Ideas and Perspectives: A framework for understanding efficiency losses of Ocean Alkalinity Enhancement

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Abstract

Ocean alkalinity enhancement (OAE) is a proposed carbon dioxide removal (CDR) approach in which seawater alkalinity is increased to facilitate both the enhanced uptake of atmospheric CO_2 and long-term storage in the ocean's dissolved inorganic carbon pool. Carbonate system thermodynamics provide a stoichiometric upper bound on the amount of CO_2 that can be taken up per unit of alkalinity added, but realized uptake can be lower due to dynamic physical and (bio)geochemical processes that evolve over time. This Perspective presents a structured framework for understanding these potential efficiency losses. We identify loss pathways across four categories: incomplete mineral dissolution, loss of alkalinity to solid phases, incomplete air–sea exchange, and indirect impacts on ocean biogeochemical cycles. The potential significance of each loss varies across OAE approaches and across spatial and temporal scales. We highlight that substantial knowledge gaps persist across all of these processes, and we suggest targeted research priorities to improve fundamental understanding and reduce uncertainty. By providing a common structure and definitions, this framework aims to support coordination across oceanographic disciplines and to improve assessments of OAE efficiency at both the project and global scale.

Introduction

Ocean alkalinity enhancement (OAE) has been proposed as a method for carbon dioxide removal (CDR), given potential advantages in cost and scalability by using the global ocean as a CO_2 sorbent and storage reservoir. OAE works by increasing seawater alkalinity, defined as the excess of bases over acids, mimicking the alkalinity enhancement resulting from natural rock weathering. This increase in alkalinity shifts the speciation of dissolved inorganic carbon (DIC) away from CO_2, creating a deficit with respect to atmospheric CO_2. (See Dickson, 2010 and Zeebe and Wolf-Gladrow, 2001a for detailed explanations of seawater carbonate chemistry.) For seawater in contact with the atmosphere, atmospheric CO_2 will consequently be absorbed to restore gas equilibrium. Or, for seawater with naturally high pCO_2, alkalinity enhancement will lead to reduced CO_2 outgassing. Considering carbonate system thermodynamics, between 0.77-0.96 mol of CO_2 may be taken up per mol of alkalinity added to seawater, with variation driven largely by temperature; the global average is approximately 0.84 (Schulz et al., 2023).

Because OAE operates in an open system—where both alkalinity and CO_2 concentrations evolve over time within a dynamic environment—the actual CO_2 uptake can be lower than the

thermodynamic limit. The maximum, thermodynamically-defined uptake can only be achieved if added alkaline material fully dissolves, and if the subsequent alkalinity is not consumed by environmental processes, remains in surface waters long enough to fully equilibrate with atmospheric CO_2, and does not alter other biogeochemical processes that influence carbon cycling. How much atmospheric CO_2 is ultimately removed per unit alkalinity added, and over what timescale, is a central question defining the *efficiency* of OAE interventions.

OAE efficiency is typically expressed as:

$$\eta(t) = \Delta DIC(t)/\Delta Alk \quad \text{Equation 1}$$

where ΔAlk is the increase in seawater alkalinity, and ΔDIC is the corresponding increase in dissolved inorganic carbon (DIC) resulting from atmospheric CO_2 uptake (He and Tyka, 2023). Because equilibration with atmospheric CO_2 is not instantaneous, η inherently evolves over time, and thus defined at a specific timepoint following alkalinity enhancement.

In this context, η is a measure of *gross* CDR. This metric differs from broader discussions of CDR efficiency, which assess *net* CDR after consideration of lifecycle emissions. The emphasis on gross CDR in OAE reflects the fact that the full amount of atmospheric CO_2 uptake following alkalinity enhancement cannot be measured directly, and -- as a result -- considerable research is focused on developing models relating CO_2 uptake (ΔDIC in Equation 1) to a known amount of added alkalinity (Fennel, 2026). While Equation 1 provides a common mathematical framework for describing OAE efficiency, it does not specify which processes driving ΔDIC (or ΔAlk) should be included. For example, several recent studies have pointed out that η changes when atmospheric CO_2 evolution and Earth-system feedbacks are included (Schwinger et al, 2024; Jeltsch-thommes, 2024; Tyka, 2025; Yamamoto; Grosselindeman, 2026). While these studies are valuable for assessing long-term CDR efficacy, they address different questions than process-level considerations relevant on more immediate timescales. More generally, most assessments of OAE efficiency in ocean models consider only physical controls on CO_2 uptake, and assume that alkalinity is conserved, i.e. that ΔAlk does not vary with time and is equal to the alkalinity added to the ocean (Anderson et al., 2026; Burt et al., 2021; He and Tyka, 2023; Nagwekar et al., 2026; Wang et al., 2023; Zhou et al., 2025a). Here, we consider a broader suite of physical and bio(geochemical) processes that mediate both ΔDIC and ΔAlk. Although many of these processes are the focus of active research, they have not yet been organized into a common framework for understanding overall OAE efficiency.

In this Perspective, we focus on the processes that potentially reduce η following the addition of alkalinizing agents to the ocean. We define an efficiency loss as any reduction in CO_2 uptake compared to the thermodynamic maximum predicted for a given alkalinity enhancement, or—for mineral applications—the *expected* alkalinity enhancement from mineral dissolution. (We note that alkalinity is, by definition, dissolved, i.e., a property of solutions; solid, alkaline feedstocks may contain embodied alkalinity, but do not constitute alkalinity until they dissolve.) We identify nine loss pathways, grouped into four categories: incomplete mineral dissolution,

alkalinity loss to solids, incomplete air–sea equilibration, and indirect impacts on ocean biogeochemical cycles that affect CO_2 uptake (Figure 1).

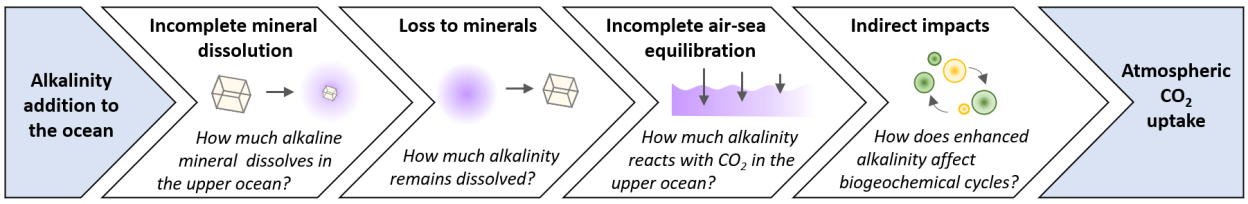


Figure 1. Four categories of loss processes that may reduce OAE efficiency, i.e., the amount of atmospheric CO_2 uptake per unit of alkalinity added to the ocean. Losses can be considered in sequential order, however in practice they are often interactive.

