

Three Years of Field Trials Indicate a Sustained Enhanced Rock Weathering Signal with Limited CO₂ Removal

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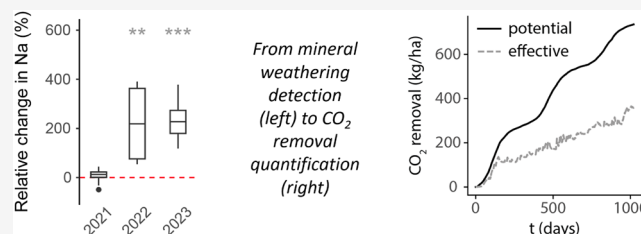
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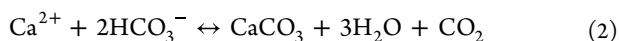
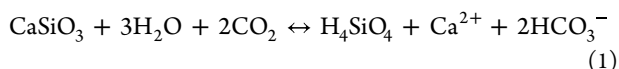
ABSTRACT: Enhanced rock weathering (ERW) is a CO₂ removal technology that involves spreading finely ground silicate rock on fields. The chemical weathering of this rock powder removes atmospheric CO₂ in the form of bicarbonate ions and secondary carbonates. Despite some promising theoretical simulations and laboratory findings, results from field trials that evaluate the ERW's impact on soil biogeochemistry and CO₂ removal are still scarce. This study investigated the impact of basaltic rock powder applied at the equivalent rate of 20 t per hectare (2 kg m⁻²) in three temperate vineyard fields in Switzerland over 1000 days. Analyses of soil pore water revealed that most standard ERW monitoring proxies (pH, electrical conductivity, total dissolved inorganic carbon, calcium, and magnesium concentrations) did not increase significantly. By contrast, sodium concentration in soil pore water was on average 3-fold higher in the rock powder-treated plots, indicating active mineral dissolution. Integrating the pore water results with model analyses, we estimated that the average CO₂ removal rate was 100 ± 30 kg CO₂ ha⁻¹ yr⁻¹, which is 10 to 30 times lower than the upper rates reported in some previous modeling and experimental studies. Future work is now needed to improve our understanding of ERW's CO₂ removal potential and soil contamination under a variety of soils, rock feedstocks, and climate conditions.

KEYWORDS: enhanced weathering, enhanced silicate weathering, soil remineralization, negative emission technology, nature-based solution, carbon sequestration



1. INTRODUCTION

Terrestrial enhanced rock weathering (ERW) is gaining traction as a decisive CO₂ removal technology to mitigate climate change.^{1–3} ERW involves applying silicate rock powders to soils—mainly agricultural ones. The dissolution of silicate minerals rich in base cations (Ca²⁺, Mg²⁺, K⁺, Na⁺) leads to the removal of CO₂ in the form of dissolved inorganic carbon^{4,5} (esp. bicarbonate ions; see the example of wollastonite weathering in eq 1). The dissolved fraction will be transported through soils and rivers to the ocean, where the aqueous carbon removal can be considered stable for >1 kyrs, and even longer if calcite removes it from solution as a precipitate.⁶ In the case of calcite precipitation (eq 2), 50% of the initially removed CO₂ would be degassed and 50% would be locked in a solid mineral form for hundreds of thousands to millions of years.⁶ The CO₂ locked in dissolved inorganic carbon and in carbonates in the ocean makes ERW an almost permanent carbon sink on a human time scale.



On a global scale, basalt's natural weathering is estimated to remove 0.2 metric gigaton (Gt) CO₂ annually.⁷ Based on

molar concentrations of base cations, basaltic rocks are estimated to have an overall CO₂ removal potential of 0.3–0.4 t (t) CO₂ per t of rock.^{8–11} If applied at high and frequent doses (rates between 20 and 50 t per hectare and per year are commonly used in models), the global removal potential associated with ERW is estimated between 0.2 and 4 Gt CO₂ yr⁻¹ depending on rock powder and pedoclimatic characteristics.^{2,12–16} To put these values into perspective, this order of magnitude of mitigation would compensate for 1% to 21% of the current annual atmospheric CO₂ rise¹⁷ and could significantly contribute to the 1 Gt CO₂eq yr⁻¹ reduction target expected from agriculture by 2030 in the fight against climate change.¹⁸

Currently, mafic rocks such as basalts and basanites are considered ideal candidates for ERW due to their relatively high reactivity, high base cation content, and relatively—although non-negligible—low heavy metal concentrations.^{15,19–21} Such feedstocks could deliver cobenefits such

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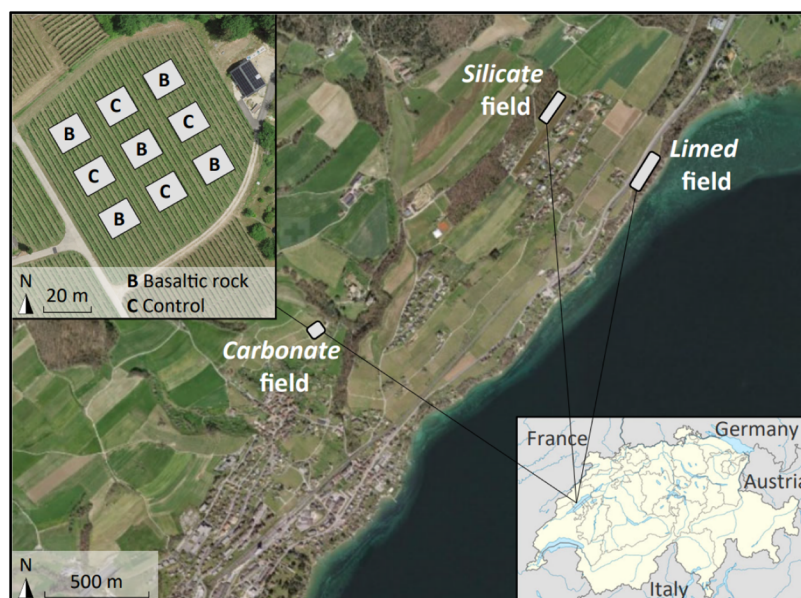


Figure 1. Field experiment site map. Location of the three experimental fields together with the experimental plan (inset, top left). (Source: ESRI (inset map), Swisstopo (aerial map)).

as base cation and silica fertilization, together with a liming effect (an increase of the soil pH) that could improve yields and food safety.^{15,22–24} Their use in highly acidic soils ($\text{pH} \leq 5$) could prove especially relevant given that most silicate minerals display their highest weathering rates in acidic conditions.²⁵

After successfully passing the proof of concept, simulation, and development stages, ERW has now reached the field validation stage. This stage is essential to assess ERW's effective ability to remove CO_2 before any large-scale adoption. As of 2025, peer-reviewed CO_2 removal estimates from ERW field trials remained limited and highly dispersed. Two studies in tropical northeastern Australia²⁶ and Malaysia²⁷ estimated either insignificant or very limited in situ CO_2 removal rates ($0\text{--}0.3 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$) due to limited feedstock reactivity (both in terms of grain size and mineralogical composition) and noncarbonic acids driving the weathering reaction.^{4,5} Another study conducted over three years in California (USA) reported a net $0.27 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ using metabasalt ($37.8 \text{ t of rock ha}^{-1} \text{ yr}^{-1}$) in a Mediterranean climate.²⁸ On the other hand, 5-year field trials in China using $100 \text{ t of basalt ha}^{-1} \text{ yr}^{-1}$ reported an average removal rate of $1.2 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$.²⁹ Clearly, these disparate results cannot be deemed satisfactory to assess ERW's CO_2 removal potential and more trials are still needed.³⁰

Detecting an enhanced weathering signal and then converting it to a CO_2 removal rate are both challenging in soils. At the field scale, the distribution of soil organisms, organic matter, and minerals, as well as topographical factors influencing moisture and aeration levels, leads to highly heterogeneous dynamics from one meter to the next.³¹ Additionally, ERW is based on accelerating a geochemical weathering cycle that already occurs in many mineral soils (eq 1). Other naturally occurring reactions, such as carbonate dissolution (eq 2, forward) and secondary carbonate precipitation (eq 2, reverse), can also alter CO_2 and ionic fluxes. To overcome this, using highly reactive feedstocks is a necessary but nonsufficient condition.^{5,32} A combination of ERW monitoring parameters (pH, electrical conductivity,

cation concentrations, carbonate content) are needed to overcome the noise associated with soil heterogeneity.³³

Among base cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+), sodium may be an overlooked yet promising potential ERW proxy. Sodium is not an essential nutrient for most plants,³⁴ meaning that it is not subject to significant biocycling. Additionally, sodium has the lowest selectivity in the lyotropic series.³⁵ This means that, when silicate weathering releases cations, sodium is the least likely to be adsorbed on reactive surfaces and withdrawn from the soil solution. Provided that the sodium bearing minerals are reactive enough, detecting a sodium signal in the soil pore water may therefore prove useful to track ERW, as was already witnessed in a 1-year field trial.³⁶

Converting the enhanced weathering signal into a CO_2 removal rate is equally—if not even more—challenging since the soil biotic and abiotic processes can alter the soil pore water composition, and decouple the alkalinity generation due to feedstock dissolution and the carbon removal process.^{37–39} This decoupling can potentially delay signal detection and dampen ERW's apparent efficiency.^{3,40,41} For example, plants and microorganisms can absorb base cations and release protons in exchange, thereby temporarily lowering the alkalinity of the soil solution and the associated CO_2 removal.⁴² To circumvent these challenges, multiphase system modeling is increasingly employed to capture the coupled dynamics of fluid flow, solute transport, and mineral interactions.^{14,40,43}

Our study aimed at contributing to ERW's field validation stage. To do so, we applied basaltic rock powder (20 t ha^{-1}) to three Swiss fields with distinct geochemical traits and monitored the evolution of soil pore water over 1000 days. Our goals were 1) to evaluate to what extent the enhanced weathering signal could be detected above the noise generated by natural weathering and nutrient cycling and 2) to estimate the associated CO_2 removal. The ERW signal was assessed using a combination of soil pore water parameters (pH, electrical conductivity, dissolved inorganic carbon and base cation concentrations) that were monitored monthly. The CO_2 removal was estimated using a first-order stoichiometric mass-

balanced approach and then compared to the ERW-tailored Soil Model for Enhanced Weathering (SMEW) that has been shown to successfully reproduce various ERW experimental results, ranging from controlled laboratory incubations to open-field mesocosm studies.⁴⁰ Due to the suboptimal mineral weathering conditions associated with temperate climates,⁴⁴ we expected the weathering signal and CO₂ removal rates to be moderate across all fields.

2. METHODS

2.1. Site Description and Rock Powder Characteristics. Our field trial investigated the impact of terrestrial ERW over three years in a temperate climate and agricultural context. The study was conducted in three organic vineyard fields located in Gorgier (Canton of Neuchâtel) in Western Switzerland (Figure 1). The site features and basaltic rock characteristics have been previously described in detail in Dupla et al. (2024)³⁶ and can also be found in the [Supporting Information](#) of the present study.

