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Field evidence for rapid precipitation of non-crystalline secondary phases during enhanced rock weathering

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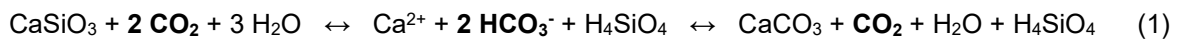
Abstract

Terrestrial enhanced rock weathering (ERW) is a proposed carbon dioxide removal strategy based on the application of silicate rock powder to soils. By introducing fresh mineral surfaces into soils, ERW can lead to the formation of reactive secondary phases, including poorly crystalline aluminosilicates such as allophane and imogolite. Despite their potential impact on both soil properties and the effectiveness of ERW, direct field evidence for the formation of these secondary phases remains elusive. Here we applied a basaltic rock powder (20 t ha⁻¹) to three temperate fields and investigated the formation of secondary phases using selective dissolution and scanning electron microscopy. We show that secondary phases formation occurs as early as seven months after rock powder application. In surface soils (0–3 cm), oxalate-extractable aluminum and silicon increased by 108% ± 30% and 682 % ± 302%, respectively, suggesting a rapid formation of poorly crystalline aluminosilicate phases. Imaging further revealed the presence of allophane-like spherules and smectite precursors on the weathering rock powder surfaces. These findings demonstrate that ERW initiates rapid pedogenic transformations on annual timescales, highlighting the need to consider secondary phase formation when assessing the effectiveness and soil impacts of ERW-based CO₂ removal.

Key words: enhanced weathering; short-range order phases, amorphous phases; rock dust; soil remineralization

Main

Terrestrial enhanced rock weathering (ERW) is a carbon dioxide (CO₂) removal technique that involves applying finely ground silicate rocks to agricultural soils. The rock powder dissolution in the soil solution increases alkalinity and can shift the carbonate equilibrium toward CO₂ removal and bicarbonate (HCO₃⁻) formation. Bicarbonate may subsequently precipitate as stable carbonate minerals in soils or downstream, enabling long-term carbon storage beyond 10-100k yrs (illustration of this principle with wollastonite in Equation 1). It has been estimated that amending two-thirds of the world's most productive croplands (9 × 10⁸ ha) with basalt powder at application rates of 10–30 t ha⁻¹ yr⁻¹ could remove between 0.5 and 4 Pg (Gt) CO₂ yr⁻¹ by 2100¹ depending on assumptions regarding land plant–soil system impacts, CDR efficiency along the land–ocean continuum².



While largescale projections are encouraging in terms of CO₂ removal rates^{1,3,4}, the relevance of ERW extends beyond inorganic carbon sequestration alone. Silicate dissolution can also increase soil pH and release essential nutrients such as Ca, Mg, K, and Si, resulting in improved soil fertility and enhanced crop yields^{5,6}. Additionally, the weathering of primary silicate minerals can lead to the formation of organo-metal complexes and inorganic secondary phases such as pedogenic oxides, clay-precursors and short-range order phases (SRO) aluminosilicates (*e.g.* allophane, imogolite). These secondary phases play a key role in the stabilization of soil organic carbon (SOC) – the largest active terrestrial carbon pool on Earth – by reducing organic matter bioavailability and susceptibility to microbial decomposition through complexation and adsorption mechanisms^{7,8}. Their highly reactive surfaces also improve water and nutrient retention, as exemplified by volcanic soils where such phases are abundant^{9,10}. These properties suggest that their formation ERW could provide additional climatic and agronomic benefits, beyond inorganic carbon sequestration^{11,12}.

Yet, despite this potential, secondary weathering products remain poorly investigated in ERW systems, especially under field conditions. To date, evidence for secondary phases formation in ERW studies has relied largely on indirect proxies such as saturation indices^{13–15} and elemental ratios measured in the soil solution^{13,16}, which only indicate that conditions may be thermodynamically favorable for precipitation. Mineralogical detection based on X-ray diffraction (XRD) spectra^{17,18}, provides direct evidence, but is restricted to crystalline phases and therefore overlooks poorly ordered or amorphous products. As a result, these approaches provide only a partial view of secondary phase formation and are insufficient to distinguish and quantify the full spectrum of phases present. On the other hand, selective dissolution techniques have proven effective in the detection of small amounts of SRO phases within complex soil mineral assemblages, as evidenced by investigations of volcanic soils properties^{8,19–28}. The presence of such phases can also be supported by direct, though non-quantitative, observations using microscopy techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM)^{29–36}. To our knowledge, only two laboratory studies have previously applied a selective dissolution approach for ERW^{37,38}. Both studies revealed a significant enrichment in amorphous phases containing Fe, Al and Si but the extent to which these mesocosm results transfer to the field remain however still unknown.

Our study aims to improve understanding of secondary phase formation following field-scale rock powder application under temperate climatic conditions. To this end, three Swiss vineyard fields contrasting in geochemical properties were amended with basanite rock powder (Table

S4, Fig. S3) at a rate equivalent to 20 t ha⁻¹. Soil samples from the 0-3 cm layer were collected 7 months and 2 years after application, and the extent of secondary phase formation was assessed using selective dissolution and scanning electron microscopy (SEM).

Selective dissolution indicates secondary phases formation

Rock powder amendment resulted in a significant increase in SRO aluminosilicate phases, as quantified by ammonium oxalate–extractable Al and Si (Al_{SRO} and Si_{SRO}) in surface soils across all three fields (Fig. 1). As early as seven months after application, Al_{SRO} increased by 0.19 ± 0.04 g kg⁻¹ (+108% ± 30%) and Si_{SRO} by 0.26 ± 0.05 g kg⁻¹ (+682% ± 302%) relative to controls (Table S1). In contrast, Fe associated with SRO, and Al, Fe and Si associated with organic complexes or crystalline oxides were not significantly affected by the treatment (Fig. S1). The magnitude of the response to rock powder amendment varied strongly among fields (Fig. 1), indicating a significant modulation by pedogenic context for both Al_{SRO} and Si_{SRO} (Table S1). XRD diffraction did not detect crystalline secondary mineral formation beyond background variability in amended soils within the investigated time frame (Fig. S2).

