

Systematic comparison of major enhanced rock weathering feedstocks highlights agronomic benefits and trace-metal concerns

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Abstract

Enhanced rock weathering (ERW) is promoted as a scalable CO₂ removal strategy. Because weathering-related processes modify soil acidity and plant-available element dynamics, ERW may ultimately impact crop yield and nutritional quality. However, robust evaluations are hindered by a lack of comparative assessment across candidate feedstocks. To address this, we compared, under identical mesocosm conditions, six feedstocks from ERW projects worldwide and monitored their impact on soil and crop properties. After 2 years, we show that ERW countered soil acidification while increasing nitrogen and bioavailable silicon – but also toxic trace-metal (Ni, Cr, Co) – contents relative to controls. Despite this trade-off, ERW drove an overall gain in crop yield (+13% ± 2%), digestibility (-34% ± 5% lignin), and energy density (+10% ± 2% raw fat). These results position ERW as a lever for global food security but underscore that careful feedstock selection is needed to balance agronomic benefits against trace-metal accumulation risks.

Introduction

Limiting global warming to 2°C requires not only deep emissions reductions but also rapid upscaling of CO₂ removal (CDR)¹. One of the proposed approaches is terrestrial enhanced rock weathering (ERW). By applying finely ground rocks to croplands, ERW aims to accelerate natural weathering reactions that remove atmospheric CO₂ and generate alkalinity, thereby offering potentially durable carbon removal². With growing commercial deployment and increasing interest from governments and private actors, ERW is increasingly framed as a prominent CDR strategy³, although uncertainties remain regarding feedstock availability, ecosystem impacts, and CDR verification⁴.

Importantly, the implications of ERW extend beyond CO₂ removal: the resulting geochemical reactions inevitably modify soil chemical conditions. In agricultural systems, these reactions can neutralize soil acidity, replenish exchangeable base cations, and increase plant-available silicon⁵; such effects could ultimately improve crop nutritional quality. However, ERW may also mobilize potentially toxic trace elements present in feedstocks, raising the risk of their accumulation in soil and plant tissue⁶. In a context where soil acidification and elemental imbalance threaten crop quality and productivity^{7,8}, the balance between these co-benefits and potential detrimental effects is not peripheral: it defines whether ERW is compatible with, or even beneficial for, global agricultural productivity and crop quality.

Unfortunately, evidence of agronomic impacts to date remains fragmented. Recent ERW trials report increases in soil pH that are often accompanied by increased elemental availability^{9–16}, but with highly variable agronomic responses¹⁷. Some experiments document yield gains and improved soil fertility^{10,13,17–19}, whereas others show limited effects^{20–24} or raise concerns about trace-metal inputs from silicate feedstocks enriched in nickel and chromium^{9,25,26,6}. This variability arguably reflects differences in feedstock selection, application rates, soil properties, climates, and crop type⁵. Additionally, most studies focus on a single feedstock under distinct conditions²⁷, thus hindering cross-study comparisons. As a result, it remains unclear whether contradictory agronomic findings reflect intrinsic feedstock properties or context-dependent experimental variability.

To fill this knowledge gap, here we report agronomic results from the first systematic comparison of six feedstocks used in large-scale ERW operations worldwide. Tested feedstocks span differences in mineralogy, base-cation content, trace-element concentrations, and weathering reactivity. They include two olivine-rich peridotites (Peridotite 1-2), three basaltic rocks (Basalt 1-3), and an alkaline industrial material derived from recycled concrete (Concrete). For all feedstocks, we performed a one-time 40 t ha⁻¹ application on a circumneutral (pH H₂O 7.2) sandy loam textured Cambisol collected from a periodically mown grassland in

Fürth, Germany, and grew a widely used forage species, perennial ryegrass (*Lolium perenne*). Identical climate and management conditions were maintained for all treatments, including feedstock-free negative controls (Methods, Fig. S1). After two years, we quantified changes in soil properties including soil pH, effective cation exchange capacity (CEC), soil organic carbon (SOC), N, P, Si, base cations (Ca, Mg, K, Na), and trace elements (Co, Cr, Cu, Mn, Ni, Zn). We also measured ERW's impact on crop yield and quality (macromolecular composition and same elements as for soils).