Briefly, all fields are permanently covered and lie on Quaternary moraines dominated by quartz, muscovite, clays, K-feldspar, and Na-plagioclase (Table S1). One field still contains a fraction of calcium carbonate ($13.8 \pm 4.4\%$), based on the total mineral carbon content from the Rock-Eval analysis.⁴⁵ Hereafter, this field is referred to as the *Carbonate* field. The second field received 100 kg ha⁻¹ dolomitic limestone annually until 2007, whereas the third field did not. For clarity, these two fields are hereafter referred to as the *Limed* field and the *Silicate* field, respectively. All soils belong to the Cambisol reference soil group according to the World Reference Base for Soil Resources⁴⁶ and have a loamy texture. The *Limed* and *Silicate* fields are slightly acidic (pH H₂O 6.5 and 6.4, respectively) while the *Carbonate* field is alkaline (pH H₂O 7.5). The effective cation exchange capacity (CEC) was 29.7, 31.5, 22.4 cmol_c kg⁻¹ for the *Carbonate*, *Limed* and *Silicate* fields, respectively, with calcium occupying >80% of exchanges sites and total base cations occupying 98–100% of them (see Table S2 for additional physicochemical soil properties measured in the top 0–10 cm layer).

The rock powder is a fine, silt-sized (80% below 52 μm) basaltic rock (commercial name “Eifelgold”, RPBL company) originating from Wassenach (quarry location: 50.448736° N, 7.278598° E) in the Eifel region, Germany. Its CO₂ removal potential reaches 400 kg CO₂ t⁻¹ of rock,⁴⁷ as calculated using the modified Steinour equation.^{10,48} The rock is classified as basanite according to the total alkali silica (TAS) classification of volcanic rocks⁴⁹ and is devoid of secondary calcite. The mineral fraction is composed of pyroxenes (augite) (45%), olivine (Fo₇₅) (18%), plagioclase (labradorite) (9%), feldspatoids (leucite) (8%), Fe–Ti oxides (10%), micas (phlogopite) (2%) and interstitial glass (8%) (Table S3). The Na-rich interstitial glass is known in basanites for its resemblance in elemental composition and weathering dynamics with nepheline.^{50,51} Microscope observations revealed that most of the feedstock was made of vesicles (Figures S1 and S2). There was a strong heterogeneity in size among minerals, ranging from 1 to 10 mm phenocrystals (augite, fresh and weathered forsterite, and phlogopite), ~50–100 μm nodules (leucite and olivine), and a submicron groundmass composed of Fe–Ti oxides and Ca–Na plagioclase minerals (mainly labradorite).

2.2. Experimental Setup. Each field was split into 9 plots of 3 × 3 m, at least 7 m apart. In each field, 5 plots received basaltic rock and 4 plots were left as controls (Figure 1). Rock

powder was only applied once over the course of the whole study. The equivalent of 20 t ha⁻¹ (2 kg m⁻²) of rock powder was applied without any mechanical incorporation. This rate is in the low- to midrange of ERW application rates.^{10,14,15,19,52,53} Two days after application, two rainfall events (1 and 8 L m⁻², respectively) facilitated the incorporation of the rock powder into the grass-covered soil, with no observable evidence of surface runoff.

On each plot, a porous ceramic suction lysimeter (SPS200, SDEC) was buried at a 45° angle reaching a depth of 25 cm and was left to equilibrate for 7 days. During a pilot trial, lysimeters were also installed at 80 cm in each field and the water chemistry was compared to the shallower depth over one year. No difference in water chemistry was detected and only the 25 cm depth was subsequently retained. Throughout the course of the experiment, the pressure inside the lysimeters was set at −0.8 bar and a minimum of 100 mL of soil pore water was collected every other week for 7 weeks and then monthly. Soil pore water was collected in 50 mL polypropylene centrifuge tubes, which were filled completely to minimize headspace and prevent gas exchange. No irrigation water was added, meaning that sampling was usually impossible during summer (June to August). In 2023, due to severe drought conditions, sampling campaigns resumed in November. The cumulated annual rainfall and snowfall represented 1066, 833, and 974 L m⁻² in 2021, 2022 and 2023, respectively, with the annual 1994–2024 average being 955 L m⁻² (Source www.meteosuisse.admin.ch). In total, 381 soil pore water samples were collected during 22 sampling campaigns between March 2021 and December 2023 (1000 days). The experiment did not include soil analyses at the end of the experiment.

2.3. ERW Signal Monitoring. After extraction, samples were immediately filtered at 0.45 μm (Simplepure, Membrane Solutions) and then frozen in polypropylene centrifuge tubes at −20 °C. After careful thawing in the dark at 4 °C, pH measurement was conducted using a combination electrode (Orion 8172BNWP ROSS Sure-Flow, Thermo Scientific).⁵⁴ Base cation concentrations (Ca, K, Mg, and Na) were measured via inductively coupled plasma–optical emission spectrometry (ICP-OES, PerkinElmer Optima 8300).⁵⁵ Electrical conductivity was measured using a Smartchem 200 equipped with an EC module (AMS Alliance). Quality control implied checking the relationship between EC and total cation charge according to Appelo and Postma (2004)⁵⁶ (Table S4). Dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) were measured using a TOC-L analyzer (TOC-L, Shimadzu).⁵⁷ Bicarbonate molar concentration was not directly measured but was estimated based on DIC molar concentration and pH.⁵⁸ We included the mixing diagram approach from Gaillardet et al.⁵⁹ (1999) based on Na-normalized Ca²⁺ to HCO₃⁻ molar concentrations (Ca/Na, Mg/Na, and HCO₃/Na) to visualize the influence of basaltic rock powder addition.

2.4. Statistical Analysis. For each response variable and for each field separately, the difference between treatment and control was statistically assessed using a *t* test (0.05 alpha level of significance). Given that the statistical goal was to control the pairwise (rock powder vs control) and not the experiment-wise rate of type I error, no correction for multiple inference was applied.⁶⁰ When necessary, a variable transformation was performed to ensure normality and homoscedasticity of the residuals.⁶¹

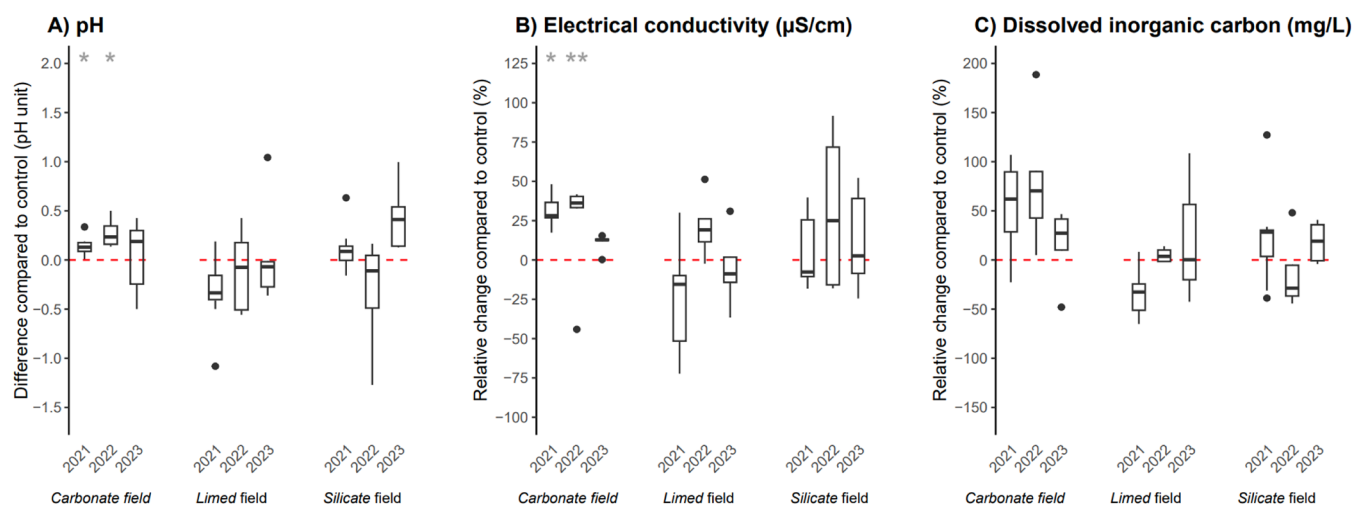


Figure 2. Evolution of soil pore water ERW proxies. Change in soil pore water pH, electrical conductivity, and dissolved inorganic carbon concentration over time. Changes are expressed as relative differences compared to control (%) except for pH, whose difference is expressed in pH units due to its logarithmic nature. Positive changes indicate higher values in rock powder-treated plots than in control plots. The measured values were averaged for each treatment and sampling campaign for each field. Relative changes were then calculated for each sampling campaign. Boxplots represent the distribution of the relative changes, with the median value represented by a bold line and outliers defined as 1.5 times the interquartile range. The year 2021 includes all samples extracted after the 24th of March 2021, the date of rock powder application. Statistical significance between treatment and control is indicated with gray stars (* < 0.05, ** < 0.01, *** < 0.001).

2.5. ERW's CO_2 Removal Assessment. ERW's CO_2 removal rates were estimated by combining a first order stoichiometric approach and a more refined approach using an ERW-tailored hydrogeochemical model.

Our first-order stoichiometric approach was based on the soil pore water concentrations of base cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+) and bicarbonate (HCO_3^- , carbon-based estimate). For each sampling campaign, we calculated the amount of base cations and bicarbonate produced by multiplying their average concentrations in the soil pore water with the weekly water balance (rainfall–evapotranspiration) provided by the neighboring Neuchâtel weather station ($47^\circ 00' 00.0''\text{N}$, $6^\circ 57' 11.2''\text{E}$). Evapotranspiration was approximated using the Penman-Monteith equation.⁶² Given the permanent vegetative cover in the inter-rows, the crop coefficient of 1 for grass was not changed. We acknowledge that this approach only constitutes a first approximation as it neglects vine root uptake beyond 25 cm and changes in soil water storage. When the interval between two measurements exceeded one month, a value derived through linear interpolation was incorporated to account for weeks exhibiting a positive water balance. This interpolation was applied exclusively to the month immediately preceding or following the subsequent measured value. The soil pH, ranging between 6.4 and 7.5, and the absence of fertilizer input promote efficient bicarbonate formation in response to alkalinity additions.⁴ We therefore assumed an entirely carbonic acid-driven weathering reaction, with 1) for the base cation approach: 2 mol CO_2 consumed per mol divalent base cation released (Ca^{2+} , Mg^{2+}) and 1 mol CO_2 consumed per mol of monovalent base cation released (K^+ , Na^+), and 2) for the bicarbonate approach: 1 mol CO_2 consumed per mol bicarbonate formed (eq 1) (additional methodological details available in SI).