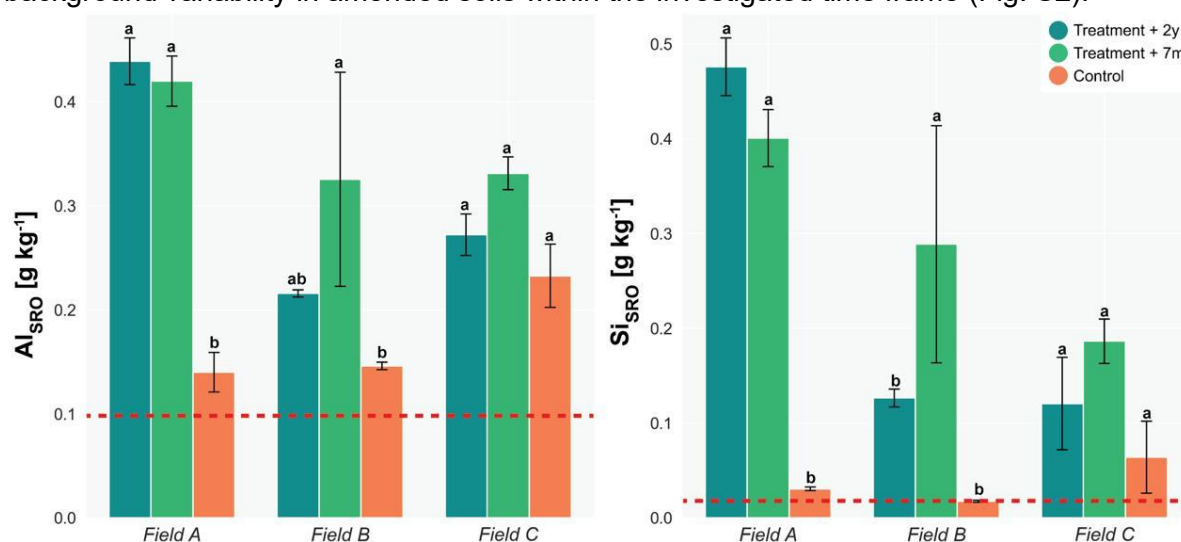


Figure 1 SRO formation. Al_{SRO} and Si_{SRO} contents (in the top 0-3 cm) 2 years after basanite application (Treatment +2y), and 7 months after application (Treatment +7m) versus no rock powder (Control). Error bars represent the standard error of the mean. Statistically significant differences (p -value < 0.05) are represented using compact letter display. The red dashed line corresponds to the amount of Al and Si extracted on the fresh rock powder and brought to a soil equivalent.

The enrichment in Al_{SRO} was mainly due to newly formed SRO phases with a marginal contribution of SRO phases already present in the feedstock (Fig. 1). Even under the most conservative scenario assuming full retention of the added rock powder within the 0–3 cm layer, the contribution of the feedstock remained below control levels, confirming that the observed increase reflects the precipitation of newly formed Al- and Si-bearing SRO phases.

The newly formed secondary phases exhibited Al–Si stoichiometries consistent with allophanic materials (Fig. 2). Following rock powder amendment, Al_{SRO} and Si_{SRO} showed strong positive linear relationships ($R^2 = 0.86–0.99$), with a mean slope of 1.34, indicating preferential incorporation of Si relative to Al during secondary phases formation. The observed stoichiometric relationships fall within the compositional range expected for allophanic materials, with a trend towards Si-rich, halloysite-like phases (Al_{SRO}/Si_{SRO} ≈ 1) rather than more Al-rich, imogolite-like phases (Al_{SRO}/Si_{SRO} ≈ 2)³⁹.

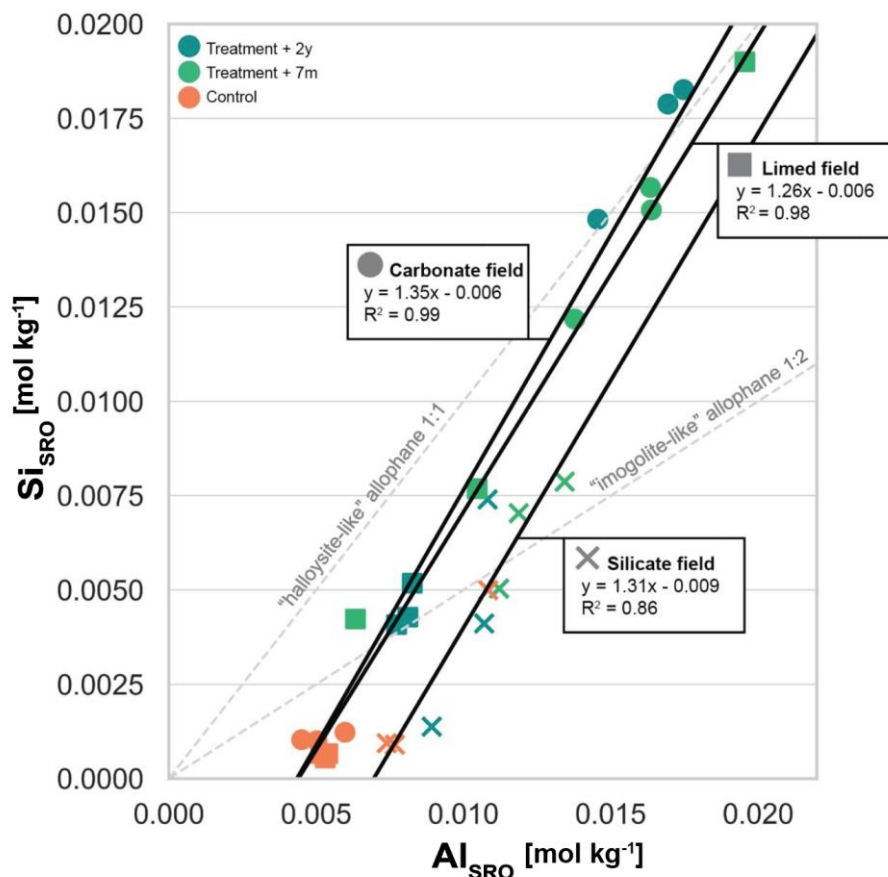


Figure 2 SRO composition. Evolution of Si and Al contents in short-range-ordered (SRO) phases with field-specific linear regressions illustrating compositional changes driven by ERW.

The selective dissolution approach indicated the preferential formation of SRO phases over organo-metal complexes by a factor of 10 to 40 (Table S2). This pattern can be attributed to the initial degree of soil organic matter saturation with metals⁴⁰. This level is commonly assessed using the $(Al_p + 0.5 Fe_p)/C_p$ ratio, where Al_p , Fe_p and C_p represent Na-pyrophosphate-extractable Al, Fe and C respectively, thus Al and Fe complexed with organic compounds. The threshold for full saturation is usually set at 0.2⁴¹. In our study, all treatments, including controls, displayed mean ratios between 0.22 and 0.28 (Table S2), thereby suggesting an already Al-saturated soil organic matter, limiting further Al complexation by organic ligands and favoring SRO formation.

Microtextural evidence supports selective dissolution patterns

After two years of in-situ incubation, rock powder grains retrieved from finely meshed nylon bags buried in each field displayed clear microtextural evidence of secondary phases precipitation, as revealed by scanning electron microscopy (SEM) (Fig. 3). The most prominent features were spherules, which are commonly interpreted as early-stage volcanic weathering products, including allophane, imogolite, halloysite, Al–Fe oxyhydroxides, and/or amorphous silica. Such spherules have been widely reported across diverse weathering environments and experimental settings^{19,39,42–52}. They occurred predominantly as continuous amorphous coatings covering the grain faces, but may also accumulate within surface

depressions or cavities, depending on the local micro-topography (Fig. 3b, c). In addition, incipient smectite neoformation appeared to originate from these coatings and followed a similar spatial distribution across the grains, forming acicular morphologies preferentially on smoother grain faces (Fig. 3a, d).