By jointly assessing changes in soil chemistry and plant nutritional profile, below we systematically evaluate whether the chemical mechanisms behind ERW effectively translate into consistent agronomic benefits.

Results

The standardized feedstock comparison confirmed ERW's capacity to alter both soil and crop properties (Fig. 1).

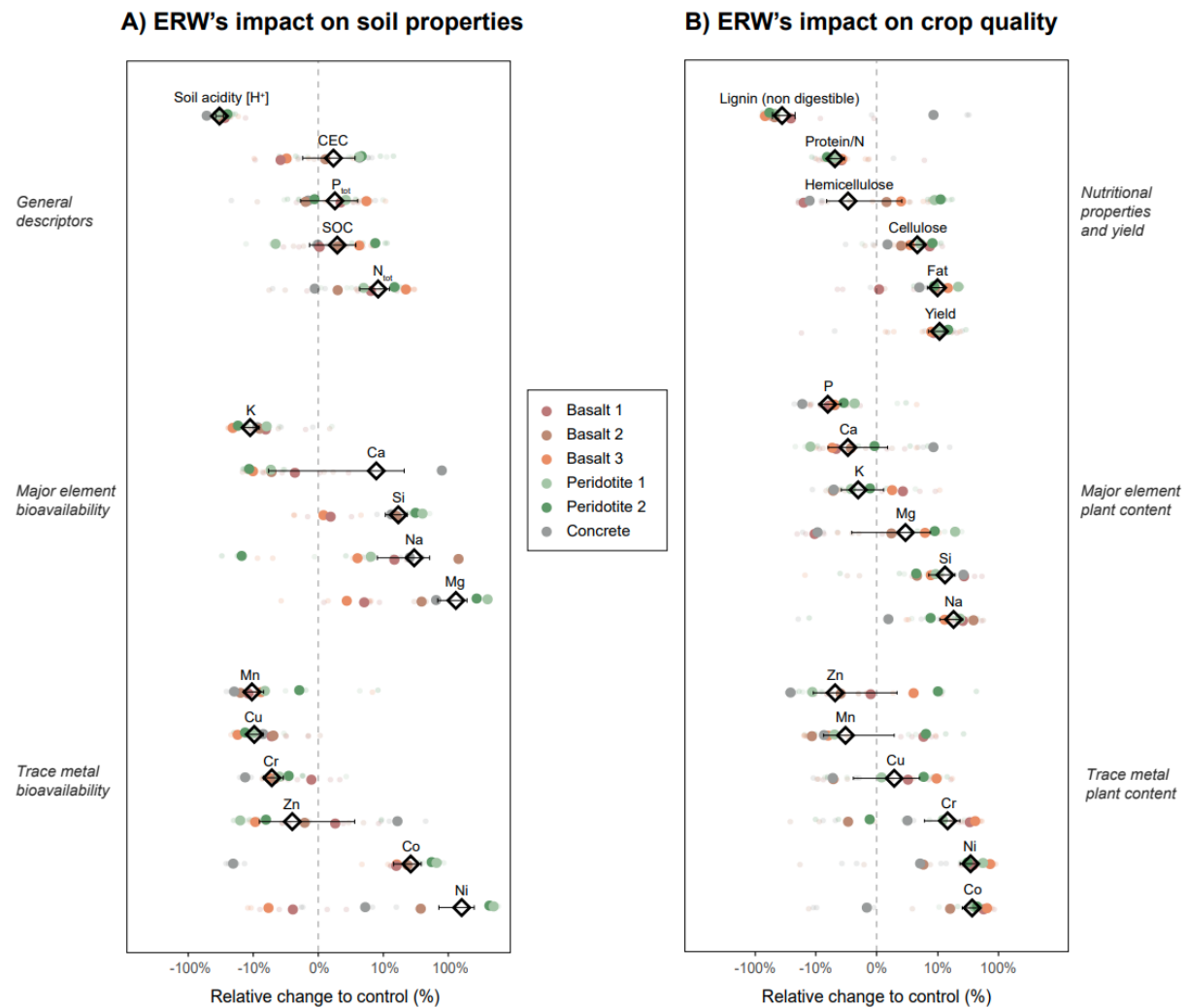


Fig 1. ERW's impact on soil and crop quality. Impact of different ERW feedstocks on plant and forage properties at the end of the 2-year mesocosm trial, expressed as relative change compared to controls (%). Black diamonds indicate the mean per variable across all ERW treatments, horizontal error bars represent 95% confidence intervals of the mean, colored points represent the mean for each feedstock treatment and individual shaded points represent individual replicates (n=4). CEC: cation exchange capacity, P_{tot}: P total content, N_{tot}: N total content, SOC: soil organic carbon.

Reduction in soil acidity

Over the two years, the control soil acidified from pH H₂O 7.2 to 6.5, corresponding to a 5-fold increase in proton concentration. By comparison, ERW feedstocks countered part of this acidification, yielding pH values 0.15-0.3 units higher than the control and representing a 33% $\pm$ 2% (mean $\pm$ SE) reduction in soil acidity (Fig. 1A, Fig. S2).

Beneficial changes in major soil and crop elements

ERW application also positively impacted some major soil and plant elements. Starting from 0.90 g kg⁻¹, soil N fell to 0.70 $\pm$ 0.01 g kg⁻¹ in the untreated control after two years but remained significantly higher at 0.80 g kg⁻¹ and 0.85 g kg⁻¹ with Peridotite 2 and Basalt 3, respectively (Fig. S3). Because external N inputs in the form of conventional N fertilizer were identical across treatments and controls (Methods), these values likely reflect enhanced N retention in the treated soils.