The second approach relied on model reanalysis using the *Soil Model for Enhanced Weathering* (SMEW).⁴⁰ SMEW simulates the ecohydrological and biogeochemical processes involved in ERW within the upper soil layers. Briefly, a hydrological component estimates water balance and water

infiltration dynamics throughout the soil matrix based on weather (daily rainfall, temperature, and wind speed) and soil parameters (soil texture, bulk density, and organic carbon content). This part is interconnected with a geochemical component that estimates the weathering dynamics of the applied minerals and the fate of the released ions and alkalinity. Due to its similarity in elemental composition and weathering dynamics with nepheline,^{50,51} the interstitial glass was included in the model as nepheline. The characteristics of the different soil phases are included (reactive phase, soil pore water, plant uptake, and organic and inorganic carbon pools) and allow the prediction of ERW's CO_2 removal both in ionic bicarbonate and solid secondary carbonate forms. Based on the given parameters, the model estimates the rock powder's theoretical weathering rate,⁶³ which is then adjusted to the measured parameters in the soil solution via a dissolution factor. For instance, a dissolution factor of 0.1 implies that the observed weathering is 10 times slower than theoretically expected. This dissolution factor helps to quantify the discrepancy between laboratory and field experiments,⁶⁴ and can be used to identify the best responding field conditions. The complete parametrization of the model is detailed in SMEW's seminal paper.⁴⁰

Weather data (daily rainfall, temperature, and wind speed) were provided by the weather station mentioned above. Soil parameters (soil texture, bulk density, organic carbon content, cation exchange capacity, and mineralogical composition) were measured in each plot before rock powder application. For each parameter, the detailed methods are available in Dupla et al.³⁶ Briefly, soil texture was measured using grainsize laser diffraction,⁶⁵ soil bulk density using the core cylinder method,⁶⁶ and soil organic carbon using Rock-Eval pyrolysis with SOTHIS correction.^{67,68} Cation exchange capacity was calculated as the sum of the base cations and aluminum ($\text{cmol}_c\cdot\text{kg}^{-1}$) extracted using an unbuffered 1 M NH_4Cl solution,⁶⁹ while mineralogical composition was determined via powder X-ray diffraction (XRD).⁷⁰ Soil pore water parameters were measured as described in the above section.

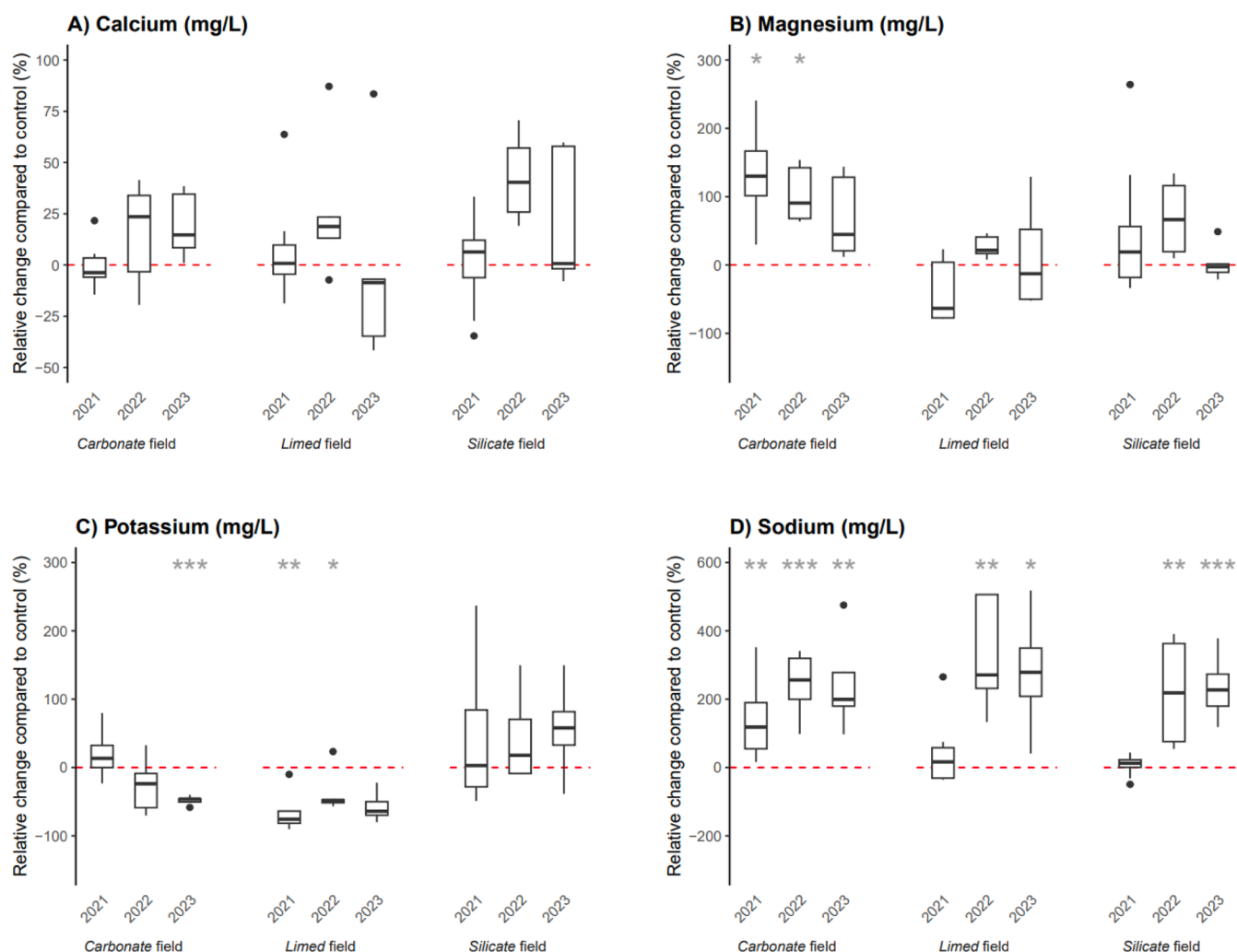


Figure 3. Evolution of base cation concentrations. Relative change (%) in base cation (Ca, Mg, K, Na) concentrations over time. Positive changes indicate higher values in rock powder-treated plots than in control plots. The measured concentrations were averaged for each treatment and sampling campaign for each field. Relative changes were then calculated for each sampling campaign. The year 2021 includes all samples extracted after the 24th of March 2021, the date of rock powder application. Statistical significance between treatment and control is indicated with gray stars (* < 0.05, ** < 0.01, *** < 0.001).

Raw weather, soil, and soil pore water results are available in [Supporting Information](#).

3. RESULTS

3.1. A Sustained Weathering Signal Mainly Detected via Sodium. The application of basaltic rock powder did not trigger a homogeneous response of ERW's common proxies. Soil pore water parameters such as pH, electrical conductivity, dissolved inorganic carbon (Figure 2) and most base cation (Ca^{2+} , Mg^{2+} , K^{+}) concentrations (Figure 3) remained vastly unaffected by basaltic rock powder application (raw values and timeline of each parameter can be found in [Supplementary Figures S3–S11](#)).

Sodium was the only base cation that yielded a clear and sustained signal across all fields. Its median concentration exceeded +200% in the second and third years in the rock powder-treated plots compared to controls (Figure 3). Using Ca/Na ratio proxy for silicate weathering,⁵⁹ we could detect an ERW signal across all fields within the first three months postapplication (Figure 4). This signal was most pronounced in the second and third years of the trial showing a transition

from a dominance of carbonate weathering to silicate weathering system (Figures 5 and S12).

3.2. Limited CO_2 Removal Rates. First-order stoichiometric estimates led to CO_2 removal rates below $100 \text{ kg ha}^{-1} \text{ yr}^{-1}$ when averaged across all fields and years (Table 1). Cation fluxes led to systematically positive CO_2 removal for the Carbonate and Limed fields with mean annual rates of $166 \pm 104 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ and $114 \pm 61 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$, respectively. The Limed field displayed strong variations in the cation fluxes—especially in calcium and potassium (Figure 3)—leading to an overall nonsignificant CO_2 removal ($-71 \pm 272 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$). Bicarbonate fluxes, derived from soil pore water pH and DIC values, confirmed the low but consistent CO_2 removal estimates in the Carbonate field while displaying more variable results in the two other fields. Given the distinct nature of the sodium signal and its tendency to be less subject to adsorption and biocycling, an exploratory pathway assuming a fixed sodium to base cations ratio was considered. It led to significant but limited CO_2 removal rates of $112 \pm 79 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ on average (additional details in SI).

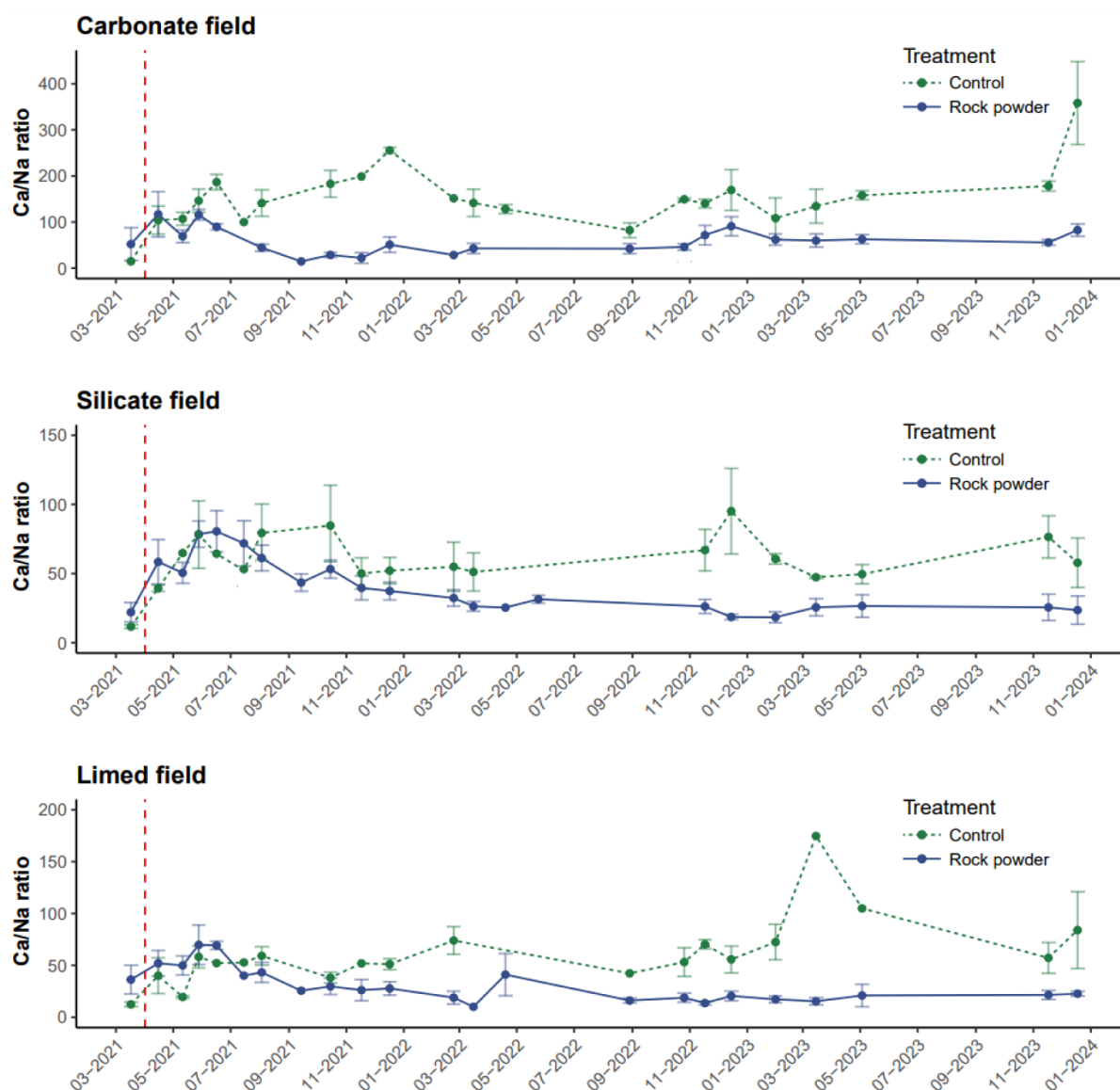


Figure 4. Carbonate vs silicate weathering signal. Evolution of the Ca/Na ratio over time for the plots treated with rock powder (blue) or left as controls (green). A decreasing Ca/Na ratio indicates an increasing influence of silicate weathering over carbonate weathering. Each dot corresponds to the average ratio for each sampling campaign and the error bar corresponds to the standard error of the mean. The date of rock powder application corresponds to the red dashed line.

