Technical Summary

For: Foundations for Carbon Removal Quantification in Enhanced Rock Weathering Deployments

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If you identify any errors or have any suggested updates to this Document, please email foundations@cascadeclimate.org.

This document is a technical summary of the information available in the "Foundations for Carbon Dioxide Removal Quantification in Enhanced Rock Weathering Deployments" publication (henceforth referred to as "Foundations").

"Foundations" represents an assessment of the science and practice of carbon dioxide removal (CDR) quantification for enhanced rock weathering (ERW) deployments, undertaken through a multi-stakeholder process from October 2023 through August 2024. The primary focus of the publication is the quantification of additional CDR generated by ERW deployments, articulating in detail the relevant biogeochemical fluxes that can impact the net carbon balance, including the current state of scientific understanding and considerations for constraining the impact of relevant fluxes in practice.

We invite all ERW stakeholders to use both the Foundations document and this Technical Summary – in particular:

- Project developers and credit issuers can integrate the scientific context, considerations, and recommendations outlined in this document into new and refined methodologies, protocols and project design documents for ERW deployments.
- Carbon removal buyers can build the considerations and recommendations provided into measurement, reporting, and verification (MRV) due-diligence requirements and contractual expectations for project developers' quantification approaches.

- Policymakers can use this document to gain a more nuanced understanding of the R&D priorities and open system-level questions in ERW quantification, which can then inform the design of targeted public funding and innovation support programs.
- The broader research community can use the multi-stakeholder assessment and key R&D priorities highlighted in the document to inform CDR quantification for field, mesocosm, and laboratory experiments, as well as inspire near-term research efforts.

This Technical Summary is intended to be a direct synthesis of "Foundations" extensive scientific and technical details. Section and equation numbers refer to their original numbering in the "Foundations" document, rather than in this technical summary. Please refer to the full "Foundations" document for more detailed information.

1 Overarching framework for net CDR quantification

1.1 Introduction to ERW

See Section 2.1 and its subsections in the "Foundations" document for more detailed explanation.

Overview
Enhanced rock weathering (ERW) is the purposeful application of crushed alkaline feedstocks to agricultural soils. Over time, the feedstock dissolves in soil porewaters, releasing base cations like Mg2+ and Ca2+ and generating alkalinity. The addition of excess base cations following feedstock dissolution shifts the balance of the carbonic acid system away from CO2(aq) and towards HCO3- and CO32-, generating a disequilibration between dissolved CO2(aq) and atmospheric or soil CO2(g), which then re-equilibrates, leading to carbon dioxide removal (CDR). Carbon dioxide removal can also occur when protons that would have driven CO2 evasion are consumed through weathering reactions. Weathering products are transported through the soil profile and into downstream systems–groundwater, surface waters, and (in many cases) eventually the ocean. The generation of additional DIC (dissolved inorganic carbon) and its durable storage (i.e., storage in a long residence time reservoir) in downstream systems is critical for CDR efficiency.

The release of excess base cations to the soil system
Carbon removal associated with ERW deployments can be thought of, and quantified, through two interrelated lenses: that of acid-base reactions and proton balance, or that of excess base cation release and charge balance. Although the consumption of H^+ and production of HCO_3^- during feedstock dissolution is ultimately an acid-base reaction, the release of excess base cations can be used to track CDR using charge balance arguments. We use these two alkalinity frameworks interchangeably throughout this document to be intentionally inclusive. While geochemists may prefer one over the other, they are considered equivalent and we treat them as such in this context (Middelburg, Soetaert, and Hagens, 2023; Wolf-Gladrow et al., 2007).

Embracing a cation accounting and charge balance frame, netCDR quantification for an ERW project can be thought of as an exercise in quantifying how many excess base cations have been released from a feedstock, how those base cations are variably charge-balanced through space and time by DIC, and what are the losses of cations and DIC from solution before reaching a durable reservoir. This can be done by tracking weathering products (i.e., excess cations) in deployment waters, monitoring their movement through different reservoirs in the soil profile with solid-phase mass balance techniques, or by trying to follow the carbon directly by monitoring the export of DIC from deployment soils or changes in the soil CO_2 efflux. We discuss the details of such measurement approaches in Sections 7.4-7.6. It is important to note that there are processes which will not change alkalinity but will change DIC (e.g., CO_2 degassing), and processes that will change base cation concentrations but not change the carbon balance (e.g., cation sorption that does not exchange acidity), which are further discussed in later sections.

Durable storage of carbon from ERW
In natural systems, the residence time of carbon spans many orders of magnitude, from the subsecond (e.g., aqueous carbonate system equilibration), monthly to yearly (e.g., dissolution of feedstocks on a field), centennial to millennial (e.g., storage of bicarbonate in the ocean), to the geologic (e.g., hundreds of millions of years of storage in carbonate rocks) (Hartmann et al., 2013; Hilton and West, 2020). The length of time that it takes a feedstock to dissolve, and the time until transport and durable storage, is a key tension in open system CDR.