A consistent framework for describing efficiency losses is important for two reasons. First, quantifying CDR from OAE ultimately requires models, which must accurately represent the suite of thermodynamic, physical, and biogeochemical processes that drive or limit CO_2 uptake. Modeling is necessary both because of measurement challenges (e.g., rapid dilution and low signal to noise) and because OAE interventions must be compared against a counterfactual scenario, which by definition must be modeled (Fennel, 2026). A clear framework for efficiency losses identifies which processes should be included for a given OAE deployment, and also helps ensure that assumptions are comparable across models. Without such a framework, incomplete accounting of losses or optimistic assumptions can lead to systematic overestimation of CO_2 uptake. At the global scale, this risks overestimating OAE's potential contribution to global CDR goals; and at the project level, it may lead to over-crediting. Second, a common framework helps coordinate scientific research across the experimental, observational, and modeling communities. A common understanding of potential losses ensures that experiments and models address the same underlying questions and evaluate efficiency with consistent assumptions.

Because efficiency losses differ across deployment strategies, it is useful to briefly outline the various approaches to OAE. OAE deployments can be organized along two primary dimensions: the source of alkalinity and the method of delivery to the ocean. Sources of alkalinity can be grouped into three functional categories, based on mineral dissolution kinetics: slower-dissolving rocks and minerals that dissolve in typical seawater conditions on the scale of days to years (e.g., olivine, limestone, and some industrial waste products like steel slag); faster-dissolving rocks and minerals that dissolve on the scale of seconds to days (e.g., Ca- Mg- and potentially Na- oxides and hydroxides, and ikaite); and direct application of alkalinity, which can be produced electrochemically or via pre-dissolution of alkaline minerals (e.g., in reactors). For solid feedstocks, some alkalinity sources—steel slag for example—may be a mixture of both faster and slower-dissolving minerals (Moras et al., 2024a). The feedstock used dictates how alkalinity can be delivered to seawater. Possible delivery methods include: coastal seafloor placement (for slower-dissolving rocks and minerals); coastal surface discharge (for dissolved alkalinity or

slurries of faster-dissolving minerals); and offshore surface discharge (e.g., dispersal from ships, likely only for faster-dissolving minerals).

Another important consideration across OAE methods is whether alkalinity is equilibrated or unequilibrated with respect to atmospheric CO_2. *Equilibrated* alkalinity has already "achieved" CDR, resulting in seawater with enhanced DIC (and circum-neutral pH), whereas seawater with *unequilibrated* alkalinity has ambient DIC (and elevated pH). For most OAE approaches, alkalinity is initially unequilibrated at the point of delivery to the ocean, and subsequently equilibrates gradually over time, given atmospheric exposure across the surface ocean. Applications using (dissolved) alkalinity directly may deploy either equilibrated or unequilibrated alkalinity; the latter use engineered systems to equilibrate seawater with atmospheric CO_2 uptake *prior* to addition to the ocean. Each deployment scenario – considering feedstock, method of delivery to the ocean, and level of equilibration – imposes different chemical and physical changes to the ocean, and therefore face different susceptibilities to potential efficiency losses.

The following sections describe each efficiency loss pathway, highlighting the physical and (bio)geochemical mechanisms that reduce expected CO_2 uptake, the spatial and temporal trends over which they operate, and key research priorities for constraining their importance (Table 1). Because the magnitude of each loss depends on deployment strategy and environmental conditions -- and also because research is ongoing -- we do not attempt to constrain rates of individual loss factors here. Rather, our objective is to provide a common framework for understanding how these processes unfold and interact to influence OAE efficiency.

Table 1. Four categories of efficiency loss pathways. Specific loss mechanisms vary by feedstock and deployment type, as well as environmental parameters.

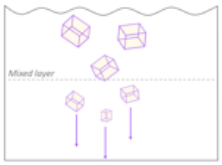
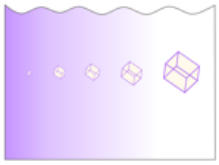
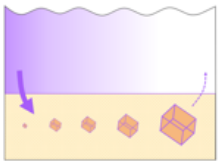
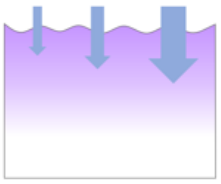
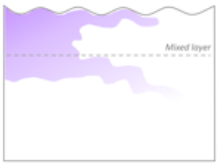
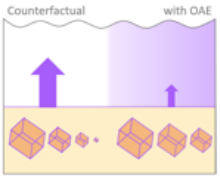
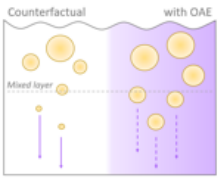
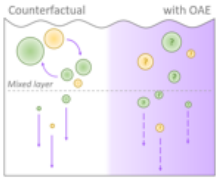
Category	Sub-category	Description	Most relevant feedstock and deployment types	Relevant parameters
Incomplete mineral dissolution	**Mineral dissolution kinetics** 	Feedstock dissolves more slowly than anticipated, and/or incompletely.	Rock and mineral feedstocks in all deployment methods	Feedstock mineralogy; particle size distribution and reactive surface area; seawater Ω near the reactive surface area, and other chemical factors; seawater temperature; sinking or advection rate
	Particle sinking 	Feedstock and/or secondary CaCO3 or other autochthonous precipitates sink out of mixed layer before fully dissolving.	Faster-dissolving feedstocks added to rivers, coastal water, or the open ocean via ships, or floor environments with (re)suspended sediments	Particle density, size distribution, and reactive surface area; mineral dissolution rate as affected by water advection close to the reactive surface area; turbulence; aggregation
Alkalinity loss to minerals	**Water column** 	Secondary minerals or solid phases form out of solution in the water column and may not redissolve.	Dissolved alkalinity and faster-dissolving feedstocks in all deployment methods	Feedstock mineralogy, particle size distribution and reactive surface area; seawater Ω (bulk and near-surface) and other chemical factors; temperature; suspended solid quality and density (nucleation sites)
	Sediments 	Alkalinity is lost within sediments via mineral precipitation, clay formation, and/or ion exchange.	All alkalinity types in coastal deployments	Porewater Ω; sediment characteristics (mineralogy, permeability, grain size distribution, etc.); porewater exchange rates; biological activity (e.g., bioturbation)

Table 1. (Continued)