SMEW reanalysis of the field data proved able to predict the observed change in soil pore water composition, with little variations in the most common ERW proxies and a significant increase of the Na concentration (Figure 6 for the *Silicate* field, and Figures S13 and S14 for the *Limed* and *Carbonate* fields). The weathering dynamics and Na accumulation were estimated to be primarily driven by Na-rich interstitial glass, which exhibited the highest weathering rate among the minerals in the basanite, followed by leucite and forsterite (Figure 7).

The estimated release of base cations corresponds to a carbon removal potential of approximately $200 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ (Figure 7)—considering a 1:1 molar ratio between base cation release and CO_2 removal as expressed in eq 1. Most of this potential was associated with the Na released by the interstitial glass, followed by K from leucite and Mg from forsterite. The Ca release was instead minimal. However, the

effective CO_2 removal—accounting for the actual formation of dissolved inorganic carbon and mineral carbonates in the soil—was estimated to be around $100 \pm 30 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ (Figure 7 and Figures S15 and S16). Roughly half of the theoretical potential was hence lost to sinks of base cations (soil adsorption, plant uptake, and secondary mineral formation) as well as suboptimal conversion of alkalinity to DIC.⁴

4. DISCUSSION

4.1. Signal Detection. This 3-year field trial revealed first that detecting an ERW signal was possible using standard analytical methods and a limited sampling resolution. Rock powder application led to a significantly different chemical signal within the first few months of the experiment (Figure 4). The Ca/Na ratio, classically used as a proxy for silicate weathering,⁵⁹ indicated an increased and sustained contribu-

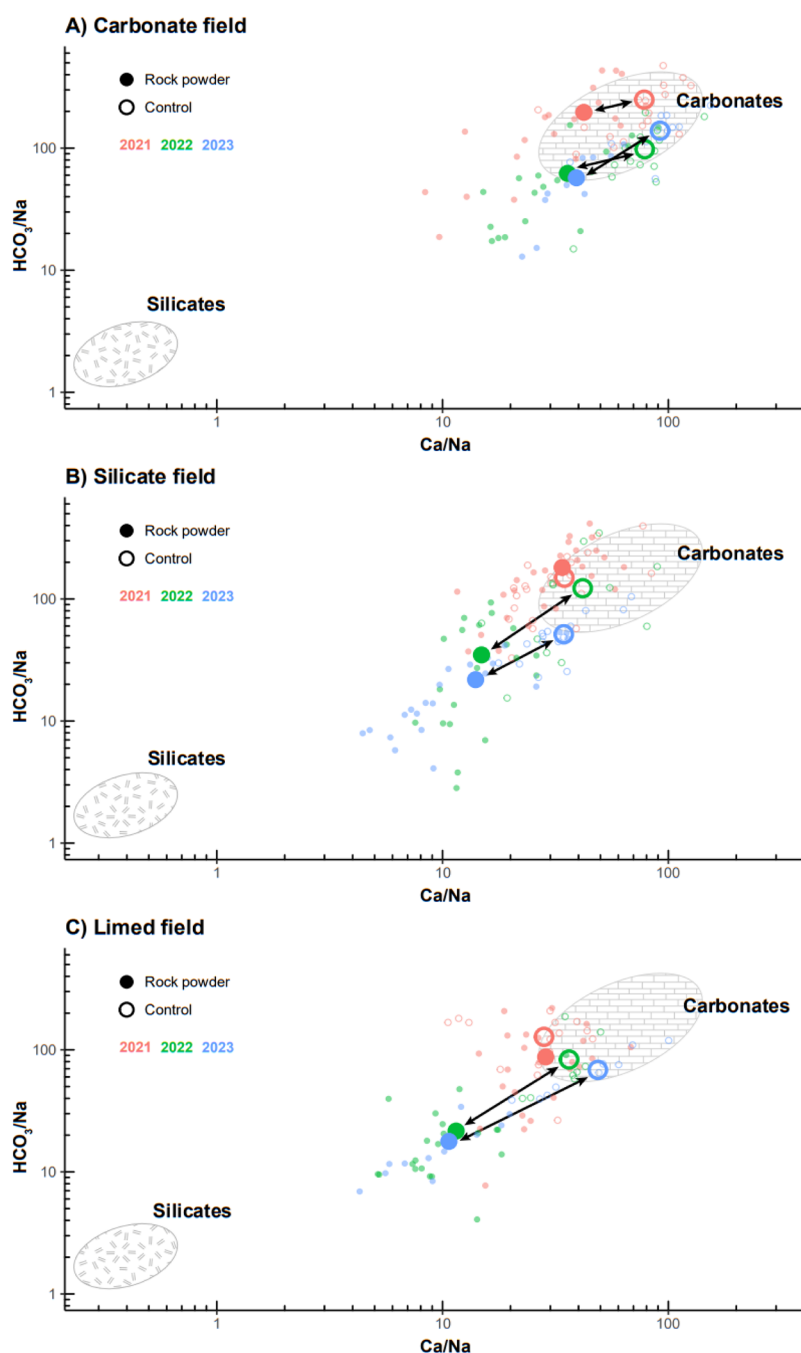


Figure 5. Carbonate vs silicate weathering Mixing diagrams. Diagram displays the average HCO_3^-/Na and Ca/Na molar ratios of the sampled soil pore waters after the application of rock powder on the 26th of March 2021 for the years 2021 (red), 2022 (green) and 2023 (blue). Each dot corresponds to one sampling campaign and is the average of all plots treated with rock powder (filled circles) or left as control plots (hollow circles). Each large dot corresponds to the yearly average of all treated plots (filled circle) or of all control plots (hollow circle). When treated and control yearly averages were distant from each other, double-headed arrows were inserted to facilitate visualization. Silicate and carbonate end-members (ellipses) were inserted following Gaillardet et al.⁵⁹

tion of silicate weathering to the soil solution chemistry throughout the experiment (Figure 5). The decrease of this ratio was mainly driven by a relatively higher release of sodium (+200% on average) compared to calcium (Figure 3) (see Figures S6 and S9 for the evolution over time of calcium and sodium concentrations, respectively). The rapid increase in sodium in the soil pore water is in line with the findings from a 46-day incubation experiment that noticed a + 533% sodium increase when mixing the same “Eifelgold” basanite rock powder with cattle slurry.⁷¹

In both cases, the sodium release was arguably primarily driven by the weathering of the Na-rich interstitial glass fraction (Figure 7). At circumneutral pH, this phase is indeed known for its relatively high weathering rate ($10^{-8.6} \text{ mol m}^{-2} \text{ s}^{-1}$ at pH 7 and 25 °C).⁷² For comparison, at neutral pH and room temperature, this phase weathers one to 2 orders of magnitude faster than olivine-rich rocks,²⁵ often promoted in ERW studies for their fast-weathering nature.^{73–75}

However, most of the commonly recommended ERW proxies, such as pH, electrical conductivity, inorganic carbon

Table 1. First Order CO₂ Removal Estimates^a

		CO ₂ removal rates (kg CO ₂ ha ⁻¹)					
		via base cation stoichiometry			via bicarbonate stoichiometry		
		2021	2022	2023	2021	2022	2023
Carbonate field	Rock powder	500	1252	1090	685	627	683
	Control	433	977	935	431	413	575
	Rock powder—Control	67	275	155	254	214	109
Limed field	Rock powder	586	682	697	654	332	412
	Control	867	446	867	1167	311	472
	Rock powder—Control	−281	236	−170	−513	21	−60
Silicate field	Rock powder	737	589	834	1102	404	450
	Control	691	456	671	970	453	346
	Rock powder—Control	46	133	163	132	−50	104
Average across all fields	Rock powder	607	841	874	814	454	515
	Control	664	626	824	856	392	464
	Rock powder—Control	−56	214	49	−42	62	51

^aCO₂ removal rates (kg CO₂ ha⁻¹) derived from first-order stoichiometric calculation using the soil pore concentrations of base cations (Ca, Mg, K, Na) and bicarbonate (HCO₃⁻).

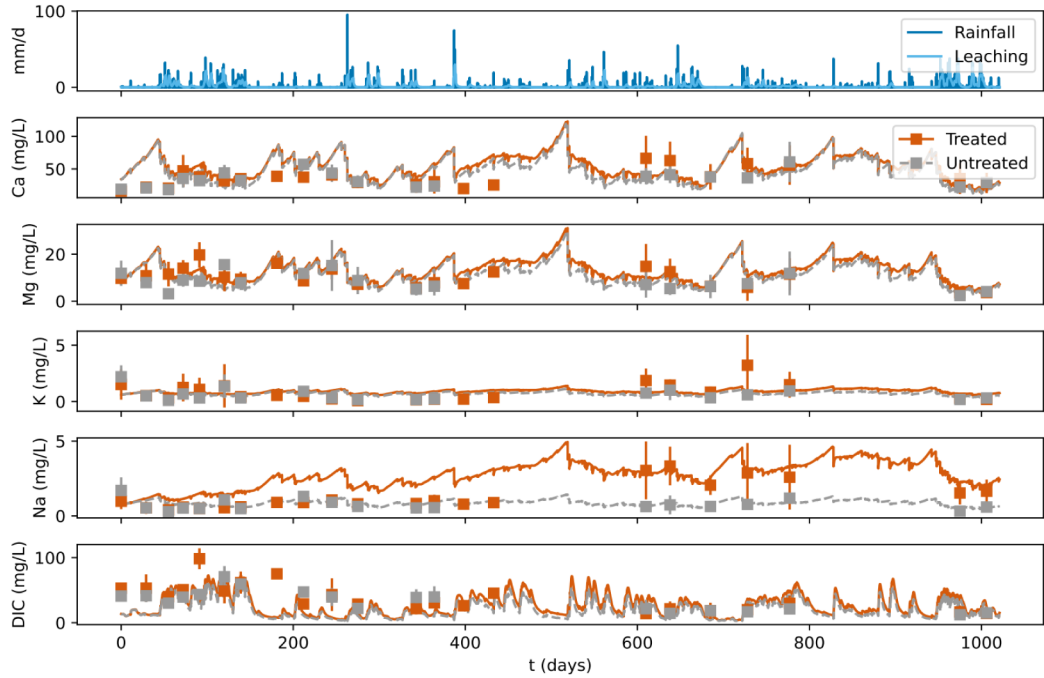


Figure 6. Model-observation comparison of pore-water concentrations. From top to bottom: Rainfall and leaching dynamics; calcium; magnesium; potassium; sodium; and dissolved inorganic carbon (DIC) concentrations. Continuous and dashed lines represent modeled dynamics (SMEW), while square markers indicate field measurements. Orange symbols represent treated plots; gray symbols represent control plots. Shown are the results for the Silicate field (see Figures S11 and S12 for analogous results in the Limed and Carbonate fields).

concentration and Ca and Mg concentrations,³³ failed to indicate a clear weathering signal across all fields. The inaptitude of these proxies was also noted in the trials set up by the Carbon Drawdown Initiative in Germany, despite having applied twice as much (40 t ha⁻¹) of the same basanite rock powder as in our study (details on their 1-year review webpage).