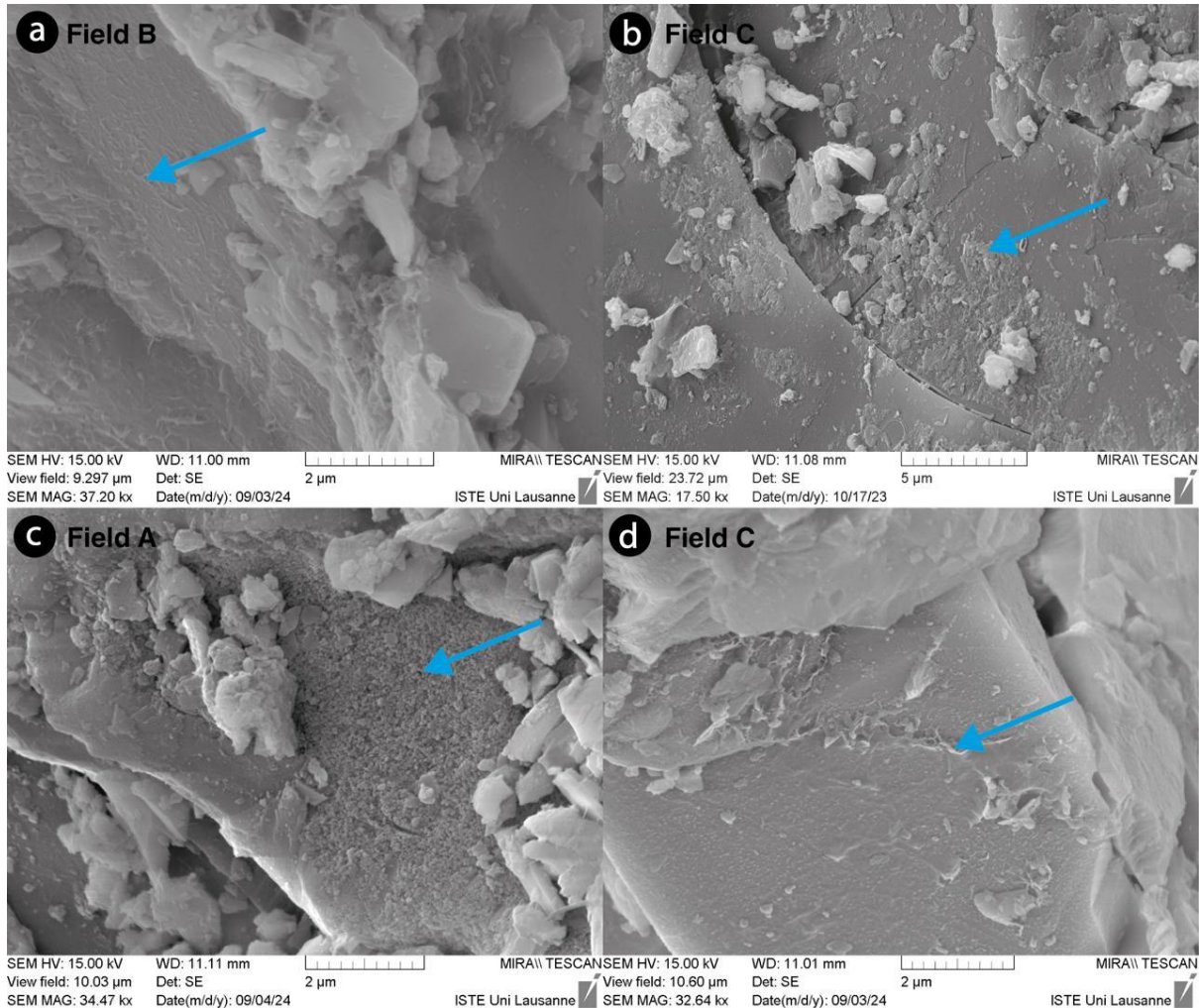


Figure 3 SEM imaging. Basanite grains from the weathering bags after 2 years. a: smectite neoformation (blue arrow), b and c: spherule coating, d: smectite neoformation (blue arrow) and spherule coating.

Environmental controls on SRO formation

These field-derived findings are consistent with observations from experiments across a broad range of weathering conditions. A soil column study conducted under highly accelerated conditions (45 °C, 2678 mm yr⁻¹) reported a 27% increase in Al_{SRO} phases in the 0–10 cm depth interval 24 weeks after diabase application (15 t ha⁻¹)³⁸. Comparable increases in SRO phases have also been documented under milder conditions (~20 °C; soils maintained at 70% of their water holding capacity), with significant enrichment in Si_{SRO} and Fe_{SRO} phases occurring ~60 days after dunite application at rates of 20–220 t ha⁻¹³⁷. In contrast with these controlled conditions, our study was conducted in a temperate climate over the coldest season of the year (average temperature of 8.1°C for a total rainfall of 582 mm over 7 months). The rapid formation of SRO in such a climatic context may therefore seem surprising. However, non-crystalline secondary phases are suspected to be able to form within days^{13,53–55}. In addition, if temperature is a key driver of weathering rates, lower temperatures do not

necessarily prevent the formation of SRO phases. Once local supersaturation is reached, non-crystalline secondary phases can precipitate rapidly, and allophane has been reported to form even under cool climatic conditions⁵⁶.

SRO formation in our field trial may have also been further promoted by the fact that mineral weathering occurred in a permanently grass-covered topsoil, which concentrates most of the rhizosphere – i.e., the fraction of soil under the direct biochemical influence of plant roots. In the rhizosphere, pH can be two to three units lower than in the surrounding soil^{57,58}. This together with the chelating agents produced by roots and microorganisms may thus have sustained or even enhanced mineral dissolution rates under temperate conditions^{31,57,59–65}. In addition, topsoils tend to experience more frequent drying–wetting cycles caused by soil evaporation and plant transpiration, further promoting soil solution supersaturation towards secondary phases⁶⁶, consistent with the accumulation of SRO between 0–3 cm. Together, the specific characteristics of the topsoil create a favorable environment for the rapid formation and accumulation of allophanic SRO products that we witnessed in our study.

Implication of SRO phases formation on CO₂ removal and soil fertility

The formation of significant amounts of SRO phases following rock powder amendment may have several implications for ERW. First, SRO phases can coat the surface of reactive minerals. This process, known as surface passivation, may reduce weathering rates and thereby decrease CO₂ removal efficiency^{67–69}.