Incomplete air-sea equilibration	**Kinetics of air-sea exchange** 	Air-sea CO_2 equilibration takes time. Early timepoints have lower apparent efficiency than later timepoints.	All (unequilibrated) alkalinity types, all deployment methods	Physical factors controlling air-sea gas exchange, including factors affecting ΔpCO_2 (e.g., mixing)
	Subduction and diapycnal mixing 	Complete air-sea equilibration may take years; during this time, unequilibrated alkalinity may subduct or mix into the ocean interior.	All alkalinity types, all deployment methods	Downwelling; diapycnal mixing; air-sea exchange rate
Indirect impacts	**Decreased sediment alkalinity flux** 	Dissolution of carbonate minerals in sediments is suppressed by elevated Ω, decreasing benthic flux of alkalinity to the water column.	All alkalinity types in coastal deployments (near-term); potentially relevant for all deployment methods (long-term)	Porewater Ω; sediment characteristics (mineralogy, permeability, grain size distribution, etc.); porewater exchange rates
	Increased carbonate counterpump 	Export of carbonate minerals from the surface ocean increases due to enhanced production and/or reduced dissolution.	All alkalinity types, all deployment methods	Seawater Ω; plankton community
	Altered organic carbon cycling 	Export of organic carbon from the surface ocean is altered due to changes in productivity, respiration, and/or ballasting.	All alkalinity types, all deployment methods	Seawater Ω; plankton community

1. Incomplete mineral dissolution

For OAE applications using solid alkaline feedstocks, it cannot be assumed that alkalinity embodied within minerals fully dissolves in the upper ocean. Slower than expected or incomplete dissolution results in discrepancies between expected and actual alkalinity enhancement,

lowering efficiency. For open-ocean applications, particle sinking speed, in combination with dissolution rate, also dictates how much alkalinity is added to the surface ocean versus how much sinks below the mixed layer. Because these two interrelated mechanisms—dissolution rate and sinking speed—may require different analytical approaches, we discuss them here separately.

Mineral dissolution kinetics

Dissolution kinetics, or the rate at which particles dissolve, determines how quickly, and how much, alkalinity is added to seawater over a certain timescale. Dissolution kinetics are well-parameterized for pure minerals in ideal solutions, and—in theory—rates can be calculated given particle surface area (or grain size), temperature, salinity, and mineral saturation state (Ω), etc. (Adkins et al., 2021; Oelkers et al., 2018; Rimstidt et al., 2012; Saez Moreno et al., 2026). However, environmental conditions at the mineral surface may differ from bulk seawater, precluding direct calculation of dissolution rates. For example, in OAE applications, hydrodynamic conditions can be an important control on seawater chemistry. Optimal dissolution kinetic parameters are generally derived in stirred experiments, reducing Ω at the mineral surface (c.f. Pokrovsky and Schott, 2004). In the ocean however, advection energy is typically lower than in a stirred reactor, resulting in higher Ω at the mineral surface and slower dissolution rates (Moras et al., 2026).

For faster-dissolving feedstocks, high Ω around particles can also result in a dynamic interplay between dissolution and secondary mineral precipitation (described in the next section). If dissolution is sufficiently rapid but transport of resulting alkalinity away from the grain surface is limited, supersaturation with respect to carbonate minerals may occur, leading to mineral precipitation (aragonite in seawater and calcite in freshwater) (Cloud Jr et al., 1962; Hartmann et al., 2023; Moras et al., 2022; Pytkowicz, 1965). Further, precipitation on the feedstock surface potentially slows dissolution rates. Therefore, the role of dissolution kinetics on OAE efficiency must be considered in tandem with loss of alkalinity to carbonate formation, especially for applications with fast-dissolving feedstock.

Slower-dissolving feedstocks used in coastal seafloor applications may also experience slower than expected dissolution rates. At the most fundamental level, silicate dissolution is well known to slow over time as mineral surfaces age; thus, ideal rates quickly become inapplicable (Brantley, 2025; Daval et al., 2018; White and Brantley, 2003). Olivine, for example, may develop passivation layers that slow dissolution on relatively short timescales, and/or experience incomplete dissolution (e.g., serpentinization) on longer timescales (Geerts et al., 2025). In addition, porewater chemistry typically differs from the overlying water in Ω, pH, and redox state, which can increase or decrease dissolution rates relative to the water column, depending on conditions. In cohesive sediment with little porewater advection, porewater is likely to become saturated with respect to the feedstock, slowing dissolution of buried particles (Fuhr et al., 2023, 2024). High energy environments like sandy beaches may be less prone to these issues, via increased porewater flushing that decreases Ω, and/or prevention of passivation layers by physical abrasion. However, as with fast-dissolving minerals, a dynamic interplay between dissolution and secondary precipitation can occur, resulting in less alkalinity enhancement than

expected (England and Bach, 2025). Because dissolution kinetics change over time, potential efficiency losses must be integrated over (potentially long) timescales for slow-dissolving minerals. Measuring small dissolution signals, that become increasingly small over time, against a dynamic background in field deployments is challenging (Fuhr et al., 2023). Thus, modeling will realistically be necessary to extrapolate local measurements across larger areas and over longer time periods. Developing confidence in such extrapolations will require improved understanding of sediment diagenesis across a range of sediment types – e.g., with varying levels of organic matter, mineralogy, porosity, kinetic energy, etc.

Particle sinking

In open ocean applications, faster-dissolving minerals can be used for OAE if they dissolve sufficiently rapidly before sinking below the mixed layer (Renforth et al., 2022). Sinking speed can be modelled simplistically with Stokes Law; however, in real-world conditions, turbulence can significantly affect settling, potentially increasing sinking speed by orders of magnitude (Yang et al., 2025) Rapid sinking can result in negligible dissolution in the mixed layer, even for small particles of fast-dissolving minerals (e.g., MgO with < 10 µm diameter) (Yang and Timmermans, 2024). Settling rates may also increase as a result of particle aggregation (Nishino and Yoshikawa, 2024; Takeuchi et al., 2019). On the other hand, dissolving alkaline particles may form carbonate precipitates at the µm scale, which may remain suspended for longer periods of time within the mixed layer (Suitner et al., 2025). Studies of particle sinking have thus far focused on observation of natural particles and/or numerical simulations. Experimental lab and field observations are needed to confirm these results for OAE applications, as well as improve models with relevant processes. Proper modelling must consider interactions between particle dissolution, alkalinity generation, potential carbonate formation (discussed in the next section), and aggregation, coupled to the movement of particles through the mixed layer. Such models do not yet exist.

Settling rate is also an important consideration for near-shore applications, as particles may sink to the seabed (Kitidis et al., 2024). Fast-dissolving feedstocks may dissolve over time on the sediment surface, with resulting alkalinity entrained into nearshore water. However, complex sediment interactions may result in alkalinity loss not anticipated in the water column (described in next section). For these reasons, mineral sinking rates should also be considered in the design of near-shore OAE deployments.