There are two primary durable storage pathways for CO_2 removed through weathering reactions: (1) storage as a carbonate mineral in downstream systems, and (2) storage as dissolved inorganic carbon (DIC) in a long residence time reservoir. DIC includes all of the dissolved species of the 'carbonic acid system': dissolved CO_2, carbonic acid (H_2CO_3, which will only be present in small quantities), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). The durability of carbon storage as DIC and in carbonate minerals will be site-dependent and require careful consideration of the many variables that allow for carbon storage on long timescales, further outlined in Section 9.

1.2 Introduction to the quantification framework of CDR in ERW deployments

The overall framework for quantification and carbon accounting of CDR in ERW deployments presented here divides the full system into two non-spatially overlapping "conformance zones", which we define as the Near-Field Zone and the Far-Field Zone.

Potential sources of acidity

In addition to fertilizer inputs to the soil, existing acidity in soils and non-carbonic acids along flow paths are sources of acidity in the near field and far field zone.
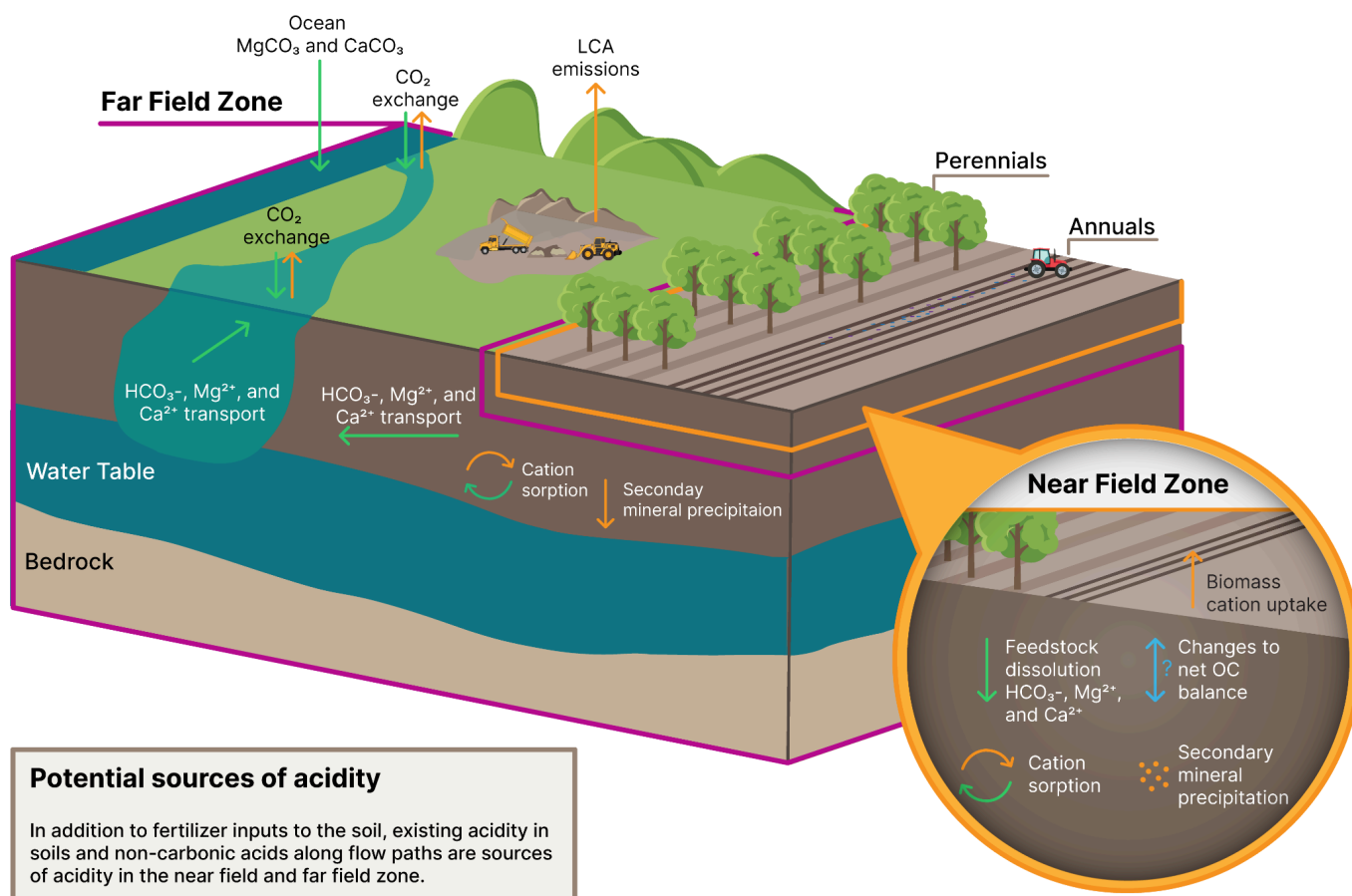
The Near-Field Zone (NFZ; depicted in the orange box in Figure 1) is the region of the upper soil profile in which the ERW deployment must be directly tracked through empirical measurements, accounting for feedstock dissolution, cation sinks, and other carbon fluxes that impact netCDR. This includes directly tracking both the magnitude of these fluxes and the timescale over which they occur.