Second, SRO formation can influence the partitioning of weathering-derived base cations between the soil solution and solid phase, with consequences for alkalinity generation and associated CO₂ removal^{70–72}. Retention of base cations by the soil solid phase limits alkalinity generation when weathering-derived cations adsorb onto negatively charged mineral and organic surfaces that collectively constitute the soil cation exchange capacity (CEC). When these cations dislodge acid cations such as H⁺ and Al³⁺ on exchange sites, acidity initially consumed during weathering is effectively returned to solution, offsetting net alkalinity generation. This mechanism, although important in base cation depleted soils, was likely negligible in our system because the soils were already almost fully saturated with base cations prior to amendment (99.9% base saturation⁷³). Consequently, any newly adsorbed base cations would primarily displace native base cations rather than exchangeable acidity, rendering this specific pathway neutral to net alkalinity export.

SRO phases may additionally create new reactive surfaces capable of retaining weathering-derived base cations⁷⁴. However, their contribution to soil CEC could not be detected in this study because only limited quantities were formed. In *Field A*, for example, the estimated allophane content after amendment was ~0.45 g kg⁻¹ soil. Assuming a CEC of 150 cmol_c kg⁻¹ for allophane at pH 7.5⁷⁵, this corresponds to only ~0.07 cmol_c kg⁻¹ soil. At this rate, nearly fifteen successive applications of 20 t ha⁻¹ rock powder would be required to increase soil CEC by 1 cmol_c kg⁻¹. Limited SRO formation also restricts the incorporation of base cations into secondary aluminosilicates, such as smectite precursors. Unlike exchangeable cations, structurally incorporated cations are less readily remobilized and therefore represent a more persistent sink for weathering-derived alkalinity. Together, the high initial base saturation of the soils and the limited abundance of newly formed SRO phases suggest that retention of weathering-derived base cations was minimal in the present study.

The magnitude of these processes may nevertheless be substantially greater in other ERW settings. This field trial was conducted under temperate and relatively dry conditions (see ⁷⁶), employed a modest application rate (20 t ha⁻¹), and involved no incorporation of the material into the soil, thereby limiting soil-rock contact. In contrast, ERW is increasingly being deployed in tropical regions, where warmer and wetter conditions promote substantially higher weathering rates. Tropical soils are also commonly acidic and depleted in exchangeable base cations ^{3,5}, while the formation of SRO phases is expected to be more extensive. Together, these conditions are likely to amplify the retention pathways described above, increasing the fraction of weathering-derived base cations retained within the soil system. Consequently, higher weathering rates may not necessarily translate into proportionally greater CO₂ removal efficiencies.

Beyond their implications for CO₂ removal, the formation of SRO phases may also provide important agronomic benefits. Owing to their high specific surface area (700–1500 m² g⁻¹) and mixed surface charges, allophanic phases can enhance nutrient and water retention in agricultural soils. They are also known to interact strongly with organic matter, reducing its mineralization and promoting soil organic carbon stabilization^{8,39}. In our case, however, no changes in bulk soil pH, CEC, or SOC were detected within the 0–10 cm layer following a single rock powder application in a companion field study⁷³, due to the limited gain in CEC as explained above. The 0.07 cmol_c kg⁻¹ increase in CEC equates to an electrostatic capacity of stabilizing at best ~350 mg SOC kg⁻¹ soil (assuming an organic matter CEC of 200 cmol_c kg⁻¹). Compared to the average SOC content across the three fields (30 g SOC kg⁻¹ of soil, Table S3), this gain therefore represents a stabilization potential of less than 1.2% of the current SOC stock – a fraction easily masked by natural spatial variability. Greater agronomic effects, including SOC stabilization, may nevertheless emerge under conditions favoring more extensive SRO formation, including longer time frame, higher application rates, or repeated applications.

Sustained accumulation of allophanic products may nevertheless pose agronomic challenges. It is generally considered that only >5 wt% allophane is required for a soil to develop allophanic properties⁷⁷. Such materials exhibit a strong affinity for phosphate, with P-retention capacities reaching up to 99%, rendering a large fraction of adsorbed phosphorus unavailable to plants⁷⁸. Consequently, even moderate accumulation of allophanic phases warrants careful monitoring when assessing the long-term agronomic implications of ERW.

Beyond their immediate implications for CO₂ removal and soil fertility, important uncertainties remain regarding the long-term evolution of secondary mineral phases in ERW systems. As metastable secondary products, SRO phases are expected to recrystallize into more stable clays and oxides over time, although the rates of these transformations under ERW remain unknown. In natural volcanic soils, allophanic materials are expected to ripen into halloysite and kaolinite²⁰. Yet in ERW, because the rock powder applications are repeated, the system may not follow the classic mineralogical sequence and the ongoing supply of Si and Al could maintain SRO phases for longer than expected. Similar uncertainties apply to the fate of smectite precursors and their implications for cation fixation, alkalinity generation and soil management. Overall, our study demonstrates that ERW modifies pedogenic pathways and is likely to trigger new soil mineral assemblages. Further work is needed to quantify how these mineralogical modifications shape ERW outcomes, from soil functioning to the magnitude, efficiency and predictability of CO₂ removal.

Materials and methods

Site description and sampling

This study took place in three fields belonging to an organic wine-growing estate in the town of La Grande Béroche, Switzerland (46° 55' 55" north, 6° 49' 00" east). They are located on the western shore of Lake Neuchâtel, on the Swiss Plateau (Fig. 4).

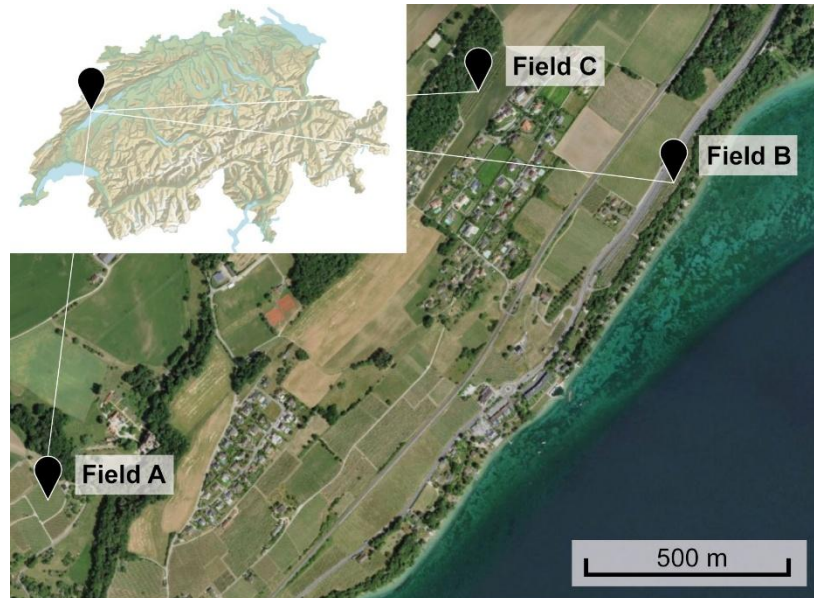


Figure 4 Field location. Field location in the commune of La Grande Béroche (NE), on the north-western shore of Lake Neuchâtel (Source: map.geo.admin.ch).