2. Alkalinity loss to minerals

Following mineral dissolution, alkalinity can potentially be lost via subsequent precipitation to, or reaction with, solid minerals. This concept is sometimes referred to as alkalinity *stability* (Hartmann et al., 2023). Loss to minerals can occur in both the water column and/or in sediments, and can take place over dynamic timescales – ranging from spontaneous, runaway precipitation for high Ω conditions, to delayed loss for more moderate conditions, and slower interactions with sediments over timescales of porewater cycling. These losses are possible with both equilibrated and unequilibrated alkalinity, although precipitation thresholds are crossed more readily with

unequilibrated alkalinity (Suitner et al., 2024). The mineralogy of the precipitated solid phase will also affect loss timescales, and determine whether the loss is transient (e.g., potentially for $Mg(OH)_2$) or effectively permanent (e.g., potentially for carbonate minerals) (Suitner et al., 2025). The potential, rate, and durability of alkalinity loss to minerals depend on environmental conditions and feedstock properties, so understanding these pathways mechanistically is essential for evaluating the efficiency of specific OAE deployments.

Loss to minerals in the water column

In the water column, mineral precipitation may occur when seawater becomes sufficiently oversaturated following an increase in alkalinity. In an OAE context, the most likely minerals to precipitate include calcium carbonate ($CaCO_3$) polymorphs and magnesium hydroxide ($Mg(OH)_2$) (Haas, 1916; Hartmann et al., 2023; Hashim et al., 2025a; Kapp, 1928; Moras et al., 2022; Suitner et al., 2024, 2025; Varliero et al., 2024). Although seawater is naturally oversaturated with respect to $CaCO_3$ in most locations, precipitation is kinetically inhibited, and significant oversaturation is required to facilitate spontaneous precipitation (Berner, 1975; Morse et al., 2007; Zeebe and Wolf-Gladrow, 2001b). If sufficiently oversaturated, $CaCO_3$ precipitation may then occur either homogeneously, i.e., from the association of dissolved calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}) without the need for a pre-existing mineral surface area, or heterogeneously and pseudo-homogeneously, i.e., by precipitation on suspended particles and colloids (Marion et al., 2009; Morse and He, 1993a). The latter is more likely to occur at lower Ω, and will occur more quickly on surfaces with higher lattice compatibility, e.g., $CaCO_3$ or calcium-rich particles. Therefore, available surface area plays a key role in the precipitation process (Moras et al., 2022; Suitner et al., 2025). Similarly, temperature and salinity also have a role in triggering precipitation (Morse and He, 1993b). The second mineral likely to precipitate is $Mg(OH)_2$. Seawater is typically undersaturated with respect to $Mg(OH)_2$, however increasing alkalinity can result in a rapid rise in pH, and therefore OH^- concentration. Once reaching a pH of ~10.5, $Mg(OH)_2$ precipitates concomitantly with alkalinity increase (Haas, 1916; Hashim et al., 2025a; Kapp, 1928; Ringham et al., 2024; Suitner et al., 2024; Varliero et al., 2024).

Which of these secondary minerals precipitate must be considered in assessments of OAE efficiency. $CaCO_3$ precipitation can be conservatively assumed to be a long-term loss of alkalinity, given that the ocean is oversaturated with respect to $CaCO_3$ (Berner, 1995; Renforth and Henderson, 2017). The stability of precipitated $Mg(OH)_2$ is not well understood, though some research suggests it may dissolve over longer timescales, i.e., months to years (Moras et al., 2026). For both $CaCO_3$ and $Mg(OH)_2$, two moles of alkalinity are lost per mole of mineral formed. For $CaCO_3$, one mole of DIC is also lost; this sequestration of carbon (C) in mineral form may still constitute CDR, albeit at a reduced efficiency than if the DIC had remained dissolved. (In seawater with a thermodynamic efficiency of 0.8 mols atmospheric CO_2 sequestered per mol alkalinity increase, precipitation of alkalinity as $CaCO_3$ results in an efficiency of 0.3 mols CO_2 per mol alkalinity.) In contrast, no C is sequestered if alkalinity is lost permanently to $Mg(OH)_2$.

Potential loss to mineral precipitation will vary by feedstock and deployment scenario. Applications deploying (dissolved) unequilibrated alkalinity may trigger immediate $Mg(OH)_2$

precipitation if rapid pH spikes exceed the critical pH >10. In these conditions, $CaCO_3$ precipitation may be limited, as the absence of mineral surface area allows for higher Ω thresholds (Hartmann et al., 2023; Suitner et al., 2024). In coastal applications, however, suspended sediments may facilitate heterogenous $CaCO_3$ precipitation (Bustos-Serrano et al., 2009; Moras et al., 2022; Tian et al., 2025; Wurgaft et al., 2016, 2021). Mineral precipitation is less likely when using equilibrated alkalinity, as reaching critical thresholds requires a much greater increase in alkalinity. In contrast to methods that increase alkalinity directly, the use of solid, faster-dissolving feedstocks should result in $CaCO_3$ precipitation before $Mg(OH)_2$ buffering. $CaCO_3$ may precipitate on the surface of dissolving feedstock particles heterogeneously, or in the diffusive boundary layers of these particles where micro-environments may promote homogeneous precipitation (Moras et al., 2022). Such precipitation may enter a runaway process, where more alkalinity is lost than the amount added (Hartmann et al., 2023; Hashim et al., 2025b; Moras et al., 2022, 2024b, 2026; Suitner et al., 2024). The exact pH and Ω of precipitation thresholds will vary with environmental conditions. Tailored research is required to understand these thresholds across salinities and temperatures gradients, and the effect of potential inhibitors like Mg or dissolved organic matter, all of which may vary significantly across the land-ocean transition zone (Chave and Suess, 1970; Pytkowicz, 1965; Saez Moreno et al., 2026; Simkiss, 1964). Further, the effect of dilution, i.e., lowering precipitation thresholds, following runaway carbonate formation should also be better understood.

Loss to minerals in sediments

Spontaneous mineral precipitation can also occur when alkalized seawater interacts with sediments. Precipitation thresholds may be lower in sediments compared to the water column, due to buffering by in situ minerals, alkalinity production by anaerobic respiration, and the potential for heterogenous precipitation onto mineral surfaces. This has only been studied with respect to OAE in a few publications to date, with observed alkalinity loss presumed to be caused by mineral precipitation (Bach, 2024; England and Bach, 2025). Within sediments, alkalinity may be lost to $CaCO_3$ precipitation on relatively short timescales, and/or to silicate minerals (clays, i.e., reverse weathering) on longer timescales (Geerts et al., 2025; Turchyn et al., 2021). For iron-containing feedstocks like olivine, iron hydroxide precipitation may also result in indirect alkalinity loss (Griffioen, 2017). Formation of more soluble minerals like $Mg(OH)_2$ is also possible if porewater Ω is sufficiently elevated, although this may be transient for pulsed deployments, redissolving upon the return of less saturated seawater. As in the water column, precipitation of $CaCO_3$ sequesters CO_2, while silicate and hydroxide minerals are alkalinity sinks with no associated C sequestration.