This lack of detectable response can be explained by a low dissolution of the applied rock powder coupled with soil heterogeneity and the rapid cycling of most chemical species between the different compartments of the soil and plants.^{76,77} Interestingly, we failed to detect a general increase in the pH of the soil pore water—the most responsive compartment—despite the known capacity of silicate weathering to generate

alkalinity. Indeed, although most silicate minerals have abrasion pH values ranging between 7 and 10, these minerals tend to alkalinize soils only up to the 6.5–7 pH mark due to the buffering capacity of the soil system⁷⁸ and to the low weathering rates of silicate minerals at circumneutral pH values.⁶³ This fundamental property has been confirmed in past agronomic trials using mafic rock powder.⁵ During such trials, the soil pH never exceeded the 6.5–7 pH range optimum for nutrient availability, despite doses of rock powder sometimes exceeding 100 t ha⁻¹ (as reviewed by Dupla et al.).⁵ Additionally, given that, in our case, the rock powder was only applied to the soil surface and not tilled in, an increase in soil pH within the top few centimeters of the soil profile cannot be excluded. A previous study conducted on these field however

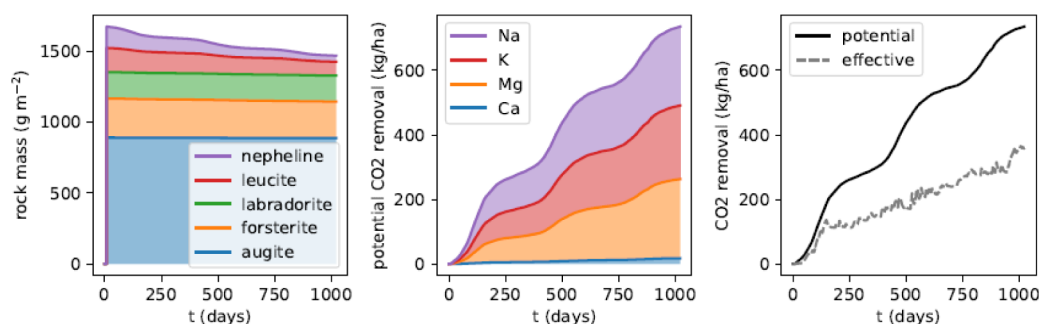


Figure 7. Weathering dynamics and CO₂ removal. From left to right: Evolution of the minerals composing the applied basanite rock powder; theoretical CO₂ removal potential based on base cation release; comparison of potential (cation-based) versus effective (carbon-based) CO₂ removal. Results refer to the *Silicate* field; see Figures S15 and S16 for the analogous results in the *Limed* and *Carbonate* fields.

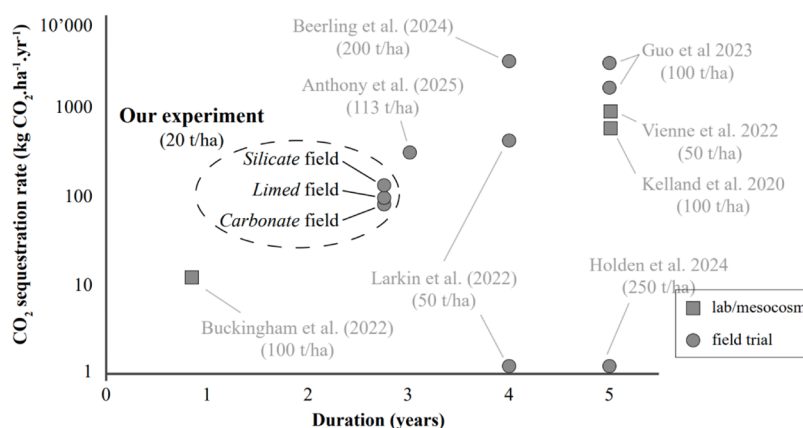


Figure 8. Comparison of the CO₂ removal rates estimated during this study with the rates from ERW studies using basaltic rocks.^{27,28,32,53,93–96} Among the upper rates, note that Beerling et al. (2024)³³ report a potential CO₂ removal rate (discounting any time-lag in cation and bicarbonate release) and that the rates from Kelland et al. (2020)⁹³ and Vienne et al. (2022)⁹⁴ are derived from experiments that lasted 120 and 99 days, respectively, then extrapolated to 5 years using reactive transport modeling.

showed no pH change in the 0–10 cm layer 1 year after rock powder addition.³⁶ Although the present study only monitored soil pore water pH, we can therefore expect that soil pH, notably slower to respond due to multiple buffering mechanisms, likewise remained stable.⁷⁷ This study therefore reinforces the view that soil pH should only be considered a robust ERW monitoring proxy in moderately to strongly acidic soils (pH < 6) and provided that the monitoring is located at the right soil depth.

4.2. Sodium as an Overlooked ERW Proxy? The sustained sodium signal obtained in this trial raises the question of whether sodium could serve as a universal proxy for enhanced rock weathering. Despite the several advantages offered by sodium, as already mentioned in the introduction (i.e., being less subject to cation scavenging via adsorption and biocycling), sodium may not constitute a universal ERW proxy for several reasons.

First, the low affinity of sodium for cation exchange sites implies that it will be easily desorbed in soil solution in favor of cations higher on the lyotropic series (e.g., potassium, magnesium, or calcium).^{79,80} Any increase in these cations due to ERW, or other operations such as fertilization, could then lead to the appearance of a sodium signal, without any of the Na-rich minerals having weathered. In our case, this was unlikely the case as 1) sodium was only detected as a trace on the CEC before rock powder was applied (Table S2), and 2) another experiment on the same fields showed that sodium actually increased on the CEC after basanite application (+

0.5% points one month post application).³⁶ Nevertheless, this argument could limit the use of sodium, especially in saline and sodic soils.

Second, with the exception of nepheline ((Na,K)AlSiO₄), many sodium-rich silicate minerals found in basaltic rocks do not exhibit fast weathering rates. Sodium-rich plagioclase (e.g., albite NaAlSi₃O₈) and sodium pyroxenes (e.g., aegirine NaFeSi₂O₆) have indeed weathering rates that are one to 3 orders of magnitude below fast weathering minerals like olivine and calcium plagioclase.^{81–83} When sodium is present in these minerals, it is therefore less likely to rapidly influence soil solution chemistry.

Third, sodium is sometimes found in minerals, whose weathering would confound ERW and CO₂ budget calculations. Traces of halite (NaCl) can first be found in basalts, which have interacted with saline fluids during or after formation (e.g., via hydrothermal alteration or exposure to seawater).^{84,85} The high solubility of halite implies that any sodium present in this mineral would be the first one to be released in the soil solution.⁸⁶ Hydrothermal activity can also lead to the formation of zeolites in basalts.^{87,88} These secondary minerals, used in the industry as water softeners, contain loosely bound cations, such as sodium, which readily desorb in favor of more selective cations, such as calcium and magnesium.^{89,90} The weathering of both halite and zeolites would release sodium without the associated CO₂ removal, making sodium unsuitable as an ERW proxy when these minerals are present.

In our case, the rock powder contained no traces of halite or zeolite, with most sodium being in reactive phases (interstitial glass and submicrometric plagioclase). This situation allowed for a clear and continuous detection of the ERW signal. Sodium also proved surprisingly adequate for estimating CO₂ removal based on simple elemental proportion in the rock (Table S5), probably due to near-congruent dissolution of the surface of basanite grain. While not a universal ERW proxy, our study suggests that sodium could nevertheless represent a promising monitoring tool in systems where appropriate mineralogical validation has been conducted beforehand.

4.3. Limited CO₂ Removal Rates. Although rock powder application led to a rapid and sustained weathering signal, the associated CO₂ removal remained limited. The average removal rate was estimated at $100 \pm 30 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$, which, over three years, represents 3.8% of the feedstock's maximum CO₂ removal potential ($400 \text{ kg CO}_2 \text{ t}^{-1}$ of rock applied at 20 t ha^{-1}). This rate was within the same order of magnitude as first-order estimates derived from stoichiometric calculation (Table 1 and Table S5). These results also offer the opportunity to estimate the CO₂ removal associated with the natural weathering of soil minerals (Control plots in Table 1), which in this study ranged between 300 and $1100 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$. These values are consistent with the upper end of global estimates for temperate agricultural soils, underscoring that natural weathering already represents a non-negligible CO₂ sink under baseline conditions.^{1,91,92}

In this study, the net CO₂ removal rate associated with rock powder addition is 1 order of magnitude lower than some of the modeled rates derived from laboratory and mesocosm experiments^{93,94} (Figure 8). The other field trials using basaltic rocks displayed wide differences between insignificant direct CO₂ removal in tropical soils due to noncarbonic acid driving the weathering reaction^{26,27} and, in temperate zones, $1\text{--}2 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ removal results²⁹ that lie in the range of theoretical estimates.^{32,95}

The last two studies used, however, 5 to 10 times more rock powder than our trial. Interestingly, if the CO₂ removal rates are expressed per t of rock powder, then most field-based studies converge around $10 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1} \text{ t}^{-1}$ of rock applied. This amount represents 3.3% of basalt's overall CO₂ removal potential being realized annually. This rate should not imply that basalt would reach its full removal potential within 30 years, however, as mineral weathering rates are known to decrease with time.⁷⁸ This decrease is due to the exhaustion of the most reactive phases, sometimes associated with mineral surfaces becoming coated—or passivated—by secondary phases.^{97–99} Given that ERW field trials lasted 5 years maximum, these measured rates arguably represent the high end of ERW's CO₂ removal efficiency over time. While these trials demonstrate that enhanced weathering can remove CO₂ under field conditions, they highlight the urgent need for additional trials across a wider range of climates and using a broader diversity of rocks.

4.4. Limitations to This Study. This 2021–2023 multisite field trial was able to detect and estimate a rapid and sustained ERW signal. Several limitations to our study must nevertheless be mentioned. First, the experimental approach relied solely on soil pore water samples. This approach made us dependent on the weather and water balance to be able to extract samples. Prolonged dry periods (summer droughts and dry winter months) limited the percolation of water through the soil profile down to the

suction lysimeters.¹⁰⁰ This situation created significant gaps in our data set, particularly in the summers of 2022 and 2023, as also experienced in ERW field trials conducted in California.^{28,75} When designing the experiment, we had rejected irrigation to avoid artificially accelerating mineral weathering rates. This potentially influenced the ERW signal by delaying its detection to the next significant rainfall event and altering its nature by reducing ion mobility and promoting secondary phase precipitation.³³

Second, from a modeling perspective, we acknowledge some limitations that warrant further investigation. As with most ERW models,^{2,101} SMEW assumes a uniform distribution of minerals across the various grain sizes of the rock powder. However, our thin-section observations of fresh rock samples revealed a pronounced heterogeneity in mineral content among different particle sizes (Figures S1 and S2). To our knowledge, neither ERW experiments nor models have explicitly accounted for the grain-size-dependent mineral distribution in their feedstock. Observationally, this could be addressed through automated mineral mapping, whereby the mineralogy of different grain-size fractions would be determined via spectroscopic techniques (e.g., Raman spectroscopy) and quantified through image analysis.^{102–104} Integrating this approach into both feedstock characterization and modeling would improve the accuracy of CO₂ removal estimates in ERW applications.