This area has a mean annual temperature of 9,5°C and receives approximately 1555 mm yr⁻¹ of precipitation (mean values 1991-2021)⁷⁹. Soils formed in Quaternary deposits, *i.e.* Rhodanian moraines from the Würm period⁸⁰. As one of the three fields still contains carbonates inherited from Urgonian limestones and has an alkaline pH, it will be referred to as the *Field A* field. The two soils devoid of naturally-occurring carbonates will be referred to as the *Field C* field and *Field B* field. This distinction is because the latter has received dolomite amendments between 1996 and 2006. According to the World Reference Base for Soils Resources (WRB 4th edition 2022), soil type in the *Field A* field is a *Calcaric Hypereutric Cambisol*, whereas soil type in the two other fields is *Eutric Cambisols*. Routine pedological parameters for the 0-10 cm layer are reported in Table S1⁷⁶.

Rock powder application

Each field was divided into 9 plots (3x3 m). Three plots received no rock powder (Control). To test for short and longer-term effects, the remaining plots were amended with rock powder at two different dates. Three plots received rock powder (2 kg m⁻²) in April 2021, and three others in September 2022 at the same rate. No mechanical incorporation into the soil was carried out. In addition, 'weathering bags' (25 µm porous nylon bags) containing fresh basanite rock powder were buried 5 cm deep at the foot of the vines in April 2021.

Soil samples were collected in March 2023. For treated soils, rock powder application had therefore happened 2 years and 7 months ago, respectively. For each plot, 5 samples were

taken between 0-3 cm and then composited. When still intact, weathering bags were also sampled in all fields.

Rock powder characterisation

The rock powder is a basanite according to Total Alkali-Silica chemical classification of volcanic rocks (TAS)⁸¹, mined in the German mountain range Eifel (commercial name 'Eifelgold', RPBL company). Grainsize analysis revealed that 80% of the basanite was below 52 µm with a loam texture. XRD analyses further showed that it was dominated by augite (48.4%), forsteritic olivine (19.8%), and plagioclase (10.0%), along with lesser amounts of leucite, Fe-Ti oxides, and phlogopite (Table S3).

In addition, the rock powder was embedded in epoxy resin, and, after hand polishing, cross-sections were observed by scanning electron microscopy (SEM) in both backscattered (BSE) and secondary electron (SE) modes, and analysed by energy-dispersive X-ray spectroscopy (EDS), which provided an overall picture of the texture of the grains, i.e. micro-phenocrysts of forsterite, augite and Ti-Fe oxides in an aphanitic matrix (Fig. S3).

Laboratory analyses

The soil samples were air dried (48h at 45°C) and sieved to 2 mm. All analyses were completed on this fine earth fraction. The contents of the weathering bags were stored in 50 ml Falcon tubes after two weeks of drying at 45°C.

Selective dissolution

Secondary phases in soil samples were quantified by selective dissolution (Dahlgren 1994). Al and Fe present in organo-metallic complexes (Al_p and Fe_p) were extracted by adding 50 ml of Na-pyrophosphate solution (0.1 M, pH 10) to 50 ml propylene tubes containing 1 g of soil. The tubes were shaken at 175 rpm at room temperature for 16 hours. The suspension was centrifuged for 30 minutes (5200 x g) before filtration of the supernatant through a 0.45 µm cellulose acetate filter. Filtrates were then diluted 3 times with deionized water prior to analysis.

Using the same soil:solution ratio (1:50), an ammonium oxalate – oxalic acid buffer (0.2 M, pH ~3) was used to measure the Al, Fe and Si contained in poorly crystalline phases (SRO such as imogolite and allophane). Centrifuge tubes were shaken at 175 rpm for 4 h in the dark prior to centrifugation and filtration. Filtrates were then diluted 5 times with deionized water prior to analysis. To only account for the SRO fraction, the OM-bound fraction was subtracted from the oxalate-extracted Al and Fe fraction ($Al_{SRO} = Al_o - Al_p$ and $Fe_{SRO} = Fe_o - Fe_p$). The OM-bound Si fraction being negligible, the oxalate extracted Si was equated to the SRO fraction ($Si_{SRO} = Si_o$).

Finally, Al, Fe and Si present in pedogenic oxides (Al_d , Fe_d and Si_d) were extracted using a citrate-bicarbonate dithionite solution. To this end, 50 mL of a citrate–bicarbonate solution containing 0.3 M Na-citrate and 1.0 M Na-bicarbonate was added to 1 g of soil in 100 ml centrifuge tubes. The tubes were heated in a water bath to 80°C and stirred regularly with a glass rod until they reached temperature. Next, 1 g of Na dithionite powder was added. The samples were stirred intermittently and after 10 min, a further 1 g of Na dithionite powder was added. The digestion was carried out for 1 hour, at which point soils were grey. Once cooled,

extracts were centrifuged and filtered as described above. Filtrates were then diluted 10 times with deionized water prior to analysis. The concentration of ions in all extracts was measured using inductively coupled plasma optical emission spectrometry (Perkin Elmer Optima 8300 ICP-OES) and converted in g kg⁻¹ of soil.

Each extraction was also carried out on 10 replicates of ‘fresh’ basanite to quantify the contribution of the fresh feedstock on soil measurements. To this end, we opted for the most conservative scenario and assumed that 100% of rock powder remained in the 0-3 cm layer. Based on the bulk density (BD) of each field as reported in Dupla et al. (2024), we calculated the soil mass of the 0-3 cm layer and estimated the amount of each Al, Fe, and Si fraction initially brought by the fresh rock powder to the soils knowing that 2 kg m⁻² of rock powder was added to the fields (Equation 2).

$$[M^+]_{soil} = \frac{2*[M^+]_{rock\ powder}}{0,03*BD} \quad (2)$$

where $[M^+]_{soil}$ is the content of Al, Fe or Si extracted from soil samples (g kg⁻¹), $[M^+]_{rock\ powder}$ is the content of Al, Fe or Si extracted from pure rock powder (g kg⁻¹) and BD is the field's mean bulk density.

Selective dissolution results were interpreted with criteria typically used in the study of Andosols. As proposed by ⁸², the Al_{SRO}/Si_{SRO} ratio provides an index of the relative abundance of Al-rich allophane (imogolite-like) versus Si-rich allophane (halloysite) among the SRO; values closer to 1 indicate an Si-rich composition, while values approaching 2 suggest Al predominance. The Al_p/Al_{SRO} ratio is used to assess the dominance of aluminum in humus complexes vs. SRO, as the oxalate ammonium extraction also dissolves OM-complexes ^{10,40}. Finally, the (Al + Fe)_p/C_p ratio quantifies the saturation of soil organic matter with iron- and aluminum-bound complexes. When the ratio exceeds 0.1-0.2, the organic matter is considered saturated with Fe–Al complexes; values below this threshold suggest under-saturation in OM complexes ⁸³.