A related loss pathway is ion exchange, in which dissolved ions exchange with ions adsorbed to mineral surfaces. For example, cation exchange can occur if elevated concentrations of base cations (Na^+, Mg^{2+}, Ca^{2+}, etc.) displace H^+ from sediment grain surfaces, thus reducing alkalinity. This phenomenon is increasingly identified as a significant alkalinity sink for terrestrial enhanced rock weathering (Hasemer et al., 2024). Although there have not yet been targeted studies in OAE applications, similar processes have been shown experimentally in sediments, where proton

buffering and exchange of bicarbonate complexes can occur following changes in pH or CO_2 concentration (Griffioen, 1993). The effect of ion exchange on alkalinity may be ephemeral as OAE-impacted seawater dilutes, or could lead to more permanent alkalinity loss by facilitating mineral precipitation.

Alkalinity losses to sediments would logically be most significant for shallow coastal deployments, where alkalinity is elevated in water masses with prolonged sediment contact, and/or for mineral deployments on the seafloor. The magnitude of loss is likely a function of the level of alkalinity enhancement (as above, with water column precipitation) and sediment properties like permeability and mineralogy. Experimental research is needed across these variables. Furthermore, observational hydrodynamic data are needed to define the extent to which seawater interacts with sediments. Ultimately, these data could be integrated into coupled sediment-water column models to estimate alkalinity loss to sediments near the deployment site and at regional scales.

3. Incomplete air-sea CO_2 equilibration

Air-sea CO_2 exchange is a primary control on OAE efficiency following an increase in (unequilibrated) seawater alkalinity; incomplete equilibration can depress CO_2 uptake over CDR-relevant timescales (years to decades). Approaches deploying equilibrated alkalinity avoid this inefficiency (although equilibration rates in reactors are still controlled by gas exchange rates, even under optimal reactor conditions). In this loss category, we distinguish between two key controls on air–sea CO_2 equilibration: 1) surface air–sea gas exchange processes, and 2) the physical redistribution of alkalized waters through mixing and subduction that limits their atmospheric exposure. These two processes are intricately related and are estimated with the same global circulation modeling tools. We distinguish them here to highlight their different consequences and timescales: air-sea gas exchange is associated with increasing efficiency over time as full equilibration is reached over years to decades, whereas loss of alkalinity to mixing and subduction may result in effectively permanent efficiency loss, considering CDR-relevant time horizons (Zhou et al., 2025a).

Kinetics of air-sea CO_2 exchange

With unequilibrated alkalinity, equilibration between atmospheric CO_2 and surface seawater is not instantaneous following alkalinity enhancement. The flux, or exchange of CO_2 across the air-sea interface, occurs gradually and is controlled by many environmental factors. This flux is often described as F (mol m^{-2} s^{-1}):

$$F = k\, K_o\, (pCO_w - pCO_a) \qquad \text{Equation 2}$$

where k (m s^{-1}) is the gas transfer velocity, K_o (mol m^{-3} Pa^{-1}) is the aqueous-phase solubility of CO_2, pCO_a (Pa) is the partial pressure of CO_2 in air, and pCO_w (Pa) is the partial pressure of CO_2 in water (Wanninkhof et al., 2009).

Key kinetic drivers of the gas transfer velocity (*k*) include: 1) wind dynamics (i.e., velocity, direction, and fetch), 2) wave dynamics (i.e., breaking and bubble entrainment), and 3) surface layer properties (i.e., surfactant concentrations, micro-organism presence and activity, gel particles, and obstructions like sea ice). In practice, k is typically parameterized by wind speed, although recent research suggests this approach may significantly underestimate air-sea exchange rate in some coastal waters (Dobashi et al., 2026). The key factors that affect the air-sea pCO_2 difference (ΔpCO_2) are temperature, biological C cycling, and alkalized water transport (including mixed layer depth). Both k and ΔpCO_2 can vary strongly across location and season.

Following alkalinity enhancement, CO_2 uptake is initially rapid but slows as the air-sea pCO_2 difference decreases. Complete equilibration of alkalized seawater in the surface mixed layer can take anywhere from months to decades, depending on local and regional conditions (Zhou et al., 2025b). This equilibration timescale is longer than that for the atmospheric pCO_2 perturbation from anthropogenic emissions, where the global average equilibration time is approximately one year (Jones et al., 2014). In ideal locations where lateral flow retains alkalized water at the ocean surface (e.g., subpolar latitudes), near-complete equilibration may be reached relatively rapidly, within a few years. However, in less ideal locations, equilibration may take significantly longer (>15 years) as shallow overturning and a deep mixed layer decrease ΔpCO_2 (Zhou et al., 2025b). This delay in complete equilibration has two important implications for the efficiency of OAE deployments. First, on shorter timescales prior to complete equilibration, estimates of CDR will inherently have lower effective efficiency than those after complete equilibration. After complete equilibration, maximum efficiency is reached, and the "loss" for this category approaches zero. Second, alkalized waters may subduct or mix into the ocean interior before they can fully equilibrate with the overlying atmosphere (described in the next section).

CO_2 uptake curves can be modeled for specific deployment scenarios to estimate efficiency at any given timepoint. Accurate parameterization of such uptake will require site- and condition-specific hydrodynamic modeling (e.g., nearfield turbulent models and regional ocean models), coupled to global ocean models. Experimental work is also needed to better constrain k values, especially in coastal waters.

Physical transport

For air-sea CO_2 exchange to occur, alkalized waters must remain at the ocean surface. Alkalinity that moves into the ocean interior prior to full equilibration cannot interact with atmospheric CO_2, and may be effectively lost on timescales beyond the intent of CDR intervention. This loss may result from either subduction of the alkalized water mass, from diapycnal mixing with deeper water masses, or from other physical processes. These processes depend on oceanographic conditions that vary by location, as well as seasonally, interannually, and with weather (He and Tyka, 2023; Zhou et al., 2025b). Losses can be minimized by deploying in locations without significant downwelling, and at times of year with less turbulent mixing between water masses.

The timescale of alkalinity subduction (or mixing) and potential return to the ocean surface also varies by location. If OAE is deployed in regions where deep water is formed, it may be hundreds of years to millennia before the water resurfaces and the equilibration process can resume (Reith et al., 2016; Siegel et al., 2021). During that time, biological processes within the subducted water mass may consume some of the unequilibrated alkalinity, however this will have no impact on atmospheric CO_2 (Wolf-Gladrow et al., 2007). Air-sea equilibration and CO_2 uptake (and/or decreased CO_2 outgassing) may proceed when the water mass returns to the surface, if any excess alkalinity remains. Estimating the impact on atmospheric CO_2 upon resurfacing requires coupled physical-biogeochemical ocean models.

