC. 2008. The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump. *Biogeosciences* 5:385–406. **https://doi.org/10.5194/bg-5-385-2008**

Jürchott M, Oschlies A, Koeve W. 2023. Artificial upwelling—a refined narrative. *Geophys. Res. Lett.* 50:e2022GL101870. **https://doi.org/10.1029/2022GL101870**

Kantola IB, Masters MD, Beerling DJ, Long SP, DeLucia EH. 2017. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biol. Lett.* 13:20160714. **https://doi.org/10.1098/rsbl.2016.0714**

Kantzas EP, Val Martin M, Lomas MR, Eufrasio RM, Renforth P, et al. 2022. Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. *Nat. Geosci.* 15:382–89. **https://doi.org/10.1038/s41561-022-00925-2**

Kaplan MB, Solomon S. 2016. A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. *Mar. Policy* 73:119–21. **https://doi.org/10.1016/j.marpol.2016.07.024**

Khatiwala S, Tanhua T, Mikaloff Fletcher S, Gerber M, Doney SC, et al. 2013. Global ocean storage of anthropogenic carbon. *Biogeosciences* 10:2169–91. **https://doi.org/10.5194/bg-10-2169-2013**

Kheshgi HS. 1995. Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy* 20:915–22. **https://doi.org/10.1016/0360-5442(95)00035-F**

Kirwan ML, Megonigal JP, Noyce GL, Smith AJ. 2023. Geomorphic and ecological constraints on the coastal carbon sink. *Nat. Rev. Earth Environ.* 4:393–406. **https://doi.org/10.1038/s43017-023-00429-6**

Koweek DA. 2022. Expected limits on the potential for carbon dioxide removal from artificial upwelling. *Front. Mar. Sci.* 9:841894. **https://doi.org/10.3389/fmars.2022.841894**

Krause-Jensen D, Duarte CM. 2016. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* 9:737–42. **https://doi.org/10.1038/ngeo2790**

La Plante EC, Simonetti DA, Wang J, Al-Turki A, Chen X, et al. 2021. Saline water-based mineralization pathway for gigatonne-scale CO_2 management. *ACS Sustain. Chem. Eng.* 9:1073–89. **https://doi.org/10.1021/acssuschemeng.0c08561**

Lane J, Greig C, Garnett A. 2021. Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nat. Clim. Change* 11:925–36. **https://doi.org/10.1038/s41558-021-01175-7**

Macreadie PI, Costa MDP, Atwood TB, Friess DA, Kelleway JJ, et al. 2021. Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* 2:826–39. **https://doi.org/10.1038/s43017-021-00224-1**

Mahadevan A. 2016. The impact of submesoscale physics on primary productivity of plankton. *Annu. Rev. Mar. Sci.* 8:161–84. **https://doi.org/10.1146/annurev-marine-010814-015912**

Malhotra A, Schmidt TS. 2020. Accelerating low-carbon innovation. *Joule* 4:2259–67. **https://doi.org/10.1016/j.joule.2020.09.004**

Marinov I, Gnanadesikan A, Sarmiento JL, Toggweiler JR, Follows M, Mignone BK. 2008. Impact of oceanic circulation on biological carbon storage in the ocean and atmospheric $p\mathrm{CO}_2$. *Glob. Biogeochem. Cycles* 22:GB3007. **https://doi.org/10.1029/2007GB002958**

May C, Crimmins AR, Cooley SR, Fleishman E, Grossman EE, et al. 2023. Focus on blue carbon. In *Fifth National Climate Assessment*, ed. AR Crimmins, CW Avery, DR Easterling, KE Kunkel, BC Stewart, TK Maycock, chap. F5. Washington, DC: US Glob. Change. Res. Program. **https://doi.org/10.7930/NCA5.2023.F5**

McClimans TA, Handå A, Fredheim A, Lien E, Reitan KI. 2010. Controlled artificial upwelling in a fjord to stimulate non-toxic algae. *Aquac. Eng.* 42:140–47. **https://doi.org/10.1016/j.aquaeng.2010.02.002**