Third, given the absence of continuous chemical analyses on soils, plants, and gas exchanges after rock application, our model reanalysis relied exclusively on soil porewater data. This limitation precluded validation of model outputs related to secondary mineral formation, plant uptake, cation adsorption, and biological activity, which are key processes for robustly quantifying weathering fluxes.¹⁰⁵ Given the high initial base saturation of the three fields (i.e., 100%, 100% and 98% for the *Carbonate*, *Limed* and *Silicate* fields, respectively, cf. Table S2), we expected no, or very limited, net base cation adsorption on exchange sites. This hypothesis now awaits to be tested as ERW has the ability to increase cation exchange capacity via pH increase and secondary mineral formation.¹⁰⁶ On the contrary, plant uptake and secondary minerals may have acted as cation sinks (note that, in our results, SMEW's *effective* CO₂ removal was half the *potential* CO₂ removal due to these processes, Figure 7 and Figures S15–16). Dedicated measurements of these cation pools at the end of the experiment would help improve weathering and CO₂ removal quantification. In the absence of postapplication soil analyses, our estimates were based on the agreement between modeled and observed porewater concentrations for many elements, supported by prior validation of the SMEW model in accurately partitioning alkaline cations released into solution.⁴⁰

Within this framework, the model offered a best-guess data-driven and process-based reconstruction of field weathering fluxes, which required a correction factor of approximately 0.02, indicating dissolution rates nearly 50 times slower than those predicted by theoretical kinetics.⁶³ This reanalysis underscores the limited predictive power of state-of-the-art weathering rate formulations,⁶³ shared across ERW models^{2,40,101}, when applied to field conditions.⁶⁴ Given that current ERW models still lack mechanistic representations of critical processes—such as biotic interactions, mineral surface passivation, comprehensive soil pH buffering mechanisms and diffusive transport limitations^{41,105,107–109}—theoretical simu-

lations using boosted weathering rates risk overestimating ERW's CO₂ removal potential.

Despite the costs and additional noise induced by open-field conditions, field trials are more than ever necessary to improve our understanding of the dynamics and climate-mitigation potential of ERW in soils. Such trials need to be repeated across climates and soil types, assessing different rocks applied at different grainsizes, doses, and frequencies. Only then will we know if ERW has passed the field validation stage and if it can be deployed on a large scale as both an efficient and safe climate mitigation technology.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.5c09820>.

Parameter details of weather, rock, soil, and leachate (XLSX)

Additional methodological details and results on soil and rock analyses. Thin sections of basanite under natural light and polarized light. Evolution of soil leachate parameters over time (pH, dissolved inorganic carbon, electrical conductivity, Ca, Mg, Na, K concentration). Mg/Na vs Ca/Na mixing diagram. Relationship between EC ($\mu\text{S}/\text{cm}$) and total cation charge balance of Ca²⁺, Mg²⁺, K⁺ and Na⁺ (mmol/L). Model-observation comparison of pore-water concentrations for the Carbonate and Limed fields. Modeled weathering dynamics and CO₂ removal for the Carbonate and Limed fields. Additional details on first-order stoichiometric approach to estimate CO₂ removal rates (PDF)

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Notes

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■ REFERENCES

- (1) Hartmann, J.; West, A. J.; Renforth, P.; Köhler, P.; De La Rocha, C. L.; Wolf-Gladrow, D. A.; Dürr, H. H.; Scheffran, J. Enhanced Chemical Weathering as a Geoengineering Strategy to Reduce Atmospheric Carbon Dioxide, Supply Nutrients, and Mitigate Ocean Acidification. *Rev. Geophys.* **2013**, *51* (2), 113–149.
- (2) Beerling, D. J.; Kantzas, E. P.; Lomas, M. R.; Wade, P.; Eufrazio, R. M.; Renforth, P.; Sarkar, B.; Andrews, M. G.; James, R. H.; Pearce, C. R.; et al. Potential for Large-Scale CO₂ Removal via Enhanced Rock Weathering with Croplands. *Nature* **2020**, *583* (7815), 242–248.
- (3) Calabrese, S.; Wild, B.; Bertagni, M. B.; Bourg, I. C.; White, C.; Aburto, F.; Cipolla, G.; Noto, L. V.; Porporato, A. Nano- to Global-Scale Uncertainties in Terrestrial Enhanced Weathering. *Environ. Sci. Technol.* **2022**, *56* (22), 15261–15272.
- (4) Bertagni, M. B.; Porporato, A. The Carbon-Capture Efficiency of Natural Water Alkalinization: Implications For Enhanced Weathering. *Sci. Total Environ.* **2022**, *838*, 156524.
- (5) Dupla, X.; Brantley, S. L.; Paulo, C.; Möller, B.; Power, I. M.; Grand, S. Geochemical Drivers of Enhanced Rock Weathering in Soils. In *Geoengineering and Climate Change: Methods, Risks, and Governance*; Beech, M., Eds.; Wiley, 2025; pp. 207–230.
- (6) Renforth, P.; Henderson, G. Assessing Ocean Alkalinity for Carbon Sequestration. *Rev. Geophys.* **2017**, *55* (3), 636–674.
- (7) Dessert, C.; Dupré, B.; Gaillardet, J.; François, L. M.; Allègre, C. J. Basalt Weathering Laws and the Impact of Basalt Weathering on the Global Carbon Cycle. *Chem. Geol.* **2003**, *202* (3–4), 257–273.
- (8) Goff, F.; Guthrie, G.; Lipin, B.; Fite, M.; Chipera, S.; Counce, D.; Kluk, E.; Zioc, H. *Evaluation of Ultramafic Deposits in the Eastern United States and Puerto Rico as Sources of Magnesium for Carbon Dioxide Sequestration*; Los Alamos National Lab., NM (US), 2000.
- (9) O'Connor, W. K.; Dahlin, D. C.; Rush, G. E.; Gerdemann, S. J.; Penner, L. R.; Nilsen, D. N. *Aqueous Mineral Carbonation. Final Report—doe/arc-TR-04-002*; U.S. Department of Energy, 2005.
- (10) Renforth, P. The Potential of Enhanced Weathering in the UK. *Int. J. Greenhouse Gas Control* **2012**, *10*, 229–243.
- (11) Rinder, T.; von Hagke, C. The Potential of Carbon Dioxide Removal through Enhanced Weathering of Basalt on Agricultural Land in Austria. *Copernicus Meetings* Copernicus GmbH 20212277
- (12) Lenton, T. M. The Potential for Land-Based Biological CO₂ Removal to Lower Future Atmospheric CO₂ Concentration. *Carbon Manage.* **2010**, *1* (1), 145–160.
- (13) Smith, P.; Davis, S. J.; Creutzig, F.; Fuss, S.; Minx, J.; Gabrielle, B.; Kato, E.; Jackson, R. B.; Cowie, A.; Kriegler, E.; et al. Biophysical and Economic Limits to Negative CO₂ Emissions. *Nat. Clim. Change* **2016**, *6* (1), 42–50.
- (14) Taylor, L. L.; Quirk, J.; Thorley, R. M. S.; Kharecha, P. A.; Hansen, J.; Ridgwell, A.; Lomas, M. R.; Banwart, S. A.; Beerling, D. J. Enhanced Weathering Strategies for Stabilizing Climate and Averting Ocean Acidification. *Nat. Clim. Change* **2016**, *6* (4), 402–406.
- (15) Beerling, D. J.; Leake, J. R.; Long, S. P.; Scholes, J. D.; Ton, J.; Nelson, P. N.; Bird, M.; Kantzas, E.; Taylor, L. L.; Sarkar, B.; Kelland, M.; DeLucia, E.; Kantola, I.; Müller, C.; Rau, G.; Hansen, J. Farming with Crops and Rocks to Address Global Climate, Food and Soil Security. *Nat. Plants* **2018**, *4* (3), 138–147.
- (16) Smith, P.; Calvin, K.; Nkem, J.; Campbell, D.; Cherubini, F.; Grassi, G.; Korotkov, V.; Hoang, A. L.; Lwasa, S.; McElwee, P.; et al. Which Practices Co-Deliver Food Security, Climate Change Mitigation and Adaptation, and Combat Land Degradation and Desertification? *Global Change Biol.* **2020**, *26* (3), 1532–1575.
- (17) Shukla, P. R.; Skea, J.; Buendia, E. C.; Masson-Delmotte, V.; Pörtner, H.-O.; Roberts, D. C.; Zhai, P.; Slade, R.; Connors, S.; van Diemen, R.; et al. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; IPCC, 2019.