As weathering products and DIC travel further down the soil profile, they are exported into the Far-Field Zone (FFZ; depicted in the purple box in Figure 1). Section 4 provides a detailed discussion of how the spatial extent of the NFZ and boundary between the Near-Field and Far-Field Zones can be defined in a site-specific

way. The FFZ encompasses the entirety of the flow path traveled by the weathering flux en route to durable storage after exiting the NFZ. This can include deeper portions of the soil profile and lower vadose zone, groundwater systems, surface waters, and the ocean. While weathering and the subsequent export of carbon and alkalinity out of the NFZ can and should be empirically measured, models and geochemical calculations must be used to constrain carbon dynamics in the FFZ (see Section 9).

The other key category of carbon fluxes that must be quantified is project **life cycle emissions**, which can take place both upstream of the deployment and throughout the project lifetime (Section 10). These emissions are considered and estimated separately from NFZ and FFZ carbon dynamics.

1.2.1 Term balance for ERW in the NFZ

The NFZ and FFZ conformance zones are used to develop the high-level term balance presented in Section 5.2 where netCDR is quantified. In this framework for ERW carbon accounting, CDR is quantified over discrete time intervals referred to as reporting periods (RP). In each reporting period, netCDR is quantified according to the following term balance:

$$CDR_{Net, RP} = CO_2e_{NFZ, RP} + CO_2e_{FFZ, RP} - CO_2e_{LCA\ emissions, RP} \quad \text{(Eq. 5.2.1)}$$

Where:
- $CDR_{Net, RP}$ is the net CO_2 removed by the ERW deployment during the reporting period.

- $CO_2e_{NFZ, RP}$ is the net additional CDR in the NFZ during the reporting period (Section 5.4.1).

- $CO_2e_{FFZ, RP}$ is the calculated net additional CDR in the FFZ assigned to the reporting period (Section 9). **Importantly, in the quantification framework presented here, only net carbon *loss* in the FFZ is considered. This value is thus always negative.** FFZ CO_2 losses are amortized across reporting periods as described in Section 5.3.2.

- $CO_2e_{LCA\ emissions, RP}$ is the calculated life cycle emissions assigned to the reporting period. Emissions are amortized across reporting periods as described in Section 10.3.

Each of these terms can be further broken down into the difference between a treatment term and a counterfactual (CF) term:

$$CO_2e_{NFZ, RP} = CO_2e_{Treatment\ NFZ, RP} - CO_2e_{CF\ NFZ, RP} \quad \text{(Eq. 5.2.2)}$$

$$CO_2e_{FFZ, RP} = CO_2e_{Treatment\ FFZ, RP} - CO_2e_{CF\ FFZ, RP} \quad \text{(Eq. 5.2.3)}$$

$$CO_2e_{LCA\ emissions, RP} = CO_2e_{Treatment\ LCA\ emissions, RP} - CO_2e_{CF\ LCA\ emissions, RP} \quad \text{(Eq. 5.2.4)}$$

Where:
- The terms representing the "Treatment" are statistical estimates of the quantity of CO_2 removed from the atmosphere (or in Eq. 5.2.4, emitted to the atmosphere as life cycle emissions) in reporting period RP, as measured or estimated in the scenario where alkaline feedstock has been applied.

- The terms representing the "Counterfactual" are statistical estimates of counterfactual CO_2 fluxes if the ERW deployment had not occurred (Section 5.5). In order to keep track of avoided emissions separately from atmospheric removals, these terms must be non-negative (Section 5.5.4).

All terms in Eq.s 5.2.1 to 5.2.4 are expressed in units of tonnes CO_2.

1.2.2 Overview of the Near-Field Zone

Although the ERW deployment is initiated with baseline sampling and the actual spreading of feedstock, no carbon can be removed from the atmosphere until the feedstock dissolves and alkalinity is released from the mineral lattice into the soil system (Section 8.2). We consider feedstock dissolution to represent the initiation of carbon removal–i.e., when *potential* CDR is generated. However, feedstock dissolution is not the end of the NFZ story (Section 5.4.1 and Section 8).

The NFZ hosts a suite of biogeochemical processes that can lead to both durable and transient losses of base cations, and therefore alkalinity and carbon, as well as direct losses of carbon. For example, base cations can be incorporated into pedogenic carbonate minerals and other phases that commonly form within the soil profile, removing alkalinity from the system and therefore reducing carbon removal efficiency (e.g., Eq. 2.1.2.1, Section 8.5, Section 8.6). Shifts in soil chemical and physical properties induced by ERW deployments can also result in changes to the net carbon flux through connected biogeochemical pathways (e.g., by influencing the soil *organic* carbon balance). For this reason, additional measurements or models are required in the NFZ beyond tracking feedstock dissolution to quantify these permanent and transient sinks of alkalinity and carbon as part of carbon removal deployments. The significant NFZ processes discussed here include: pH dynamics and non-carbonic acid weathering (Section 8.3), cation sorption (Section 8.4), secondary carbonate formation (Section 8.5), secondary silicate and other secondary phase formation (Section 8.6), alkalinity loss due to biomass uptake (Section 8.7), and changes to the net organic carbon balance (Section 8.8).

Importantly, these biogeochemical processes may lead to permanent or transient changes to the net carbon balance, and the timescales of reversal for transient carbon or alkalinity sinks can vary from seasons to decades. This leads to consequential questions about the temporal dynamics of CDR, and how to develop a consistent accounting framework that can account for carbon gain and loss processes that occur over very different timescales in ERW quantification (Section 5.3).