Advancements in such coupled models are needed to better constrain both the controls on air-sea CO_2 equilibration related to CO_2 exchange kinetics, and the surface residence time of alkalized water set by subduction and mixing (Fennel et al., 2022, 2023a). This will require coordinated efforts across a model hierarchy, from nearfield turbulence and plume models, to regional circulation and biogeochemistry models, to global Earth system models. Most relevant models have not yet been configured for OAE applications, and parameters important for long-term OAE performance, like interannual variability, must be integrated (Fennel et al., 2023a). In addition, more complex deployment scenarios – e.g., coastal sites, seafloor applications, timed pulses – must also be represented. Finally, standardized, model intercomparisons are needed to help identify biases and reduce uncertainties.

4. Indirect Impacts

The loss pathways described above directly affect the availability and/or reactivity of added alkalinity. OAE activities can also impact ocean biogeochemical cycling, *indirectly* affecting seawater alkalinity and/or the rate of atmospheric CO_2 uptake. Potential efficiency losses from indirect impacts include suppression of alkalinity flux from sediments, an increase in the $CaCO_3$ counterpump, and perturbation to organic carbon cycling, e.g., the soft tissue pump. These impacts are likely to operate over large spatial and temporal scales.

Indirect impacts are sometimes referred to as “additionality” considerations (Bach, 2024). In general, additionality refers to the extent to which an intervention results in CDR above and beyond what would have happened in a counterfactual (no intervention) scenario. At the broadest level, additionality considerations range from regulatory and financial incentives to impacts on ecological processes (as discussed here). Some approaches to calculating the efficiency of CDR interventions decompose net CDR into a) observed CO_2 uptake resulting directly from the activity itself, and b) indirect impacts on baseline ecological processes (i.e., additionality considerations), which are typically assumed to decrease C sequestration (Bach et al., 2024a). However, so-called direct CO_2 uptake and indirect impacts may physically and temporally overlap, and the resulting net CO_2 uptake is an emergent result of interactive physical and bio(geochemical) processes spread over large spatial areas and temporal scales. Thus, it is functionally difficult to quantitatively distinguish CO_2 uptake resulting *directly* from the alkalinity

enhancement itself from *indirect* processes that mediate this uptake. We therefore consider so-called direct losses and indirect losses equally within our framework, and do not ascribe the latter alone to additionality considerations. Ultimately, defining reductions in gross CO_2 uptake as integrated efficiency losses (as done here), or changes to a baseline (additionality considerations), is simply an accounting choice; either approach is appropriate as long as all potential losses are accounted for.

Decreased sediment alkalinity flux

Sediments can be a significant source of dissolved alkalinity to the water column, due in part to dissolution of carbonate minerals (Krumins et al., 2013; Trapp-Müller et al., 2025). OAE-induced elevation of Ω may suppress this dissolution, effectively reducing the natural flux of benthic alkalinity. Thus, the unperturbed, counterfactual scenario will have a higher input of benthic alkalinity to the water column, relative to the OAE scenario. This difference effectively reduces the net alkalinity enhancement of the OAE scenario. There has been little research on this subject to date, so the magnitude of potential efficiency loss remains unconstrained. In extreme experimental scenarios, alkalinity enhancement can suppress sediment $CaCO_3$ dissolution such that the OAE scenario results in lower net alkalinity enhancement than natural sediments alone (Bach, 2024).

Functionally, suppression of benthic $CaCO_3$ dissolution and $CaCO_3$ precipitation within sediments may be difficult to disentangle: precipitation and dissolution are in dynamic equilibrium with one another, representing two ends of a spectrum. Here, we include them as separate loss pathways since end-member conditions may be relatively more important in different situations: $CaCO_3$ precipitation may be most significant near deployments, whereas suppressed dissolution is more likely as a diffuse impact over the continental shelf. The two mechanisms may be integrated in different ways into nearfield and/or global ocean models. For deployments using solid minerals, another consideration is the interaction between benthic alkalinity flux and feedstock dissolution rates: mutual buffering between OAE feedstock and $CaCO_3$ in sediments likely reduces the dissolution kinetics of both alkalinity sources.

Constraining losses associated with these processes requires measurements and experiments that resolve how benthic alkalinity flux responds to changes in bottom water chemistry. Experiments with both high and low levels of alkalinity enhancement are needed across sediment types and hydrodynamic conditions to assess local impacts near deployments, as well as diffuse impacts at regional to global scales. These data can then be used to inform nearfield and global models. Projections of OAE scalability must also consider that benthic alkalinity flux from $CaCO_3$ dissolution is expected to increase in the future in response to ocean acidification, in both shallow coastal and deep ocean sediments (Eyre et al., 2014; Lunstrum and Berelson, 2022; Sulpis et al., 2018). Continued OAE deployments may increasingly suppress this alkalinity flux, resulting in greater effective efficiency loss.

Increased carbonate counterpump

In the natural C cycle, the sinking of biogenic carbonate minerals exports an estimated 1 Gt of inorganic C from the surface ocean per year (equivalent to approximately 10 Mmol of alkalinity) (Liang et al., 2023; Sulpis et al., 2021). This export of alkalinity is often referred to as the "carbonate counterpump", as it *increases* pCO_2 at the ocean surface (in contrast to the biological or soft tissue pump–described in the next section—that *decreases* pCO_2 at the ocean surface). OAE may enhance the carbonate counterpump by increasing calcification and/or decreasing dissolution of particles before sinking, in both cases resulting in alkalinity loss from the surface ocean. While there is currently no evidence of either process in OAE-specific research, global ocean observations show a clear, positive correlation between seawater alkalinity and calcification, suggesting that OAE may indeed lead to increased formation of $CaCO_3$ (Lehmann and Bach, 2025). Palaeoceanographic data also indicate a shift toward more heavily calcified planktonic species and increased carbonate export in response to warming and subsequent weathering over geologic (10^5 y) timescales; whether such ecological changes could occur on CDR-relevant timescales (e.g., $<10^2$ y) remains unknown (Harbich et al., 2024). Dissolution of biogenic $CaCO_3$ has also been shown to slow at higher Ω (Subhas et al., 2022). Despite these observations, the exact relationship between saturation state and carbonate export remains difficult to define, and likely depends on other processes (e.g., temperature, nutrients, respiratory-driven dissolution, etc.) (Liang et al., 2023). Given the early stages of research on this topic, much of what is known is extrapolated from ocean acidification studies, which do not show clear directional impacts between carbonate export and seawater pH (Planchat et al., 2024).

Species-level assays can help inform the mechanistic impacts of OAE on calcification. However, micro- and mesocosm experiments at the community-level are needed to understand the net impact on both calcification and dissolution, and the emergent impact on export rates. Identifying alkalinity thresholds, below which there is no measurable impact on export, would be useful for constraining deployment design. Recent experiments are starting to be published on this topic, but more work is needed across different marine biogeographies (Suessle et al., 2025). Systematic efforts like the Ocean Alkalinity Enhancement Pelagic Impact Intercomparison Project (OAEPIIP) will help fill this gap (Bach et al., 2024b). If significant results are observed, incorporating experimental data into global biogeochemical components of ocean models is critical (Fennel et al., 2023a).