- (18) Wollenberg, E.; Richards, M.; Smith, P.; Havlík, P.; Obersteiner, M.; Tubiello, F. N.; Herold, M.; Gerber, P.; Carter, S.; Reisinger, A.; et al. Reducing Emissions from Agriculture to Meet the 2 °C Target. *Global Change Biol.* **2016**, *22* (12), 3859–3864.
- (19) Amann, T.; Hartmann, J.; Struyf, E.; de Oliveira Garcia, W.; Fischer, E. K.; Janssens, I. A.; Meire, P. M.; Schoelynck, J. Enhanced Weathering and Related Element Fluxes-A Cropland Mesocosm Approach. *Biogeosciences* **2020**, *17* (1), 103–119.
- (20) Suhrhoff, T. J. Phytoprevention of Heavy Metal Contamination From Terrestrial Enhanced Weathering: Can Plants Save the Day? *Front. Clim.* **2022**, *3*, 3.
- (21) Dupla, X.; Möller, B.; Baveye, P. C.; Grand, S. Potential Accumulation of Toxic Trace Elements in Soils during Enhanced Rock Weathering. *Eur. J. Soil Sci.* **2023**, *74* (1), No. e13343.
- (22) de Oliveira Garcia, W.; Amann, T.; Hartmann, J.; Karstens, K.; Boysen, L.; Popp, A.; Smith, P.; Goll, D. Impacts of Enhanced Weathering on Biomass Production for Negative Emission Technologies and Soil Hydrology. *Biogeosciences* **2020**, *17*, 2107–2133.
- (23) Oppong Danso, E.; Dietzen, C.; Arthur, E.; Rosing, M. T. Enduring Increases in Maize Yield Are a Co-Benefit of Enhanced Weathering of Greenlandic Glacial Rock Flour in Ghana. *Nutr. Cycl. Agroecosyst.* **2025**, 1–12.
- (24) Swoboda, P.; Döring, T. F.; Hamer, M. Remineralizing Soils? The Agricultural Usage of Silicate Rock Powders: A Review. *Sci. Total Environ.* **2022**, *807*, 150976.
- (25) Zhang, G.; Kang, J.; Wang, T.; Zhu, C. Review and Outlook for Agromineral Research in Agriculture and Climate Mitigation. *Soil Res.* **2018**, *56* (2), 113–122.
- (26) Holden, F. J.; Davies, K.; Bird, M. I.; Hume, R.; Green, H.; Beerling, D. J.; Nelson, P. N. In-Field Carbon Dioxide Removal via Weathering of Crushed Basalt Applied to Acidic Tropical Agricultural Soil. *Sci. Total Environ.* **2024**, *955*, 176568.
- (27) Larkin, C. S.; Andrews, M. G.; Pearce, C. R.; Yeong, K. L.; Beerling, D.; Bellamy, J.; Benedick, S.; Freckleton, R. P.; Goring-Harford, H.; Sadekar, S. Quantification of CO₂ Removal in a Large-Scale Enhanced Weathering Field Trial on an Oil Palm Plantation in Sabah, Malaysia. *Front. Clim.* **2022**, *4*, 959229.
- (28) Anthony, T. L.; Jones, A. R.; Silver, W. L. Supplementing Enhanced Weathering With Organic Amendments Accelerates the Net Climate Benefit of Soil Amendments in Rangeland Soils. *AGU Adv.* **2025**, *6* (2), No. e2024AV001480.
- (29) Guo, F.; Sun, H.; Yang, J.; Zhang, L.; Mu, Y.; Wang, Y.; Wu, F. Improving Food Security and Farmland Carbon Sequestration in China through Enhanced Rock Weathering: Field Evidence and Potential Assessment in Different Humid Regions. *Sci. Total Environ.* **2023**, *903*, 166118.
- (30) Amann, T.; Hartmann, J. Carbon Accounting for Enhanced Weathering. *Front. Clim.* **2022**, *4*, 4.
- (31) Elkateb, T.; Chalaturnyk, R.; Robertson, P. K. An Overview of Soil Heterogeneity: Quantification and Implications on Geotechnical Field Problems. *Can. Geotech. J.* **2003**, *40* (1), 1–15.
- (32) Lewis, A. L.; Sarkar, B.; Wade, P.; Kemp, S. J.; Hodson, M. E.; Taylor, L. L.; Yeong, K. L.; Davies, K.; Nelson, P. N.; Bird, M. I.; et al. Effects of Mineralogy, Chemistry and Physical Properties of Basalts on Carbon Capture Potential and Plant-Nutrient Element Release via Enhanced Weathering. *Appl. Geochem.* **2021**, *132*, 105023.
- (33) Clarkson, M. O.; Larkin, C. S.; Swoboda, P.; Reershemius, T.; Suhrhoff, T. J.; Maesano, C. N.; Campbell, J. S. A Review of Measurement for Quantification of Carbon Dioxide Removal by Enhanced Weathering in Soil. *Front. Clim.* **2024**, *6*, 1345224.
- (34) Gorham, J. Sodium. In *Handbook of plant nutrition*; CRC Press, 2016; pp. 585–600.
- (35) Essington, M. E. *Soil and Water Chemistry: an Integrative Approach*, 2nd ed.; CRC press, 2015.
- (36) Dupla, X.; Claustre, R.; Bonvin, E.; Graf, I.; Le Bayon, R.-C.; Grand, S. Let the Dust Settle Impact of Enhanced Rock Weathering on Soil Biological, Physical, and Geochemical Fertility. *Sci. Total Environ.* **2024**, *954*, 176297.
- (37) Vitousek, P. Nutrient Cycling and Nutrient Use Efficiency. *Am. Nat.* **1982**, *119* (4), 553–572.
- (38) Anderson, D. W. The Effect of Parent Material and Soil Development on Nutrient Cycling in Temperate Ecosystems. *Biogeochemistry* **1988**, *5*, 71–97.
- (39) Lehmann, J.; Schroth, G. Nutrient Leaching. In *Trees, crops and soil fertility: concepts and research methods*, Schroth, G.; Sinclair, F. L. Eds.; Wallingford UK: CABI Publishing, 2002; 151–166.
- (40) Bertagni, M. B.; Calabrese, S.; Cipolla, G.; Noto, L. V.; Porporato, A. Advancing Enhanced Weathering Modeling in Soils: Critical Comparison With Experimental Data. *J. Adv. Model. Earth Syst.* **2025**, *17* (1), No. e2024MS004224.
- (41) Kanzaki, Y.; Planavsky, N. J.; Zhang, S.; Jordan, J.; Suhrhoff, T. J.; Reinhard, C. T. Soil Cation Storage Is a Key Control on the Carbon Removal Dynamics of Enhanced Weathering. *Environ. Res. Lett.* **2025**, *20* (7), 074055.
- (42) Wolf-Gladrow, D. A.; Zeebe, R. E.; Klaas, C.; Körtzinger, A.; Dickson, A. G. Total Alkalinity: The Explicit Conservative Expression and Its Application to Biogeochemical Processes. *Mar. Chem.* **2007**, *106* (1–2), 287–300.
- (43) Kanzaki, Y.; Zhang, S.; Planavsky, N. J.; Reinhard, C. T. Soil Cycles of Elements Simulator for Predicting TERrestrial Regulation of Greenhouse Gases: SCEPTER v0.9. *Geosci. Model Dev.* **2022**, *15* (12), 4959–4990.
- (44) Brady, P. V.; Carroll, S. A. Direct Effects of CO₂ and Temperature on Silicate Weathering: Possible Implications for Climate Control. *Geochim. Cosmochim. Acta* **1994**, *58* (7), 1853–1856.
- (45) Jiang, C.; Chen, Z.; Lavoie, D.; Percival, J. B.; Kabanov, P. Mineral Carbon MinC (%) from Rock-Eval Analysis as a Reliable and Cost-Effective Measurement of Carbonate Contents in Shale Source and Reservoir Rocks. *Mar. Pet. Geol.* **2017**, *83*, 184–194.
- (46) IUSS Working Group WRB. World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. 4th Ed., International Union of Soil Science, 2022; https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf, (accessed 03–December–2024).
- (47) Paessler, D.; Steffens, R.; Hammes, J.; Smet, I. Monitoring CO₂ Concentrations in Soil Gas: A Novel MRV Approach for Cropland-Based ERW?; Carbon Drawdown Initiative, 2023; .
- (48) Steinour, H. H. Some Effects of Carbon Dioxide on Mortars and Concrete-Discussion. *J. Am. Concr. Inst.* **1959**, *30* (2), 905–907.
- (49) Le Maitre, R. W.; Streckeisen, A.; Zanettin, B.; Le Bas, M. J.; Bonin, B.; Bateman, P.; Bellieni, G.; Dudek, A.; Efremova, S.; Keller, J. et al. Igneous Rocks. In *A Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks*; Cambridge University Press: Cambridge, 2002; .
- (50) Wolff, J. A. Crystallisation of Nepheline Syenite in a Subvolcanic Magma System: Tenerife, Canary Islands. *Lithos* **1987**, *20* (3), 207–223.
- (51) Schiano, P.; Bourdon, B. On the Preservation of Mantle Information in Ultramafic Nodules: Glass Inclusions within Minerals versus Interstitial Glasses. *Earth Planet. Sci. Lett.* **1999**, *169* (1–2), 173–188.
- (52) Anda, M.; Shamshuddin, J.; Fauziah, C. I. Improving Chemical Properties of a Highly Weathered Soil Using Finely Ground Basalt Rocks. *Catena* **2015**, *124*, 147–161.
- (53) Beerling, D. J.; Epihov, D. Z.; Kantola, I. B.; Masters, M. D.; Reershemius, T.; Planavsky, N. J.; Reinhard, C. T.; Jordan, J. S.; Thorne, S. J.; Weber, J.; Val Martin, M.; Freckleton, R. P.; Hartley, S. E.; James, R. H.; Pearce, C. R.; DeLucia, E. H.; Banwart, S. A. Enhanced Weathering in the US Corn Belt Delivers Carbon Removal with Agronomic Benefits. *Proc. Natl. Acad. Sci. U.S.A.* **2024**, *121* (9), No. e2319436121.
- (54) Thomas, G. W. Soil pH and Soil Acidity *Methods Of Soil Analysis: Part 3 Chemical Methods* John Wiley 1996 5475–490
- (55) Hou, X.; Amais, R. S.; Jones, B. T.; Donati, G. L. Inductively Coupled Plasma Optical Emission Spectrometry *Encyclopedia Of*

Analytical Chemistry: applications, Theory And Instrumentation] John Wiley 2006:1–25