NFZ CDR, or $CO_2e_{NFZ, RP}$, can be quantified as the additional DIC that has been exported from the NFZ relative to a counterfactual baseline, plus CDR occurring in the NFZ as dissolved weathering products and precipitated secondary carbonates. Changes to the soil organic carbon balance should also be included in this term balance where applicable (Section 8.8). Within the NFZ, it can be helpful conceptually to think about two endmember approaches for empirically constraining CDR, described below (see Section 5.4.1 for a more detailed description of these endmember quantification approaches).

Endmember Approach 1: Direct measurement of dissolved weathering products or DIC produced. CDR is calculated as the export of DIC above a counterfactual baseline through aqueous-phase measurements of carbonate system parameters and/or major ion concentrations at the end of the NFZ (or in drainage /

catchment waters past the NFZ). To additionally quantify CDR occuring within the NFZ, practitioners can generate an estimate of additional DIC within the NFZ relative to the counterfactual baseline, via direct measurements at a series of depths.

Endmember Approach 2: Independently constrain feedstock dissolution and each term balance component. Instead of directly measuring changes in alkalinity or DIC in the aqueous phase, the potential CDR associated with cations released through feedstock dissolution is calculated in each reporting period, tempered by the change in each potential carbon loss term relative to the last reporting period. After accounting for each potential loss term, the remaining CDR from feedstock dissolution should represent the magnitude of additional DIC stored in and exported from the NFZ.

Table 1. Components of the NFZ term balance. Here we present a summary of the carbon fluxes relevant for quantifying ERW in the Near Field Zone and their considerations. Note that the first row describes the integrated weathering flux which integrates the other components listed and is relevant for Endmember Approach 1 (excluding the row on changes to soil organic carbon).

Description of term	Considerations for CDR quantification	Recommendations for near-term path forward
Integrated weathering flux The cumulative weathering signal of the dissolved phase, including the integrated effects of feedstock dissolution, cation sorption, secondary carbonate formation, secondary silicate formation, and alkalinity loss due to biomass uptake.	The integrated weathering flux is only required for the aqueous phase approach and is part of one endmember approach for constraining the NFZ balance. If not measuring the integrated weathering flux, the components of carbon sources and losses must be accounted for individually (see below).	• Measure dissolved weathering products directly as they are generated in, and exported from, the NFZ. • Aqueous phase measurements should be taken at the end of the NFZ (or in drainage waters or downstream catchments) in order to calculate a net export flux of weathering products.
Feedstock dissolution The dissolution of minerals in the feedstock after application on the deployment site (potential CDR).	Impacted by temperature, pH, variable water content and fluid residence time, kinetic inhibitors and dissolved phases that enhance rates, the formation of secondary phases, and the impacts of biological processes.	• Collect direct empirical measurements that capture alkalinity release in the solid phase via solid-phase, mass balance-based approaches. • It is highly recommended that feedstock application rates be empirically constrained by measuring the soil concentration of an immobile element or isotope ratio before and after feedstock application.

Description of term	Considerations for CDR quantification	Recommendations for near-term path forward
pH/non-carbonic acid weathering Chemical weathering done by acids other than carbonic acid such as sulfuric, nitric, or organic acid, or in low pH soil.	• Weathering by non-carbonic acids does not lead to base cations charge-balanced by DIC, but does neutralize acidity that may have otherwise reacted with bicarbonate and caused CO2 degassing. • In strongly acidic soils (pH < 4.5-5, pCO_2 dependent), the cations released by weathering are charge-balanced by very little bicarbonate.	• Any non-carbonic acid weathering in the NFZ should be removed from netCDR. • Constrain non-carbonic acid weathering directly through aqueous phase measurements or estimate strong acid addition/production, fully discount from netCDR, and account for degassing. • For now, assume organic acids will be degraded following reaction with silicate minerals and generate an equivalent amount of DIC as carbonic acid weathering (Working Group 2). Do not include in the term balance. • To account for low pH weathering, monitor for declines in exchangeable and bound acidity.
Cation Sorption Adsorption of cations onto soil particle surfaces (e.g., clay minerals, organic matter, mineral oxides).	Cation sorption can act as a transient alkalinity sink; when base cations exchange for acidic cations on exchange sites, the removal of those cations from solution 'undoes' any CDR they were driving (or equivalently, the proton release into solution drives CO2 evasion). As base cation concentrations in the soil solution decrease or the soil begins to re-acidify, these cations can eventually re-enter the soil solution and drive CDR.	• If $CO_2e_{NFZ,RP}$ is constrained by the time-integrated alkalinity flux at or beyond the end of the NFZ, alkalinity loss from cation exchange processes has already been accounted for–no direct measurement of the exchangeable fraction required. • If feedstock dissolution is constrained independently and netCDR in the NFZ is calculated as the sum of sources and sinks, cation exchange capacity and base saturation or exchangeable acidity should be quantified using established methods.
Secondary carbonate formation Precipitation of carbonate minerals (e.g., calcite) in the soil profile.	Secondary carbonate formation in the soil profile and downstream systems can represent a stable (and measurable) store of atmospheric CO2 for ERW deployments with non-carbonate feedstocks. However, secondary carbonate formation reduces (and for carbonate feedstocks, negates) potential CDR by removing cations and charge-balancing carbonate alkalinity from solution.	• Can be directly monitored through changes in soil inorganic carbon stocks relative to business as usual plots. • Location-specific context will be needed to determine the probability of carbonate formation and how to account for it. • Potential strong acid weathering should be considered if reductions in SIC stocks between reporting periods is observed.
Secondary silicate formation Secondary silicate minerals (e.g., clays), amorphous Si, and Fe/Al oxy-hydroxides can form in many potential deployment sites, though other secondary phases–for example, Ca-phosphates–can be formed	Secondary silicate phases can form quickly (hours to days), and their formation may be spatially and temporally separated from the initial weathering reaction. Their formation will reduce CDR efficiency by removing base cations from solution. It is difficult to identify	• Potential quantification options may depend on the secondary phase of interest. • It is not recommended that early-stage commercial deployments be required to independently constrain NFZ alkalinity loss through secondary silicate formation due to