SEM and morphological features

After drying, rock powder from the weathering bags was applied with a fine paintbrush on double sided tape attached to an aluminum sample stub and coated with gold. The thickness of the coatings, ranging from 10 to 30 nm, was adapted to avoid charging effects. Samples were examined with a scanning electron microscope (SEM; Tescan Mira II LMU). Secondary electron (SE) images were obtained to detect morphological features suggesting secondary mineral phases precipitation. “Fresh” rock powder samples were also examined.

XRD analysis on the soil clay fraction

Clay mineralogy was investigated in samples collected from the 0-5 cm depth in the *Field B* field one year after rock powder application using X-ray diffraction (XRD) on oriented slides. Four samples were collected per plot. Each sample was air-dried, sieved to 2 mm and acidified with 10% HCl to remove carbonates. pH was adjusted to 6 prior to isolation of the clay fraction following the procedure of Adatte et al.⁸⁴. Two size fractions (<2 µm and <16 µm) were separated by sedimentation according to Stokes' law, transferred onto glass slides, and air-

dried. Resulting oriented slides were analyzed by XRD (Thermo ARL XTRA Powder Diffractometer) before and after ethylene glycol solvation.

Statistical analyses

Data display was performed in JupyterLab (Python 3.12). Statistical analyses were performed using R version 4.2.2⁸⁵ and SAS/STAT version 9.4⁸⁶. The effects of rock powder amendment on extractable metals were investigated using a 2-ways ANOVA. Fixed effects included treatment (control, rock powder + 7 months, rock powder + 2 years), field and the treatment * field interaction. Normality of residuals was checked using the Shapiro-Wilk test. When residuals deviated significantly from normality, the Box-Cox procedure was used to select the optimal transformation for the dependent variable⁸⁷. The homogeneity of variances was assessed using a Levene's test for each field separately and was not violated⁸⁸. For significant effects, Student's t-test were conducted to identify significant differences between means. The significance threshold for p-values was always set at 0.05 (5%).

References

1. Beerling, D. J. *et al.* Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* **4**, 138–147 (2018).
2. Schiedung, M. *et al.* Uncertainties of enhanced rock weathering for climate-change mitigation. *Nat. Rev. Earth Environ.* 1–14 (2026) doi:10.1038/s43017-026-00761-7.
3. Edwards, D. P. *et al.* Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. *Biol. Lett.* **13**, 20160715 (2017).
4. Kantola, I. B., Masters, M. D., Beerling, D. J., Long, S. P. & DeLucia, E. H. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biol. Lett.* **13**, 20160714 (2017).
5. Dupla, X. *et al.* Geochemical Drivers of Enhanced Rock Weathering in Soils. in *Geoengineering and Climate Change* (ed. Beech, M.) 207–230 (Wiley, 2025). doi:10.1002/9781394204847.ch13.
6. Swoboda, P., Döring, T. F. & Hamer, M. Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Sci. Total Environ.* **807**, 150976 (2022).
7. Sollins, P., Homann, P. & Caldwell, B. A. Stabilization and destabilization of soil organic matter: mechanisms and controls. *Geoderma* **74**, 65–105 (1996).
8. Rasmussen, C. *et al.* Beyond clay: towards an improved set of variables for predicting soil organic matter content. *Biogeochemistry* **137**, 297–306 (2018).
9. Basile-Doelsch, I., Balesdent, J. & Rose, J. Are Interactions between Organic Compounds and Nanoscale Weathering Minerals the Key Drivers of Carbon Storage in Soils? *Environ. Sci. Technol.* **49**, 3997–3998 (2015).
10. IUSS Working Group WRB. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. (2022).

11. Torn, M. S., Trumbore, S. E., Chadwick, O. A., Vitousek, P. M. & Hendricks, D. M. Mineral control of soil organic carbon storage and turnover. *Nature* **389**, 170–173 (1997).
12. Steinwilder, L. *et al.* Beyond Inorganic C: Soil Organic C as a Key Pathway for Carbon Sequestration in Enhanced Weathering. *Glob. Change Biol.* **31**, e70340 (2025).
13. Iff, N., Renforth, P. & Pogge von Strandmann, P. A. E. The dissolution of olivine added to soil at 32°C: the fate of weathering products and its implications for enhanced weathering at different temperatures. *Front. Clim.* **6**, (2024).
14. Larkin, C. S. *et al.* Quantification of CO₂ removal in a large-scale enhanced weathering field trial on an oil palm plantation in Sabah, Malaysia. *Front. Clim.* **4**, (2022).
15. Renforth, P., Pogge von Strandmann, P. A. E. & Henderson, G. M. The dissolution of olivine added to soil: Implications for enhanced weathering. *Appl. Geochem.* **61**, 109–118 (2015).
16. Buckingham, F. L., Henderson, G. M., Holdship, P. & Renforth, P. Soil core study indicates limited CO₂ removal by enhanced weathering in dry croplands in the UK. *Appl. Geochem.* **147**, 105482 (2022).
17. Burke, T. M., Kamber, B. S. & Rowlings, D. Microscopic investigation of incipient basalt breakdown in soils: implications for selecting products for enhanced rock weathering. *Front. Clim.* **7**, (2025).
18. Haque, F., Santos, R. M. & Chiang, Y. W. CO₂ sequestration by wollastonite-amended agricultural soils – An Ontario field study. *Int. J. Greenh. Gas Control* **97**, 103017 (2020).
19. Arifin, M., Devnita, R., Anda, M., Goenadi, D. H. & Nugraha, A. Characteristics of Andisols Developed from Andesitic and Basaltic Volcanic Ash in Different Agro-Climatic Zones. *Soil Syst.* **6**, 78 (2022).
20. Churchman, G. J. & Lowe, D. J. Alteration, Formation, and Occurrence of Minerals in Soils. in *Handbook of Soil Sciences* vol. Vol. 1: Properties and Processes 20.1-20.72 (CRC Press (Taylor & Francis), 2012).
21. Colman, S. M. *Chemical Weathering of Basalts and Andesites; Evidence from Weathering Rinds. Professional Paper 51* <https://pubs.usgs.gov/publication/pp1246> (1982) doi:10.3133/pp1246.
22. Fiore, S., Huertas, F. J., Huertas, F. & Linares, J. Smectite formation in rhyolitic obsidian as inferred by microscopic (SEM-TEM-AEM) investigation. *Clay Miner.* **36**, 489–500 (2001).
23. García-Romero, E. & Suárez, M. The alteration of Miraflores Basalt (Panama): Mineralogical and textural evolution. *Appl. Clay Sci.* **205**, 106036 (2021).
24. Gysi, A. P. & Stefánsson, A. CO₂–water–basalt interaction. Numerical simulation of low temperature CO₂ sequestration into basalts. *Geochim. Cosmochim. Acta* **75**, 4728–4751 (2011).