- (56) Appelo, C. A. J.; Postma, D. *Geochemistry, Groundwater and Pollution*; CRC press, 2004.
- (57) Mopper, K.; Qian, J.; Water Analysis: Organic Carbon Determinations. In *Encyclopedia of Analytical Chemistry: Applications, Theory and Instrumentation*; John Wiley, 2006.
- (58) Stumm, W.; Morgan, J. J. *Aquatic Chemistry: chemical Equilibria and Rates in Natural Waters*; 3rd ed. ed.; John Wiley & Sons, 2013.
- (59) Gaillardet, J.; Dupré, B.; Louvat, P.; Allegre, C. J. Global Silicate Weathering and CO₂ Consumption Rates Deduced from the Chemistry of Large Rivers. *Chem. Geol.* **1999**, *159* (1–4), 3–30.
- (60) Webster, R. Analysis of Variance, Inference, Multiple Comparisons and Sampling Effects in Soil Research. *Eur. J. Soil Sci.* **2007**, *58* (1), 74–82.
- (61) Box, G. E.; Cox, D. R. An Analysis of Transformations. *J. R. Stat. Soc. Ser. B: stat. Methodol.* **1964**, *26* (2), 211–243.
- (62) Allen, R. G.; Pereira, L. S.; Howell, T. A.; Jensen, M. E. Evapotranspiration Information Reporting: I. Factors Governing Measurement Accuracy. *Agric. Water Manage.* **2011**, *98* (6), 899–920.
- (63) Palandri, J. L.; Kharaka, Y. K. *A Compilation of Rate Parameters of Water-Mineral Interaction Kinetics for Application to Geochemical Modeling*; Geological Survey Menlo Park CA, 2004.
- (64) White, A. F.; Brantley, S. L. The Effect of Time on the Weathering of Silicate Minerals: Why Do Weathering Rates Differ in the Laboratory and Field? *Chem. Geol.* **2003**, *202* (3–4), 479–506.
- (65) Agrawal, Y. C.; McCave, I. N.; Riley, J. B. *Laser Diffraction Size Analysis Principles, Methods, And Application Of Particle Size Analysis*; Cambridge University Press 1991:119–128
- (66) International Organization for Standardization (ISO). ISO 11272: 2017 Soil Quality — Determination of Dry Bulk Density; 2017. <https://www.iso.org/standard/68255.html>, (accessed 26–April–2023).
- (67) Sebag, D.; Verrecchia, E. P.; Cécillon, L.; Adatte, T.; Albrecht, R.; Aubert, M.; Bureau, F.; Cailleau, G.; Copard, Y.; Decaens, T.; Disnar, J.-R.; Hetényi, M.; Nyilas, T.; Trombino, L. Dynamics of Soil Organic Matter Based on New Rock-Eval Indices. *Geoderma* **2016**, *284*, 185–203.
- (68) Hazera, J.; Sebag, D.; Kowalewski, I.; Verrecchia, E.; Ravelojaona, H.; Chevallier, T. Adjustments to the Rock-Eval® thermal analysis for soil organic and inorganic carbon quantification. *Biogeosci. Discuss.* **2023**, *20* (24), 5229–5242.
- (69) Shuman, L. M.; Duncan, R. R. Soil Exchangeable Cations and Aluminum Measured by Ammonium Chloride, Potassium Chloride, and Ammonium Acetate. *Commun. Soil Sci. Plant Anal.* **1990**, *21* (13–16), 1217–1228.
- (70) Klug, H. P.; Alexander, L. E. *X-Ray Diffraction Procedures: For Polycrystalline and Amorphous Materials*; 2nd ed.; Wiley, 1974.
- (71) Swoboda, P.; Hamer, M.; Stotter, M.; Döring, T. F.; Trimborn, M. Effects of Rock Powder Additions to Cattle Slurry on Ammonia and Greenhouse Gas Emissions. *Atmosphere* **2021**, *12* (12), 1652.
- (72) Tole, M. P.; Lasaga, A. C.; Pantano, C.; White, W. B. The Kinetics of Dissolution of Nepheline (NaAlSi₃O₈). *Geochim. Cosmochim. Acta* **1986**, *50* (3), 379–392.
- (73) Schuiling, R. D.; Krijgsman, P. Enhanced Weathering: An Effective and Cheap Tool to Sequester CO₂. *Clim. Change* **2006**, *74* (1–3), 349–354.
- (74) Renforth, P.; Pogge von Strandmann, P. A. E.; Henderson, G. M. The Dissolution of Olivine Added to Soil: Implications for Enhanced Weathering. *Appl. Geochem.* **2015**, *61*, 109–118.
- (75) Holzer, I. O.; Nocco, M. A.; Houlton, B. Z. Direct Evidence for Atmospheric Carbon Dioxide Removal via Enhanced Weathering in Cropland Soil. *Environ. Res. Commun.* **2023**, *5* (10), 101004.
- (76) Quideau, S. A.; Chadwick, O. A.; Graham, R. C.; Wood, H. B. Base Cation Biogeochemistry and Weathering under Oak and Pine: A Controlled Long-Term Experiment. *Biogeochemistry* **1996**, *35*, 377–398.
- (77) Brady, N. C.; Weil, R. R.; *The Nature and Properties of Soils*; 15th ed. ed.; Pearson, 2017.
- (78) White, A. F.; Brantley, S. L. *Chemical Weathering Rates of Silicate Minerals*; Walter de Gruyter GmbH & Co KG, 2018; 31.
- (79) Robbins, C. W.; Carter, D. L. Selectivity Coefficients for Calcium-Magnesium-Sodium-Potassium Exchange in Eight Soils. *Irrig. Sci.* **1983**, *4* (2), 95–102.
- (80) Tournassat, C.; Gailhanou, H.; Crouzet, C.; Braibant, G.; Gautier, A.; Gaucher, E. C. Cation Exchange Selectivity Coefficient Values on Smectite and Mixed-Layer Illite/Smectite Minerals. *Soil Sci. Soc. Am. J.* **2009**, *73* (3), 928–942.
- (81) Lasaga, A. C. Chemical Kinetics of Water-Rock Interactions. *J. Geophys. Res.: Solid Earth* **1984**, *89* (B6), 4009–4025.
- (82) Kump, L. R.; Brantley, S. L.; Arthur, M. A. Chemical Weathering, Atmospheric CO₂, and Climate. *Annu. Rev. Earth Planet. Sci.* **2000**, *28* (1), 611–667.
- (83) Wilson, M. J. Weathering of the Primary Rock-Forming Minerals: Processes, Products and Rates. *Clay Miner.* **2004**, *39* (3), 233–266.
- (84) Webster, J. D.; Kinzler, R. J.; Mathez, E. A. Chloride and Water Solubility in Basalt and Andesite Melts and Implications for Magmatic Degassing. *Geochim. Cosmochim. Acta* **1999**, *63* (5), 729–738.
- (85) Sibik, S.; Edmonds, M.; Villemant, B.; Svensen, H. H.; Polozov, A. G.; Planke, S. Halogen Enrichment of Siberian Traps Magmas during Interaction with Evaporites. *Front. Earth Sci.* **2021**, *9*, 741447.
- (86) Alkattan, M.; Oelkers, E. H.; Dandurand, J.-L.; Schott, J. Experimental Studies of Halite Dissolution Kinetics, 1 The Effect of Saturation State and the Presence of Trace Metals. *Chem. Geol.* **1997**, *137* (3–4), 201–219.
- (87) Robert, C.; Goffé, B. Zeolitization of Basalts in Subaqueous Freshwater Settings: Field Observations and Experimental Study. *Geochim. Cosmochim. Acta* **1993**, *57* (15), 3597–3612.
- (88) Utada, M. Zeolites in Hydrothermally Altered Rocks. *Rev. Mineral. Geochem.* **2001**, *45* (1), 305–322.
- (89) Takahashi, T.; Kimura, Y.; Kimura, T. Water Softening Effect and Detergent Action of Metal-Ion-Supporting Zeolite. *J. Home Econ. Jpn.* **2004**, *55* (3), 219–228.
- (90) Cinar, S.; Beler-Baykal, B. Ion Exchange with Natural Zeolites: An Alternative for Water Softening? *Water Sci. Technol.* **2005**, *51* (11), 71–77.
- (91) Harrington, K. J.; Henderson, G. M.; Hilton, R. G. Current Rates of CO₂ Removal Due to Rock Weathering in the UK. *Sci. Total Environ.* **2024**, *957*, 177458.
- (92) Zhang, S.; Bai, X.; Zhao, C.; Tan, Q.; Luo, G.; Wang, J.; Li, Q.; Wu, L.; Chen, F.; Li, C.; et al. Global CO₂ Consumption by Silicate Rock Chemical Weathering: Its Past and Future. *Earth's Future* **2021**, *9* (5), No. e2020EF001938.
- (93) Kelland, M. E.; Wade, P. W.; Lewis, A. L.; Taylor, L. L.; Sarkar, B.; Andrews, M. G.; Lomas, M. R.; Cotton, T. E. A.; Kemp, S. J.; James, R. H.; et al. Increased Yield and CO₂ Sequestration Potential with the C4 Cereal Sorghum Bicolor Cultivated in Basaltic Rock Dust-Amended Agricultural Soil. *Global Change Biol.* **2020**, *26* (6), 3658–3676.
- (94) Vienne, A.; Poblador, S.; Portillo-Estrada, M.; Hartmann, J.; Ijehon, S.; Wade, P.; Vicca, S. Enhanced Weathering Using Basalt Rock Powder: Carbon Sequestration, Co-Benefits and Risks in a Mesocosm Study With Solanum Tuberosum. *Front. Clim.* **2022**, *4*, 1–14.
- (95) Kantzas, E. P.; Val Martin, M.; Lomas, M. R.; Eufrazio, R. M.; Renforth, P.; Lewis, A. L.; Taylor, L. L.; Mecure, J.-F.; Pollitt, H.; Vercoulen, P. V.; Vaklifard, N.; Holden, P. B.; Edwards, N. R.; Koh, L.; Pidgeon, N. F.; Banwart, S. A.; Beerling, D. J. Substantial Carbon Drawdown Potential from Enhanced Rock Weathering in the United Kingdom. *Nat. Geosci.* **2022**, *15* (5), 382–389.
- (96) Vanderkloot, E.; Ryan, P. Quantifying the Effect of Grain Size on Weathering of Basaltic Powders: Implications for Negative Emission Technologies via Soil Carbon Sequestration. *Appl. Geochem.* **2023**, *155*, 105728.
- (97) Navarre-Sitchler, A.; Brantley, S. Basalt Weathering across Scales. *Earth Planet. Sci. Lett.* **2007**, *261* (1–2), 321–334.

- (98) Ruiz-Agudo, E.; King, H. E.; Patiño-López, L. D.; Putnis, C. V.; Geisler, T.; Rodríguez-Navarro, C.; Putnis, A. Control of Silicate Weathering by Interface-Coupled Dissolution-Precipitation Processes at the Mineral-Solution Interface. *Geology* **2016**, *44* (7), 567–570.
- (99) Oelkers, E. H.; Declercq, J.; Saldi, G. D.; Gislason, S. R.; Schott, J. Olivine Dissolution Rates: A Critical Review. *Chem. Geol.* **2018**, *500*, 1–19.
- (100) Wen, H.; Sullivan, P. L.; Billings, S. A.; Ajami, H.; Cueva, A.; Flores, A.; Hirmas, D. R.; Koop, A. N.; Murenbeeld, K.; Zhang, X.; Li, L. From Soils to Streams: Connecting Terrestrial Carbon Transformation, Chemical Weathering, and Solute Export Across Hydrological Regimes. *Water Resour. Res.* **2022**, *58* (7), No. e2022WR032314.
- (101) Kanzaki, Y.; Chiaravalloti, I.; Zhang, S.; Planavsky, N. J.; Reinhard, C. T. In Silico Calculation of Soil pH by SCEPTR v1. 0. *Geosci. Model Dev.* **2024**, *17* (10), 4515–4532.
- (102) Sutherland, D. N.; Gottlieb, P. Application of Automated Quantitative Mineralogy in Mineral Processing. *Miner. Eng.* **1991**, *4* (7–11), 753–762.
- (103) Okada, N.; Maekawa, Y.; Owada, N.; Haga, K.; Shibayama, A.; Kawamura, Y. Automated Identification of Mineral Types and Grain Size Using Hyperspectral Imaging and Deep Learning for Mineral Processing. *Minerals* **2020**, *10* (9), 809.
- (104) Schulz, B.; Sandmann, D.; Gilbricht, S. SEM-Based Automated Mineralogy and Its Application in Geo- and Material Sciences. *Minerals* **2020**, *10* (11), 1004.
- (105) Te Pas, E. E. M.; Chang, E.; Marklein, A. R.; Comans, R. N. J.; Hagens, M. Accounting for Retarded Weathering Products in Comparing Methods for Quantifying Carbon Dioxide Removal in a Short-Term Enhanced Weathering Study. *Front. Clim.* **2025**, *6*, 6.
- (106) Te Pas, E. E. M.; Hagens, M.; Comans, R. N. J. Assessment of the Enhanced Weathering Potential of Different Silicate Minerals to Improve Soil Quality and Sequester CO₂. *Front. Clim.* **2023**, *4*, 4.
- (107) Green, H.; Larsen, P.; Liu, Y.; Nelson, P. N. Carbon Dioxide Removal via Weathering of Sugarcane Mill Ash under Different Soil Conditions. *Appl. Geochem.* **2024**, *165*, 105940.
- (108) Beerling, D. J.; Reinhard, C. T.; James, R. H.; Khan, A.; Pidgeon, N.; Planavsky, N. J. Challenges and Opportunities in Scaling Enhanced Weathering for Carbon Dioxide Removal. *Nat. Rev. Earth Environ.* **2025**, *6*, 672–686.
- (109) Steinwider, L.; Boito, L.; Frings, P. J.; Niron, H.; Rijnders, J.; de Schutter, A.; Vienne, A.; Vicca, S. Beyond Inorganic C: Soil Organic C as a Key Pathway for Carbon Sequestration in Enhanced Weathering. *Global Change Biol.* **2025**, *31* (7), No. e70340.

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