Altered organic carbon cycling

The biological pump exports approximately 10 Gt of organic C per year from the ocean's surface to the deep sea – approximately ten times greater than inorganic C export via the carbonate counterpump (Nowicki et al., 2022). This export is considered a long-term sink of atmospheric CO_2, and enhanced export of organic C is assumed to increase the uptake of atmospheric CO_2; however the direct relationship between export and CO_2 uptake is an area of ongoing research (Jiang et al., 2024). OAE could potentially alter the magnitude of the biological pump directly via changes to primary productivity and respiration, and/or by changes to mineral ballasting.

Whether the net effect of these processes might increase or decrease C export is unclear; early research has not shown a significant impact in either direction (Paul et al., 2025; Sánchez et al., 2024; Suessle et al., 2025). The impact is likely to be different across locations and OAE deployments. For example, the use of silicate feedstocks containing micro- and macro-nutrients, such as olivine, may stimulate primary productivity more than lime or electrochemically-produced alkalinity (Bach et al., 2019). For all OAE scenarios, changes to ballasting must be considered because organic C and $CaCO_3$ export are intricately linked (Barker et al., 2003; Ziveri et al., 2007). While an enhanced carbonate counterpump would *decrease* atmospheric CO_2 uptake, enhanced organic C export would *increase* atmospheric CO_2 uptake. Thus, the balance of the two processes, if affected by OAE, is difficult to predict. Changes to organic C cycling in rivers, estuaries, and coastal ecosystems – for example, organic carbon burial in sediments -- must also be considered for river and coastal applications (Neumann et al., 2025).

As with considerations for the carbonate counterpump, species-level assays can help inform mechanistic impacts on primary productivity and respiration, although these are expected to be insignificant at dilute levels of enhanced alkalinity. Micro- and mesocosm experiments are needed to understand the net impact of OAE on organic and inorganic C cycling, and the resulting impact on export rates. Data from systematic efforts like OAEPPIIP across different biogeographies will help improve the biogeochemical modules used to account for these processes in ocean models.

Discussion

Across the potential loss pathways, efficiency is impacted by processes that alter both alkalinity and DIC. Most losses are associated with changes in alkalinity, either loss of unequilibrated alkalinity from the surface ocean by subduction and diapycnal mixing, or a reduction in net alkalinity via incomplete mineral dissolution, alkalinity loss to minerals, and indirect impacts involving natural alkalinity fluxes (Figure 2A). Most studies of η consider only loss of alkalinity from the surface ocean, implicitly assuming that alkalinity is conserved (Anderson et al., 2026; Burt et al., 2021; He and Tyka, 2023; Nagwekar et al., 2026; Wang et al., 2023; Zhou et al., 2025a). While this assumption is reasonable for studies focused on physical processes, it can create confusion when interpreted more broadly as overall OAE efficiency. To clarify the bounds of such studies, “equilibration efficiency” may be a more suitable term than “efficiency” more broadly. These studies also set ΔAlk equal to the amount of alkalinity added by the OAE activity (Alk_{Added}). In more applied studies, we suggest distinguishing Alk_{Added}, the amount of alkalinity (or assumed alkalinity from mineral dissolution) added to the ocean, from ΔAlk, the subsequent increase in seawater alkalinity. Using ΔAlk or Alk_{Added} may be functionally equivalent for modeling studies focused on equilibration efficiency, but differences may result when considering real deployments where loss of alkalinity may occur.

The exceptions to alkalinity-mediated losses include slow air-sea equilibration and altered organic carbon cycling. Slow air-sea equilibration acts strictly on the ΔDIC term, and decreases to zero over time as complete equilibration is reached. Potential changes to organic carbon cycling

primarily influence ΔDIC, although photosynthesis also alters alkalinity slightly via the consumption of mineral acids, and vice versa for aerobic respiration (Figure 2B) (Wolf-Gladrow et al., 2007). Existing mesocosm studies have not shown a significant effect of OAE on organic carbon export, suggesting that this loss pathway may be insignificant or small (Paul et al., 2024; Suessle et al., 2025). However, available observations are limited, and more work is needed before this loss can be confidently excluded from efficiency assessments.

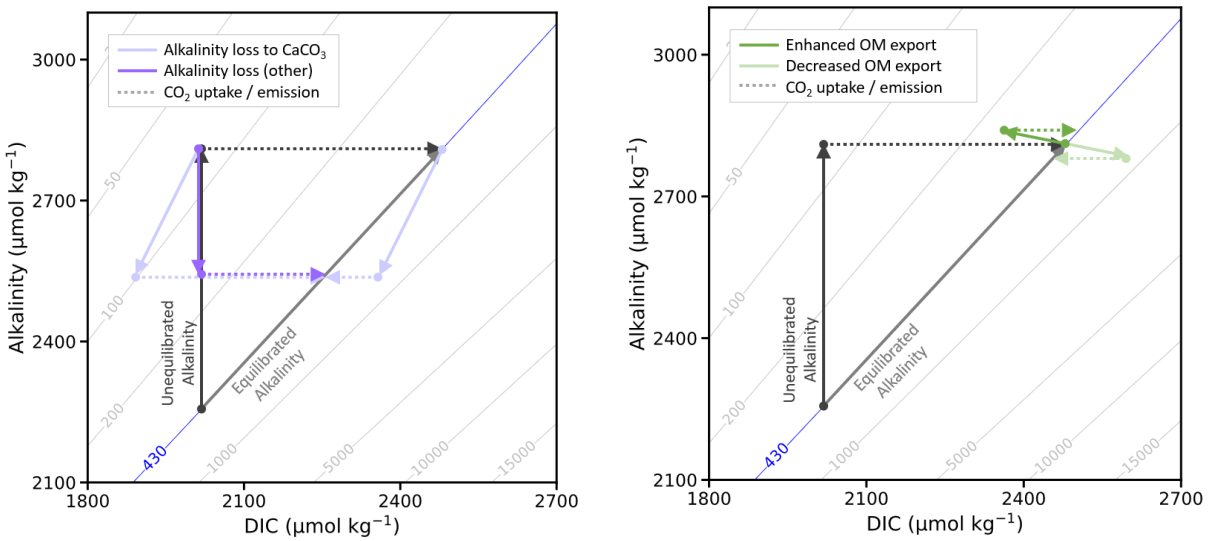


Figure 2. Alkalinity:DIC diagrams showing the impacts on carbonate chemistry from processes that reduce alkalinity (A) or alter organic matter (OM) export (B) following OAE interventions. Both unequilibrated alkalinity (black line) and equilibrated alkalinity (gray line) scenarios are shown. Solid lines represent efficiency loss mechanisms, and dashed lines represent subsequent equilibration with atmospheric CO_2. In (A), alkalinity losses result in shorter CO_2 uptake vectors or CO_2 emission (left-pointing vector) compared to the assumed uptake (black dashed line). Efficiency loss due to $CaCO_3$ cycling (precipitation and/or suppression of baseline dissolution) may occur in both equilibrated and unequilibrated alkalinity, while alkalinity loss to other processes is more likely to occur with unequilibrated alkalinity. In (B), indirect impacts could either enhance or decrease OM export, potentially leading to additional CO_2 uptake or CO_2 emission, respectively. (Overlapping lines are offset slightly for visibility. Loss vectors are illustrative and not indicative of likely magnitudes. Data modeled in PyCO2SYS at T=20, S=35).