Description of term	Considerations for CDR quantification	Recommendations for near-term path forward
in specific systems.	regimes where secondary silicate or Fe/Al oxy-hydroxide could be assumed to be fully negligible (Working Group 2), and therefore should be accounted for in netCDR.	challenges associated with direct quantification of secondary silicate phases. • Placing bounds on the potential netCDR loss through stoichiometric arguments may be a good place to start.
Biomass uptake of base cations Plants retrieve nutrients from the soil solution, including base cations such as Ca2+, Mg2+, K+, and Na+; generally accompanied by a release of protons to maintain charge balance within the plant.	Biomass uptake of base cations 'undoes' any CDR that was being driven by the base cations in solution; or equivalently, drives CO_2 evasion.	• Plant uptake should be estimated through direct measurements of the base cation content of relevant biomass, including biomass that is removed from the field. • Sufficient data does not yet exist for use of predictive frameworks to estimate element-specific plant uptake for different crop types under different growing conditions (Working Group 2).
Changes to (soil) organic carbon stocks An increase in soil organic carbon via accumulation or a decrease in soil organic carbon via respiration.	Observations thus far have demonstrated variable responses of SOC to alkaline feedstock addition in field trials, mesocosm studies, and laboratory experiments. Small changes in the balance between photosynthesis and respiration, or a destabilization of existing soil organic carbon stocks, could substantially reduce (or even completely negate) CO_2 uptake by an ERW deployment.There are some soil conditions that are at particularly high risk for SOC loss resulting from an ERW deployment.	• ERW intervention's potential impact on soil organic carbon stocks and the net organic carbon balance is nascent, and we do not yet have enough data to consider the potential for SOC mobilization resulting from an ERW deployment to be sufficiently de-risked (Working Group 2). • Deployments should not be undertaken under conditions that have been deemed at 'high risk of substantial SOC loss' until sufficient evidence has been generated to de-risk the impact of an ERW intervention on organic carbon cycling in such systems. • For deployments not considered 'high risk', monitoring of bulk SOC stocks should be implemented on a representative sub-plot within the deployment area and corresponding 'business as usual' or negative control plot. • We do not recommend that any changes to SOC stocks be directly incorporated into netCDR quantification for commercial ERW deployments at this time. • SOC monitoring data should be transparently reported in a timely manner.

1.2.3 Overview of the Far-Field Zone

Once the weathering flux is exported from the NFZ, it passes into the FFZ, which we separate into three spatial regimes: the (lower) vadose zone and groundwater systems (Section 9.2), surface water systems (Section 9.3), and marine systems (Section 9.4).

When considering the FFZ, it is first important to identify the ultimate carbon storage reservoir and the probable transport path to that reservoir (Section 9.1). For example, while in many systems carbon will ultimately be stored as DIC in the ocean, some deployment areas may drain into long residence time groundwater systems that can be considered a durable storage reservoir, removing the need to consider potential losses in systems further downstream. Carbon may also be stored in carbonate minerals formed in the soil profile or along the flow path, and the durability of carbonate formed in different environments is discussed in Section 9.1.

Importantly, processes operating in the FFZ can lead to carbon gains and losses through time. For example, weathering reactions in highly acidic soils will consume protons in the soil profile, but do not lead to any CDR in the NFZ, as the base cations released from the feedstock will not be charge-balanced by DIC. However, when these cations eventually reach a higher pH surface water system within the FFZ, the carbonate system can re-equilibrate and drive additional CDR. Similar arguments can be made for non-carbonic acid weathering of alkaline feedstocks (Section 8.3).

Despite this, the carbon quantification framework developed here only considers *net losses* in the FFZ at this time. This conservative approach is taken because confidently predicting FFZ CDR would require robustly validated, catchment-scale models capable of simulating the site-specific proton, alkalinity, and carbon balance as a function of time for both counterfactual and deployment scenarios. The development of such predictive frameworks remains nascent; within "Foundations", we discuss simulating FFZ processes (Section 9) and explore the implications of not including gains to FFZ CDR in project-level quantification in this framework–from how this influences our understanding of CDR associated with carbonate weathering and liming (Section 5.5.1), to how we interpret the potential carbon benefits of titrating acidity from soil systems (Section 8.3).