McKee DC, Doney SC, Della Penna A, Boss ES, Gaube P, et al. 2022. Lagrangian and Eulerian time and length scales of mesoscale ocean chlorophyll from Bio-Argo floats and satellites. *Biogeosciences* 19:5927–52. **https://doi.org/10.5194/bg-19-5927-2022**

McLeod E, Chmura GL, Bouillon S, Salm R, Björk M, et al. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Front. Ecol. Environ.* 9:552–60. **https://doi.org/10.1890/110004**

McWilliams JC. 2016. Submesoscale currents in the ocean. *Proc. R. Soc. A* 472:20160117. **https://doi.org/10.1098/rspa.2016.0117**

Meysman FJR, Montserrat F. 2017. Negative CO_2 emissions via enhanced silicate weathering in coastal environments. *Biol. Lett.* 13:20160905. **https://doi.org/10.1098/rsbl.2016.0905**

Millero FJ. 2007. The marine inorganic carbon cycle. *Chem. Rev.* 107:308–41. **https://doi.org/10.1021/cr0503557**

Muirhead JR, Minton MS, Miller WA, Ruiz GM. 2015. Projected effects of the Panama Canal expansion on shipping traffic and biological invasions. *Divers. Distrib.* 21:75–87. **https://doi.org/10.1111/ddi.12260**

NASEM (Natl. Acad. Sci. Eng. Med.). 2019. *Negative emissions technologies and reliable sequestration: a research agenda*. Rep., NASEM, Washington, DC. **https://doi.org/10.17226/25259**

NASEM (Natl. Acad. Sci. Eng. Med.). 2022. *A research strategy for ocean-based carbon dioxide removal and sequestration*. Rep., NASEM, Washington, DC. **https://doi.org/10.17226/26278**

Nowicki M, DeVries T, Siegel DA. 2022. Quantifying the carbon export and sequestration pathways of the ocean's biological carbon pump. *Glob. Biogeochem. Cycles* 36:e2021GB007083. **https://doi.org/10.1029/2021GB007083**

Oreska MPJ, McGlathery KJ, Aoki LR, Berger AC, Berg P, Mullins L. 2020. The greenhouse gas offset potential from seagrass restoration. *Sci. Rep.* 10:7325. **https://doi.org/10.1038/s41598-020-64094-1**

Palter JB, Cross J, Long MC, Rafter PA, Reimers CE. 2023. The science we need to assess marine carbon dioxide removal. *Eos* 104. **https://doi.org/10.1029/2023EO230214**

Pan Y, Fan W, Zhang D, Chen J, Huang H, et al. 2016. Research progress in artificial upwelling and its potential environmental effects. *Sci. China Earth Sci.* 59:236–48. **https://doi.org/10.1007/s11430-015-5195-2**

Patterson BD, Mo F, Borgschulte A, Hillestad M, Joos F, et al. 2019. Renewable CO_2 recycling and synthetic fuel production in a marine environment. *PNAS* 116:12212–19. **https://doi.org/10.1073/PNAS.1902335116**

Queirós AM, Stephens N, Widdicombe S, Tait K, McCoy SJ, et al. 2019. Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. *Ecol. Monogr.* 89:e01366. **https://doi.org/10.1002/ecm.1366**

Rau GH, Caldeira K. 1999. Enhanced carbonate dissolution: a means of sequestering waste CO_2 as ocean bicarbonate. *Energy Convers. Manag.* 40:1803–13. **https://doi.org/10.1016/S0196-8904(99)00071-0**

Rau GH, Knauss KG, Langer WH, Caldeira K. 2007. Reducing energy-related CO_2 emissions using accelerated weathering of limestone. *Energy* 32:1471–77. **https://doi.org/10.1016/j.energy.2006.10.011**