Beyond N retention, ERW application generated a clear increase in bioavailable Si relative to the controls (+17% $\pm$ 3%; Fig. 1A, Fig. S3), driven by the release of soluble silicic acid – the form plants readily take up – from dissolving silicates. This translated into higher Si content in plants (+13% $\pm$ 3%; Fig. 1B).

ERW application also exhibited a feedstock-dependent impact on Ca and Mg (Fig. 1, Fig. S4). Ca enrichment relative to control was observed exclusively with the carbonate-rich Concrete (+80% $\pm$ 1% bioavailable Ca in soil; +8% $\pm$ 1% Ca in plant tissue). In contrast, Mg bioavailability increased in soil across all feedstocks (+131% $\pm$ 32%), but this mainly translated into higher plant Mg content for the Mg-rich feedstocks Peridotite 1 and 2 (+14% $\pm$ 2%).

Potentially adverse effects on elemental availability and accumulation

First, the observed shifts in Ca or Mg were accompanied by a suppression of uptake of the other cation (-9% $\pm$ 1% Mg with Concrete; -6% $\pm$ 2% Ca with the peridotite feedstocks), consistent with the well-documented antagonism between Ca and Mg during plant uptake^{28,29}.

The two other base cations (K and Na) displayed opposite trends. ERW induced a net decline in K bioavailability across feedstocks relative to control, decreasing by 11% $\pm$ 2% in soil, although this signal only partially propagated to plant tissue (-2% $\pm$ 1%). Na on the contrary increased both in soil (+30% $\pm$ 11% bioavailable Na) and plant tissues (+18% $\pm$ 4% total Na, Fig. 1, Fig. S4-S5).