Table 2. Considerations for the FFZ. Fluxes that should be considered for each spatial regime in the FFZ and recommended direction.

Spatial Regime	Fluxes to consider in a comprehensive accounting	Recommended near-term path forward (minimum viable product)
Lower vadose zone and groundwater flow paths	- All the fluxes in the NFZ also apply in this region. - It will be important to understand and identify permanent alkalinity sinks and changes to counterfactual alkalinity generation. - Exchange with the atmosphere is limited or nonexistent.	Largely a priority area for research and development: - Not currently feasible to require monitoring or modeling of processes in the deep vadose zone and along groundwater flow paths in commercial ERW deployments. - Undertaking deep vadose zone monitoring or installing groundwater monitoring wells in a select subset of commercial deployments, where applicable and feasible, is recommended.

Surface water systems	• Outgassing caused by DIC system equilibration. • Carbonate mineral burial. • Changes to organic matter respiration and metabolic activity in stream/river systems, including the influence on aquatic vegetation that directly takes up bicarbonate. • Authigenic clay formation and reverse weathering. • Bedrock interaction with solution and changes to counterfactual alkalinity generation. • Changes to nutrient export and nitrogen cycling.	Focus primarily on: • Outgassing caused by DIC system equilibration. • Carbonate mineral precipitation (assume it doesn't re-dissolve) It is recommended that practitioners assess the potential for net CO_2 loss due to these processes at a minimum in two spatial regimes: in the immediate discharge zone (i.e., the surface water system the weathering flux from a deployment is draining into), and in the major river system of the deployment catchment (i.e., the highest order segment in the deployment catchment).
Ocean	• CO_2 evasion due to <u>carbonic acid system equilibration</u> in the coastal ocean. • Carbon and alkalinity feedbacks due to changes to surface ocean chemistry. • Carbon and alkalinity feedbacks due to changes to diagenetic reactions in shallow marine sediments. • Long timescale marine carbonate burial.	Focus primarily on: • CO_2 evasion due to <u>carbonic acid system equilibration</u> in the coastal ocean. At a minimum, practitioners should derive a conservative assumption of evasion from carbonic acid system equilibration by considering the thermodynamic storage efficiency as a worst-case scenario, assuming complete equilibration with atmospheric CO_2 at representative temperature, salinity, and current atmospheric pCO_2.

1.2.4 Life Cycle Emissions

In addition to carbon and cation fluxes in the NFZ and FFZ, **life cycle emissions** are the third category of greenhouse gas fluxes that must be accounted for in project-level netCDR quantification. Life cycle emissions can take place both prior to the deployment ("upstream" emissions) and throughout the project lifetime. Practitioners should produce a life cycle assessment (LCA) that follows the general LCA guidelines described in ISO 14040 and ISO 14044 standards. High-level recommendations for best practices, specifically targeting substantive decisions specific to ERW deployments discussed by Working Group 5, are outlined in Section 10.

1.3 Introduction to counterfactuals, controls, time accounting, and uncertainty

Section 5 establishes a term balance for overall netCDR and calculating the carbon balance in the NFZ, FFZ, and for project life cycle emissions, and provides guidance on defining and quantifying counterfactual baseline CDR, navigating the complexities of time accounting for ERW projects, and uncertainty quantification.

Counterfactuals
In order to successfully quantify netCDR using the term balance presented here, a counterfactual baseline–i.e., a comparison to the netCDR that would have occurred had the project never been

established–is required. Before beginning a project at a new deployment site, it is important to articulate a counterfactual scenario, describing the farming practices that would be performed on the field had the ERW deployment not occurred. Given that in some contexts agricultural liming practices can be a net sink of CO_2 in the NFZ, this should include the counterfactual application rate, application frequency, and composition of the agronomic pH control practices. The counterfactual scenario should also include cropping and tillage practices, fertilizer usage, and irrigation practices.

In ERW deployments, to quantify any netCDR in the NFZ associated with the counterfactual scenario, practitioners are recommended to maintain business as usual (BAU) plots on which all counterfactual practices are implemented. This would allow for more accurate quantification of the NFZ CDR of that counterfactual practice, as well as would provide a much-needed baseline from which to compare shifts in time-varying parameters (e.g., SOC, SIC, dissolved solutes). However, in some cases this will not be feasible on working farms with constantly shifting practices and logistical constraints. Instead, a conservative estimate of $CO_2e_{CF\,NFZ,\,RP}$ due to liming practices may be developed by assuming that all of the applied liming agent dissolves and drives netCDR at 100% field efficiency (Section 5.5.3.1). As per the definitions and recommendations in section 5.5.4.2, adjustments to the final netCDR calculation should be made such that carbon removal credits are not awarded for avoided emissions.

Time accounting
A prevailing challenge across CDR pathways is that CO_2 emissions and removals do not occur simultaneously with the initiation of a project. The carbon balance of an ERW deployment is arguably best thought of as a timeseries of carbon 'gains' (removal from the atmosphere) and losses through time. Upstream LCA emissions occur before and during the initial spreading of the alkaline feedstock. Feedstock dissolution will occur over a period of years. Following the release of alkalinity through feedstock dissolution, the transport and storage of cations in the soil profile can lead to non-negligible lags between feedstock dissolution and when DIC is produced and exported from the NFZ (Amann et al., 2020; Kanzaki et al., 2024). Carbon can continue to be lost and gained as the weathering products are transported through downstream systems to an eventual durable storage reservoir (Section 9). The choice of a time accounting framework is ultimately a normative decision, but one that has many implications. Importantly, developing cohesive frameworks for time accounting within and across CDR pathways is very much a work-in-progress and critical challenge for the broader CDR community in the coming years.