Regnier P, Resplandy L, Najjar RG, Ciais P. 2022. The land-to-ocean loops of the global carbon cycle. *Nature* 603:401–10. **https://doi.org/10.1038/s41586-021-04339-9**

Renforth P. 2019. The negative emission potential of alkaline materials. *Nat. Commun.* 10:1401. **https://doi.org/10.1038/s41467-019-09475-5**

Renforth P, Henderson G. 2017. Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* 55:636–74. **https://doi.org/10.1002/2016RG000533**

Resplandy L, Hogikyan A, Bange HW, Bianchi D, Weber T, et al. 2024. A synthesis of global coastal ocean greenhouse gas fluxes. *Glob. Biogeochem. Cycles* 38:e2023GB007803. **https://doi.org/10.1029/2023GB007803**

Rimstidt JD, Brantley SL, Olsen AA. 2012. Systematic review of forsterite dissolution rate data. *Geochim. Cosmochim. Acta* 99:159–78. **https://doi.org/10.1016/j.gca.2012.09.019**

Ross F, Tarbuck P, Macreadie PI. 2022. Seaweed afforestation at large-scales exclusively for carbon sequestration: critical assessment of risks, viability and the state of knowledge. *Front. Mar. Sci.* 9:1015612. **https://doi.org/10.3389/fmars.2022.1015612**

Schindler Murray L, Milligan B, Ashford OS, Bonotto E, Cifuentes-Jara M, et al. 2023. *The Blue Carbon Handbook: blue carbon as a nature-based solution for climate action and sustainable development*. Rep., High Level Panel Sustain. Ocean Econ., London. **https://oceanpanel.org/publication/blue-carbon**

Schmitz OJ, Wilmers CC, Leroux SJ, Doughty CE, Atwood TB, et al. 2018. Animals and the zoogeochemistry of the carbon cycle. *Science* 362:eaar3213. **https://doi.org/10.1126/science.aar3213**

Schuiling RD, Krijgsman P. 2006. Enhanced weathering: an effective and cheap tool to sequester CO_2. *Clim. Change* 74:349–54. **https://doi.org/10.1007/s10584-005-3485-y**

Schulz KG, Bach LT, Dickson AG. 2023. Seawater carbonate chemistry considerations for ocean alkalinity enhancement research: theory, measurements, and calculations. In *Guide to Best Practices in Ocean Alkalinity Enhancement Research*, ed. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, et al., chap. 2. Göttingen, Ger.: Copernicus. **https://doi.org/10.5194/sp-2-oae2023-2-2023**

Service RF. 2024. Startups aim to curb climate change by pulling carbon dioxide from the ocean—not the air. *Science* 383:1400–1. **https://doi.org/10.1126/science.ziiddcx**

Sharma R, Swearer SE, Morris RL, Strain EMA. 2021. Testing the efficacy of sea urchin exclusion methods for restoring kelp. *Mar. Environ. Res.* 170:105439. **https://doi.org/10.1016/j.marenvres.2021.105439**

Sharmila GV, Kumar DM, Pugazhendi A, Bajhaiya AK, Gugulothu P, Banu JR. 2021. Biofuel production from macroalgae: present scenario and future scope. *Bioengineered* 12:9216–38. **https://doi.org/10.1080/21655979.2021.1996019**

Siegel DA, DeVries T, Doney SC, Bell T. 2021. Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environ. Res. Lett.* 16:104003. **https://doi.org/10.1088/1748-9326/ac0be0**

Sloyan BM, Wanninkhof R, Kramp M, Johnson GC, Talley LD, et al. 2019. The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP): a platform for integrated multidisciplinary ocean science. *Front. Mar. Sci.* 6:445. **https://doi.org/10.3389/fmars.2019.00445**

Strefler J, Amann T, Bauer N, Kriegler E, Hartmann J. 2018. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* 13:034010. **https://doi.org/10.1088/1748-9326/AAA9C4**