Because each loss pathway modifies efficiency through different mechanisms over different timescales, there is no straightforward implementation that is suitable across all deployment scenarios. Conceptually, the losses described in this framework can be summarized as:

$$\eta(t) = (\Delta DIC_{max} - L_{Dissolution}(t) - L_{Precipitation}(t) - L_{Equilibration}(t) - L_{Indirect}(t)) / Alk_{Added} \quad \text{Equation 2}$$

Where ΔDIC_{max} is the maximum thermodynamically predicted CO_2 uptake for Alk_{Added}, and L(t) terms represent the four categories of efficiency losses, estimated at a given point in time. This expression is intended only as a conceptual summary of losses, rather than a quantitative approach for calculating efficiency since losses may be interactive, and because appropriate treatment of losses will vary by deployment strategy and time or scale of interest. Best practices for estimating each loss pathway will also continue to evolve as scientific understanding advances. Ultimately, quantitative assessments must represent relevant loss pathways in spatial and temporally explicit models.

Efficiency must be assessed for a specific point in time because losses act across different temporal scales. For example, mineral sinking and precipitation may occur essentially immediately, over the course of seconds to days, whereas incomplete mineral dissolution and incomplete air-sea flux gradually decrease over time, on the scale of years (Hartmann et al., 2023; Zhou et al., 2025b). Indirect impacts on biogeochemical cycling may continue to develop over even longer timescales. Beyond the processes considered here, long-term redistribution of carbon among Earth system reservoirs—for example either increasing atmospheric CO_2 through continued emissions, or decreasing atmospheric CO_2 through broad deployment of CDR – will also impact OAE efficiency at scale (Keller et al., 2018). However, these unavoidable feedbacks between global C reservoirs affect all CDR pathways, and are typically not considered in deployment-scale or shorter-term assessments of CDR efficiency. Likewise, potential changes to non-CO_2 greenhouse gas fluxes and albedo would also affect efficiency at scale, however there is no research to date exploring potential impacts of OAE (Bange, 2022; Frouin and Iacobellis, 2002).

Losses also have different spatial footprints. Those associated with short timescales, for example mineral sinking and precipitation to solids, are primarily a concern near the deployment site. These may be avoidable with careful deployment design at small coastal deployments, but will likely require process models to constrain for larger or open ocean deployments. Losses associated with physical mixing and air-sea flux occur over larger spatial scales, and must be assessed with regional and global models; such models remain under active development (Fennel et al., 2023b). Integrating additional losses that may act over large scales into these modeling efforts, e.g., those associated with indirect impacts, will require new biogeochemical parameterizations informed by experiments, field observations, and process models.

As illustrated in Figure 1, overall efficiency emerges from the combined effects of all loss pathways. Losses often cannot be treated as independent processes however, since they interact through coupled physical and (bio)geochemical feedbacks. For example, mineral dissolution, precipitation, and sinking determine the initial increase in seawater alkalinity and by extension the ΔpCO_2 that drives air-sea equilibration; physical transport of alkalinity impacts not only air-sea equilibration, but also how quickly alkalinity is diluted to below precipitation thresholds, as well as the extent of sediment exposure; and changes to organic and inorganic carbon cycling interact with each other through the biological pump. Consequently, the cumulative impact on efficiency is an emergent system property, rather than a sum of individual losses. Integrating these processes into quantitative efficiency assessments requires ocean models that represent

relevant physical and (bio)geochemical processes across appropriate spatial and temporal scales. As described in the preceding sections, many of these processes remain poorly constrained, and measurements are needed to develop and validate model parameterizations. By organizing the processes that contribute to efficiency losses into a common conceptual framework, we hope to provide a shared structure that aligns parallel efforts in experimental, observational, and process model development. Such a framework helps ensure that measurements provide the data needed for model development, and conversely that models appropriately account for losses identified through observations and experimental work.

This framework also helps clarify losses for broader assessments of *net* CDR efficiency, and by extension, OAE's potential contribution to climate mitigation goals. Lifecycle and technoeconomic assessments of OAE technologies necessarily require assumptions about gross efficiency, η, in order to calculate net efficiency that accounts for upstream emissions. Most assessments to date assume either no efficiency losses (i.e., thermodynamic maximum efficiency), or only those associated with subduction of alkalinity based on ocean models (Campo et al., 2026; Foteinis et al., 2022; Lunstrum et al., 2026). Studies with mineral feedstocks further assume ideal dissolution kinetics (Foteinis et al., 2023; Yang and Feng, 2026). Such assessments almost certainly overestimate net efficiency, especially over shorter timescales. More recent studies are beginning to consider additional losses, including mineral precipitation risk in the water column (Delval et al., 2026; Myridinas et al., 2026). Similarly, integrated assessment models and other economic optimization models rely on both efficiency and cost estimates from lifecycle and technoeconomic assessments as key inputs (Mendez et al., 2025; Morrow et al., 2023; Strefler et al., 2025). Results from these models thus inherit the assumptions embedded in gross OAE efficiency estimates. Using optimistic efficiency estimates that fail to consider realistic losses can overestimate OAE's potential role in climate mitigation, and/or bias OAE compared to other CDR methods. Although studies at this level of analysis do not need to explicitly consider individual loss pathways, they do require realistic estimates of their combined effect on gross OAE efficiency. More comprehensive consideration of potential losses, for example in the lifecycle and technoeconomic assessments that feed into these larger studies, will support more robust estimates of OAE's potential contribution to climate mitigation

This perspective provides a common conceptual framework for understanding how individual loss pathways contribute to overall OAE efficiency. Losses may occur across four categories: incomplete mineral dissolution, alkalinity loss to solids, incomplete air–sea equilibration, and indirect impacts on ocean biogeochemical cycles. To date, most assessments of OAE efficiency have focused on the third of these -- air-sea equilibration -- whereas losses associated with the other processes are less well constrained and often not considered. Reducing these uncertainties will require coordinated effort across experiments, observations, and model development. By providing a shared framework and consistent terminology, we hope to align these parallel efforts, and focus attention on shared research priorities. Ultimately, more comprehensive accounting of efficiency losses will support more realistic estimates of OAE's potential contribution to global climate goals.

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