25. Legros, J.-P. *Les grands sols du monde*. (EPFL Press, 2007).
26. Nanzzyo, M. & Kanno, H. Non-crystalline Inorganic Constituents of Soil. in *Inorganic Constituents in Soil: Basics and Visuals* (eds Nanzzyo, M. & Kanno, H.) 59–95 (Springer, Singapore, 2018). doi:10.1007/978-981-13-1214-4_4.
27. Rennert, T. Wet-chemical extractions to characterise pedogenic Al and Fe species – a critical review. *Soil Res.* **57**, 1–16 (2018).
28. Zehetner, F., Miller, W. P. & West, L. T. Pedogenesis of Volcanic Ash Soils in Andean Ecuador. *Soil Sci. Soc. Am. J.* **67**, 1797–1809 (2003).
29. Levard, C. *et al.* Structure and distribution of allophanes, imogolite and proto-imogolite in volcanic soils. *Geoderma* **183–184**, 100–108 (2012).
30. Jongmans, A. G., Verburg, P., Nieuwenhuys, A. & van Oort, F. Allophane, imogolite, and gibbsite in coatings in a Costa Rican Andisol. *Geoderma* **64**, 327–342 (1995).
31. Lybrand, R. A. *et al.* A coupled microscopy approach to assess the nano-landscape of weathering. *Sci. Rep.* **9**, 5377 (2019).
32. Lybrand, R. A. *et al.* Fungal hyphae develop where titanomagnetite inclusions reach the surface of basalt grains. *Sci. Rep.* **12**, 3407 (2022).
33. Hellevang, H., Haile, B. G. & Tetteh, A. Experimental study to better understand factors affecting the CO₂ mineral trapping potential of basalt. *Greenh. Gases Sci. Technol.* **7**, 143–157 (2017).
34. Ruiz-Agudo, E., Putnis, C. V., Rodriguez-Navarro, C. & Putnis, A. Mechanism of leached layer formation during chemical weathering of silicate minerals. *Geology* **40**, 947–950 (2012).
35. Gislason, S. R. & Oelkers, E. H. Mechanism, rates, and consequences of basaltic glass dissolution: II. An experimental study of the dissolution rates of basaltic glass as a function of pH and temperature. *Geochim. Cosmochim. Acta* **67**, 3817–3832 (2003).
36. Ducasse, T. *et al.* Alteration of synthetic basaltic glass in silica saturated conditions: Analogy with nuclear glass. *Appl. Geochem.* **97**, 19–31 (2018).
37. te Pas, E. E. E. M., Comans, R. N. J., Bisseling, S. & Hagens, M. Enhanced weathering and biochar co-deployment boosts CO₂ sequestration through changing soil properties. *Geoderma* **466**, 117668 (2026).
38. Silva, R. C. da, Guimarães, C. C. B., Azevedo, A. C. de, Alves, M. R. & Demattê, J. A. M. Precipitation of amorphous iron and aluminum during the weathering of rock dust in soil columns. *Sci. Agric.* **81**, e20230219 (2024).
39. Parfitt, R. L. Allophane and imogolite: role in soil biogeochemical processes. *Clay Miner.* **44**, 135–155 (2009).

40. Shoji, S., Dahlgren, R. & Nanzyo, M. Chapter 3 Genesis of Volcanic Ash Soils. in *Developments in Soil Science* (eds Shoji, S., Nanzyo, M. & Dahlgren, R.) vol. 21 37–71 (Elsevier, 1993).
41. Garrido, E. & Matus, F. Are organo-mineral complexes and allophane content determinant factors for the carbon level in Chilean volcanic soils? *CATENA* **92**, 106–112 (2012).
42. Baumgarten, W., Dörner, J. & Horn, R. Microstructural development in volcanic ash soils from South Chile. *Soil Tillage Res.* **129**, 48–60 (2013).
43. Eswaran, H. Morphology of allophane, imogolite and halloysite. *Clay Miner.* **9**, 281–285 (1972).
44. Garcia, B. *et al.* Experiments and geochemical modelling of CO₂ sequestration by olivine: Potential, quantification. *Appl. Geochem.* **25**, 1383–1396 (2010).
45. Gasparini, A. S., Fontes, M. P. F., Pacheco, A. A. & Ker, J. C. Gibbsite Crystallinity and Morphology in Ferralsols and Bauxites. *Minerals* **12**, 1441 (2022).
46. Gérard, M., Caquineau, S., Pinheiro, J. & Stoops, G. Weathering and allophane neoformation in soils developed on volcanic ash in the Azores. *Eur. J. Soil Sci.* **58**, 496–515 (2007).
47. Kawano, M. & Tomita, K. Amorphous Aluminum Hydroxide Formed at the Earliest Weathering Stages of K-Feldspar. *Clays Clay Miner.* **44**, 672–676 (1996).
48. King, H. E., Plümpner, O. & Putnis, A. Effect of Secondary Phase Formation on the Carbonation of Olivine. *Environ. Sci. Technol.* **44**, 6503–6509 (2010).
49. Kleber, M., Mikutta, C. & Jahn, R. Andosols in Germany—pedogenesis and properties. *CATENA* **56**, 67–83 (2004).
50. Riezebos, P. A. & Lustenhouwer, W. J. Characteristics and significance of composite particles derived from a colombian andosol profile. *Geoderma* **30**, 195–217 (1983).
51. Ristić, M., Krehula, S. & Musić, S. Microstructural Properties of Natural Allophane/Gibbsite from a White Bauxite Deposit in Montenegro. *Croat. Chem. Acta* **91**, (2018).
52. Wilson, M. A., Burt, R., Engel, R. J., Sobecki, T. M. & Hipple, K. Soil Properties and Genesis of Pans in Till-Derived Andisols, Olympic Peninsula, Washington. *Soil Sci. Soc. Am. J.* **60**, 206–218 (1996).
53. Amann, T. *et al.* Enhanced Weathering and related element fluxes – a cropland mesocosm approach. *Biogeosciences* **17**, 103–119 (2020).
54. Wood, C., Harrison, A. L. & Power, I. M. Impacts of dissolved phosphorus and soil-mineral-fluid interactions on CO₂ removal through enhanced weathering of wollastonite in soils. *Appl. Geochem.* **148**, 105511 (2023).