Strefler J, Bauer N, Humpenöder F, Klein D, Popp A, Kriegler E. 2021. Carbon dioxide removal technologies are not born equal. *Environ. Res. Lett.* 16:074021. **https://doi.org/10.1088/1748-9326/ac0a11**

Strong AL, Cullen JJ, Chisholm SW. 2009. Ocean fertilization: science, policy, and commerce. *Oceanography* 22(3):236–61. **https://doi.org/10.5670/oceanog.2009.83**

Taylor LL, Quirk J, Thorley RMS, Kharecha PA, Hansen J, et al. 2016. Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Change* 6:402–6. **https://doi.org/10.1038/nclimate2882**

Tilbrook B, Jewett EB, DeGrandpre MD, Hernandez-Ayon JM, Feely RA, et al. 2019. An enhanced ocean acidification observing network: from people to technology to data synthesis and information exchange. *Front. Mar. Sci.* 6:337. **https://doi.org/10.3389/fmars.2019.00337**

Torres O, Kwiatkowski L, Sutton AJ, Dorey N, Orr JC. 2021. Characterizing mean and extreme diurnal variability of ocean CO_2 system variables across marine environments. *Geophys. Res. Lett.* 48:e2020GL090228. **https://doi.org/10.1029/2020GL090228**

USGS (US Geol. Surv.). 2021. *Mineral commodity summaries 2021*. Rep., USGS, Reston, VA. **https://doi.org/10.3133/mcs2021**

van der Heijden LH, Kamenos NA. 2015. Reviews and syntheses: calculating the global contribution of coralline algae to total carbon burial. *Biogeosciences* 12:6429–41. **https://doi.org/10.5194/bg-12-6429-2015**

Wanninkhof R, Pickers PA, Omar AM, Sutton A, Murata A, et al. 2019. A surface ocean CO_2 reference network, SOCONET and associated marine boundary layer CO_2 measurements. *Front. Mar. Sci.* 6:400. **https://doi.org/10.3389/fmars.2019.00400**

Webb R. 2021. *The law of enhanced weathering for carbon dioxide removal: volume 2—legal issues associated with materials sourcing*. Pap., Sabin Cent. Clim. Change Law, Columbia Law Sch., New York. **https://scholarship.law.columbia.edu/sabin_climate_change/40**

White A, Björkman K, Grabowski E, Letelier R, Poulos S, et al. 2010. An open ocean trial of controlled upwelling using wave pump technology. *J. Atmos. Ocean. Technol.* 27:385–96. **https://doi.org/10.1175/2009JTECHO679.1**

Willauer HD, DiMascio F, Hardy DR, Lewis MK, Williams FW. 2011. Development of an electrochemical acidification cell for the recovery of CO_2 and H_2 from seawater. *Ind. Eng. Chem. Res.* 50:9876–82. **https://doi.org/10.1021/ie2008136**

Williamson P, Gattuso J. 2022. Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Front. Clim.* 4:853666. **https://doi.org/10.3389/fclim.2022.853666**

Wolf-Gladrow DA, Zeebe RE, Klaas C, Körtzinger A, Dickson AG. 2007. Total alkalinity: the explicit conservative expression and its application to biogeochemical processes. *Mar. Chem.* 106:287–300. **https://doi.org/10.1016/j.marchem.2007.01.006**

Wolske KS, Raimi KT, Campbell-Arvai V, Hart PS. 2019. Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions. *Clim. Change* 152:345–61. **https://doi.org/10.1007/s10584-019-02375-z**

Xi F, Davis SJ, Ciais P, Crawford-Brown D, Guan D, et al. 2016. Substantial global carbon uptake by cement carbonation. *Nat. Geosci.* 9:880–83. **https://doi.org/10.1038/ngeo2840**

Yoon JE, Yoo KC, Macdonald AM, Yoon HI, Park KT, et al. 2018. Reviews and syntheses: ocean iron fertilization experiments—past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project. *Biogeosciences* 15:5847–89. **https://doi.org/10.5194/bg-15-5847-2018**