We first introduce a series of frameworks for considering when CDR is generated in the NFZ in Section 5.3. A common thread to all of these frameworks is that *potential* CDR is generated upon feedstock dissolution, and thus crediting should not be considered until alkalinity release from the feedstock has been empirically demonstrated. These proposed frameworks largely differ in the details of how the potential for time-varying alkalinity sinks within the NFZ are treated.

Uncertainty and statistical methods
Uncertainty in each parameter being estimated (e.g., analytical error of measurements, sampling uncertainty of each NFZ parameter) must be appropriately propagated through the netCDR calculation. Estimators for netCDR and novel statistical methods used should be validated to characterize bias and variance, ideally both empirically and through theoretical justifications. The use of statistical approaches to develop a robust, site-specific sampling plan is paramount. Care must be taken when designing deployments in order to demonstrate a causal relationship between alkaline feedstock application and a quantified carbon removal effect. In particular, including multiple replicates of both control and treatment field areas is important to avoid pseudoreplication, and projects should take care to avoid systematic bias in how field areas are assigned to control or treatment.

2 Project level considerations

2.1 Measurements for ERW

ERW impacts the solid, aqueous, and gaseous phases of the soil system. Measuring each of these phases provides a different lens into the system that comes with its own considerations, assumptions, and uncertainties.

Solid phase measurements
Solid phase sampling is used to measure the addition of feedstock to the soil profile, loss of cations over time, and the decrease in soil acidity, and may be able to estimate carbon removed from the NFZ. Grappling with soil heterogeneity at various spatial scales is key to determining the sampling density, location, and types of analyses necessary to quantitatively demonstrate net carbon removal. Rather than directly recommending a particular minimum sampling density that would hold across deployment contexts, we strongly encourage pre-registration and transparent uncertainty characterization. Failing to take sufficient samples will result in a lack of resolvable signal, and therefore no net carbon removal quantified. Some justification for the chosen sample size for each soil parameter should be provided in a project design document, likely in the form of an explicit or numerical power analysis.

In addition to the considerations for soil heterogeneity, sampling rounds should be planned over the course of the project to capture baseline observations, both prior to and post feedstock application. Types of sampling rounds that should be considered are discussed in Section 7.4.1.

Aqueous phase measurements
Aqueous measurements for quantifying carbon removal associated with ERW deployments can take many forms, including measurements of soil porewater collected at various depths (e.g., Holzer et al., 2023; Paessler et al., 2023) or sampling drainage waters — such as from proximal streams or at the outlets of tile drained systems (e.g., Larkin et al., 2022). Aqueous measurements integrate the cation, alkalinity, and DIC fluxes that must be tracked for NFZ CDR quantification down to the depth where samples are collected (see Section 5.4), and can therefore provide a direct measure of CO_2 removed from the atmosphere in the soil profile. However, any sampling effort needs to capture the spatial and temporal variability in the aqueous measurements.

Aqueous measurements of key parameters for assessing CDR (e.g., cation concentrations, DIC, total alkalinity, pH) must also be compared to an estimated baseline of counterfactual fluid chemistry through time. This may be established via aqueous phase measurements on representative business as usual (BAU) plots that are hydrologically similar to, and ideally hydrologically isolated from, the deployment area. However, demonstrating that a control plot is representative can be challenging. To calculate the time-integrated export of DIC, base cations, or other weathering products from the NFZ, it is necessary to estimate the net water flux through the soil profile over time. Practitioners must account for high amounts of temporal and spatial variability in aqueous measurements. Frequent measurements (especially following precipitation events) should be taken, and methods used to temporally interpolate between sampling events should be reported. Ideally, spatial density of aqueous samples should be informed by the baseline variability of dissolved species being measured at the site.

Gaseous phase measurements

Direct measurements of CO_2 fluxes can be another important lens on the soil system and NFZ carbon dynamics. Soil CO_2 concentrations exert a primary control on mineral dissolution rates and are an important data stream to help improve predictive modeling capabilities. Soil or ecosystem CO_2 exchange can be measured through various approaches that target different spatial scales including flux towers, flux chambers, and CO_2 profile measurements from in-situ CO_2 sensors at one or more depths in the soil profile (see Section 7.6). Resolving the inorganic component will be highly challenging given the significant background of space and time-varying carbon fixation and soil respiration, and will likely require gaseous measurements at high temporal resolution. As a broad recommendation for deployments today, soil CO_2 measurements should not be used as a sole means of quantifying CDR in ERW deployments, at least until gas-phase approaches are repeatedly co-deployed with–and validated against–high quality solid and/or aqueous-phase measurements. However, we strongly encourage the continued collection of high resolution CO_2 concentration and flux data in both laboratory and field settings where possible.