55. Pogge von Strandmann, P. A. E. *et al.* Experimental determination of Li isotope behaviour during basalt weathering. *Chem. Geol.* **517**, 34–43 (2019).
56. Parfitt, R. L., Russell, M. & Orbell, G. E. Weathering sequence of soils from volcanic ash involving allophane and halloysite, New Zealand. *Geoderma* **29**, 41–57 (1983).
57. Harley, A. D. & Gilkes, R. J. Factors influencing the release of plant nutrient elements from silicate rock powders: a geochemical overview. *Nutr. Cycl. Agroecosystems* **56**, 11–36 (2000).
58. Inside Front Cover. in *Marschner's Mineral Nutrition of Higher Plants (Second Edition)* (ed. Marschner, H.) ii (Academic Press, San Diego, 2002). doi:10.1016/B978-0-08-057187-4.50001-1.
59. Dietzen, C., Harrison, R. & Michelsen-Correa, S. Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment. *Int. J. Greenh. Gas Control* **74**, 251–258 (2018).
60. Leake, J. R. *et al.* Biological weathering in soil: The role of symbiotic root-associated fungi biosensing minerals and directing photosynthate-energy into grain-scale mineral weathering. *Mineral. Mag.* **72**, 85 (2008).
61. Raulund-Rasmussen, K., Borggaard, O. K., Hansen, H. C. B. & Olsson, M. Effect of natural organic soil solutes on weathering rates of soil minerals. *Eur. J. Soil Sci.* **49**, 397–406 (1998).
62. van Schöll, L. *et al.* Rock-eating mycorrhizas: their role in plant nutrition and biogeochemical cycles. *Plant Soil* **303**, 35–47 (2008).
63. Spaltenstein, H. *Pédologie: Science du sol.* (Les Éditions du Net, 2021).
64. Vandeginste, V., Lim, C. & Ji, Y. Exploratory Review on Environmental Aspects of Enhanced Weathering as a Carbon Dioxide Removal Method. *Minerals* **14**, 75 (2024).
65. Verbruggen, E., Struyf, E. & Vicca, S. Can arbuscular mycorrhizal fungi speed up carbon sequestration by enhanced weathering? *PLANTS PEOPLE PLANET* **3**, 445–453 (2021).
66. Cipolla, G., Calabrese, S., Porporato, A. & Noto, L. V. Effects of precipitation seasonality, irrigation, vegetation cycle and soil type on enhanced weathering – modeling of cropland case studies across four sites. *Biogeosciences* **19**, 3877–3896 (2022).
67. Béarat, H. *et al.* Carbon Sequestration via Aqueous Olivine Mineral Carbonation: Role of Passivating Layer Formation. *Environ. Sci. Technol.* **40**, 4802–4808 (2006).
68. Crovisier, J.-L., Advocat, T. & Dussossoy, J.-L. Nature and role of natural alteration gels formed on the surface of ancient volcanic glasses (Natural analogs of waste containment glasses). *J. Nucl. Mater.* **321**, 91–109 (2003).

69. Gruber, C., Zhu, C., Georg, R. B., Zakon, Y. & Ganor, J. Resolving the gap between laboratory and field rates of feldspar weathering. *Geochim. Cosmochim. Acta* **147**, 90–106 (2014).
70. Kanzaki, Y. *et al.* Soil cation storage is a key control on the carbon removal dynamics of enhanced weathering. *Environ. Res. Lett.* **20**, 074055 (2025).
71. Bijma, J. *et al.* Reviews and syntheses: Carbon vs. cation based MRV of Enhanced Rock Weathering and the issue of soil organic carbon. *Biogeosciences* **23**, 53–75 (2026).
72. te Pas, E. 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.* **6**, (2025).
73. Dupla, X. *et al.* Let the dust settle: Impact of enhanced rock weathering on soil biological, physical, and geochemical fertility. *Sci. Total Environ.* **954**, 176297 (2024).
74. Nakahara, O. & Wada, S.-I. Ca²⁺ and Mg²⁺ adsorption by an allophanic and a humic Andisol. *Geoderma* **61**, 203–212 (1994).
75. Wada, K. Chapter 4 Allophane and imogolite. in *Developments in Sedimentology* (eds Sudo, T. & Shimoda, S.) vol. 26 147–187 (Elsevier, 1978).
76. Dupla, X., Bertagni, M. B. & Grand, S. Three Years of Field Trials Indicate a Sustained Enhanced Rock Weathering Signal with Limited CO₂ Removal. *Environ. Sci. Technol.* <https://doi.org/10.1021/acs.est.5c09820> (2025) doi:10.1021/acs.est.5c09820.
77. Buurman, P., Peterse, F. & Almendros Martin, G. Soil organic matter chemistry in allophanic soils: a pyrolysis-GC/MS study of a Costa Rican Andosol catena. *Eur. J. Soil Sci.* **58**, 1330–1347 (2007).
78. Hewitt, A. E., Balks, M. R. & Lowe, D. J. Allophanic Soils. in *The Soils of Aotearoa New Zealand* (eds Hewitt, A. E., Balks, M. R. & Lowe, D. J.) 21–39 (Springer International Publishing, Cham, 2021). doi:10.1007/978-3-030-64763-6_2.
79. MétéoSuisse. <https://www.meteosuisse.admin.ch/services-et-publications/applications/ext/climate-climsheet.html> (2025).
80. Meia, J. & Becker, F. Notice explicative: Neuchâtel (1164) - Atlas géologique de la Suisse. (1976).
81. *Igneous Rocks: A Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommittee on the Systematics of Igneous Rocks*. (Cambridge University Press, Cambridge, 2002). doi:10.1017/CBO9780511535581.
82. Parfitt, R. L. & Wilson, A. D. Estimation of allophane and halloysite in three sequences of volcanic soils, New Zealand. *Catena Suppl.* **7**, 1–8 (1985).

83. Inoue, K. & Higashi, T. Al- and Fe–humus complexes in Andisols. in *Proceedings of 9th Int. Soil Classification Workshop, Japan* 535–546 (Washington D.C., 1988).
84. Adatte, T., Stinnesbeck, W. & Keller, G. Lithostratigraphic and mineralogic correlations of near K/T boundary clastic sediments in northeastern Mexico: Implications for origin and nature of deposition. in *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History* (Geological Society of America, 1996). doi:10.1130/0-8137-2307-8.211.
85. R Core Team. *R: A Language and Environment for Statistical Computing*. (R Foundation for Statistical Computing, Vienna, Austria, 2022).
86. SAS Institute Inc. *SAS Software, Version 9.4*. (2023).
87. Box, G. E. P. & Cox, D. R. An Analysis of Transformations. *J. R. Stat. Soc. Ser. B Methodol.* **26**, 211–243 (1964).
88. Brown, M. B. & Forsythe, A. B. Robust Tests for the Equality of Variances. *J. Am. Stat. Assoc.* **69**, 364–367 (1974).

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Data availability

The data supporting the findings of this study are presented in the manuscript or provided in the Supplementary Information.

Author contributions

Emma Bonvin contributed to investigation, methodology, formal analysis, visualization, data curation, writing – original draft and writing – review & editing. Xavier Dupla contributed to investigation, methodology, supervision, conceptualization, project administration and writing – review & editing. Stéphanie Grand contributed to resources, methodology, conceptualization, supervision and writing – review & editing.

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