2.2 Know your site

In this quantification framework, a "deployment area" is defined as a field or group of fields that represent the statistical population to which a single ERW treatment is applied and for which net carbon removal will be estimated. It is the grouping at which an overall statistical analysis will be performed (a quantification of netCDR with uncertainty), and for which a single project design document should be specified. All fields or field areas within the same deployment must have broadly consistent time of spreading, composition of applied feedstock, and geographic region.

Site-specific characteristics (e.g., baseline variability of soil biogeochemistry, hydrologic flow paths) should dictate the deployment layout, the definition of control and treatment areas, and the design of the monitoring plan. For each deployment site, practitioners should consider the spatial extent of the NFZ, flow paths along which weathering products move through (and are exported from) the NFZ, and how details of the baseline soil (both composition and variability) and microclimate dictate the sample density and analytical precision required to quantitatively demonstrate CDR. Section 3 provides high-level guidance on site characterization to inform project design and interpretation of monitoring results; Section 4 provides guidance and considerations for determining the spatial extent of the NFZ in a site-specific manner.

Many of the processes that impact netCDR in the NFZ will extend below the determined NFZ boundary at some sites. Recognizing the simultaneous importance and operational challenge of taking deeper measurements, a near-term approach that balances the imperative to sufficiently characterize the system with operational constraints is required. This could include a focus on comprehensive sampling that includes direct characterization and monitoring of deeper soils on targeted representative subplots of larger deployments and/or more highly monitored demonstration sites. In the context of commercial deployments, we strongly recommend that in the near-term, these "deeper NFZ monitoring" fields be included in the MRV cost of the deployment, given the central importance of these processes to the ultimate netCDR quantification.

2.3 Feedstock characterization

Characterization of the alkaline feedstock proposed for use in an ERW context is a critical component of deployment planning. Outlined here are recommendations for a suite of minimum requirements for feedstock characterization, which serves two purposes:

- **Assessing CDR potential:** Determining the feedstock's capacity to take up atmospheric CO_2 through mineral weathering reactions.

- **Identifying potential health and environmental impacts:** Assessing risks associated with the feedstock's chemical composition, mineralogy and particle size distribution.

To ensure responsible deployment, all feedstock characterization steps outlined in Section 6 should be completed, and the suitability of the feedstock confirmed based on the results, before field application commences. In the future, it could be highly beneficial for the geochemical CDR community to align around more formalized standards and regulations for feedstock and source rock characterization. The frequency of feedstock characterization sampling should depend on an analysis of the inherent variability of the feedstock's properties across the source material, occurring at least once per deployment and with protocols specifying re-characterization at a fixed tonnage frequency. Feedstock characterizations should include measurements to determine the chemical composition, mineralogy, particle size distribution, and moisture content of the feedstock. An estimated CDR potential of the feedstock should be calculated, representing a maximum CDR that might be expected from the applied feedstock over the entire project lifetime. While the modified Steinor equation can be used to approximate maximum potential CDR, it is recommended that practitioners attempt to calculate a more realistic "project-specific" estimate given the feedstock's mineralogy, particle size, and the deployment conditions.

To determine any risks to health and safety–for humans and for the broader ecosystem–practitioners should screen for potentially toxic trace elements, asbestiform minerals, respirable crystalline silica, radioactivity, and the fraction of the feedstock at respirable particle sizes as described in Section 6.2.3. Project design documents should include a comprehensive Health and Safety Risk Assessment.

3 Looking ahead

"Foundations" provides recommendations and a framework for quantification of CDR in ERW deployments. Importantly, the recommendations and framework provided now need to be tested in real world systems by conducting comprehensive netCDR quantification and transparently reporting on the results. Due to the frequent release of new findings, we recommend that meta-analyses be regularly conducted to ensure that quantification of all fluxes are being accounted for using the most up-to-date science available. These meta-analyses would incorporate new findings on topics addressed throughout this section (e.g., ERW-SOC interactions, secondary phase formation, etc.) and form the basis for a re-evaluation of quantification methods proposed in this document.

As part of this cycle of deployment-driven learning, there are a number of key areas of research that can be pursued. The full list of R&D topics described in "Foundations" are listed in an appendix to the main document. Sections 8 and 9 provide a detailed consideration of each of the fluxes/components of the term balance in the NFZ and FFZ. These sections contain context on the underlying science, state of understanding, and considerations and recommendations for capturing that flux in project-level quantification for early-stage deployments. In addition to flux-level areas of R&D, geochemical modeling of ERW represents a significant area of development and is a critical tool for understanding and interpreting the soil processes at play, including both process-based and data-driven model development. This is further discussed in Section 8.10 for the NFZ and Section 9.3.3 for the FFZ. If ERW is to reach significant scale, it is highly likely that models will eventually need to be a central component of CDR quantification such that monitoring and verification can become less reliant on high density measurement and sampling for every deployment. Thus, there is a strong need for the development of third-party, impartial systems for model validation and uncertainty analysis, such that we can evaluate the predictive skill and sensitivity of ERW models, and understand how and when they can play an increasing role in robust CDR quantification.

To support the development of ERW, answer open scientific questions, and and support the development of models, timely and transparent data sharing of both commercial and non-commercial field data will be instrumental. We urge the ERW community to proactively and transparently share data to enable rapid deployment-led learning.

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