The clearest agronomic caution emerging from this trial concerns trace metals. For Mn, Cu, and Cr, bioavailable soil concentrations declined moderately (-10% Mn $\pm$ 2%, -9% Cu $\pm$ 1%, -6% Cr $\pm$ 1%) relative to controls, yet this reduction did not translate into lower plant concentrations, and for Cr even coincided with a significant increase in plant tissue (+15% $\pm$ 4%; Fig. 1, Fig. S5-S6). Additionally, Co and Ni increased markedly in both soil (+28% $\pm$ 6%

and $+169\% \pm 48\%$, respectively) and plants ($+37\% \pm 6\%$ and $+35\% \pm 6\%$; Fig. 1A,B), consistent with the presence across all feedstocks of Co- and Ni-bearing minerals such as olivine, pyroxene (e.g., augite), and chlorite³⁰ (detailed feedstock characteristics in Table S1-S3).

An overall improved crop nutritional profile

Despite the constraints discussed above, the combined effects of acidity reduction, enhanced N retention, and Si fertilization translated into crop improvement. First, crop yield increased by $13\% \pm 2\%$ relative to controls (Fig. 1). Rock amendments also improved forage nutritional quality, significantly increasing fat content ($+10\% \pm 2\%$) while concomitantly reducing lignin concentration ($-34\% \pm 5\%$; Fig. 1, Fig. S7). Notably, all other measured forage-quality parameters (e.g., dry matter content, raw ash content, organic matter content) remained non significantly changed.

Discussion

ERW as a liming strategy

The mechanism underlying the liming effect observed here is well established: silicate and carbonate weathering consumes protons, gradually neutralizing soil acidity⁵. Notably, this effect occurred here despite the fact that silicate dissolution rates are the lowest at circumneutral conditions³¹. When starting below pH 5, other studies focused on single feedstocks have reported increases of 1-3 pH units (as reviewed in Ref.⁵ and Ref.¹⁷). The observed soil acidity consumption therefore likely represents a conservative estimate of ERW's liming potential.

From an agronomic perspective, the observed reduction in soil acidity in the ERW treatments is significant because soil acidification remains a widespread constraint on crop productivity⁷. Under highly acidic conditions (soil pH < 5.5), potentially toxic elements such as Al are present in mobile bioavailable forms. Globally, about one-third of tropical soils (around 1.7 billion ha) suffer from acidity levels that allow soluble Al to reach levels toxic to most crops³², with soil acidification reducing crop yields by an average of 13.7%³³. In regions lacking accessible lime deposits, ERW feedstocks could serve as a slow-release liming alternative. Their slower weathering kinetics³¹ complementing conventional lime's faster action could prove particularly relevant for perennial systems (orchards, managed forests, plantations) where repeated liming is difficult once crops are established³⁴.

ERW as a fertilization strategy

Two ERW feedstocks (Basalt 3 and Peridotite 1) significantly improved soil N retention. Several geochemical mechanisms, summarized in Fig. 2, can explain this preferential retention: pH-driven CEC increases compared to the control³⁵, cation bridging between organic matter and

mineral surfaces³⁶, and sorption onto newly formed reactive secondary phases such as imogolite, allophane, and ferrihydrite³⁷. These two feedstocks also produced the highest, though non-significant, SOC increases (Basalt 3: +4% SOC, Peridotite 2: +7% SOC, Fig. S3), consistent with retention of the additional N in organic form. By contrast, Concrete, which produced both the largest reduction in soil acidity ($51\% \pm 1\%$) and the largest Ca release (+80% bioavailable Ca), neither changed soil CEC nor increased N, weighing against a purely pH-driven CEC pathway and Ca-mediated cation bridging as main drivers. Organic matter stabilization through sorption onto newly formed secondary phases, possibly complemented by Mg-mediated bridging in the case of Peridotite 2, therefore appears to be the most likely pathway, although the respective contributions remain to be confirmed experimentally. Improved N retention is important for sustainable agriculture because nitrogen management carries substantial environmental cost on both ends – upstream through the energy-intensive Haber-Bosch process, downstream through leaching and eutrophication³⁸. An ERW-associated improvement in soil N retention, if confirmed at scale, would therefore represent a meaningful and currently underappreciated co-benefit.

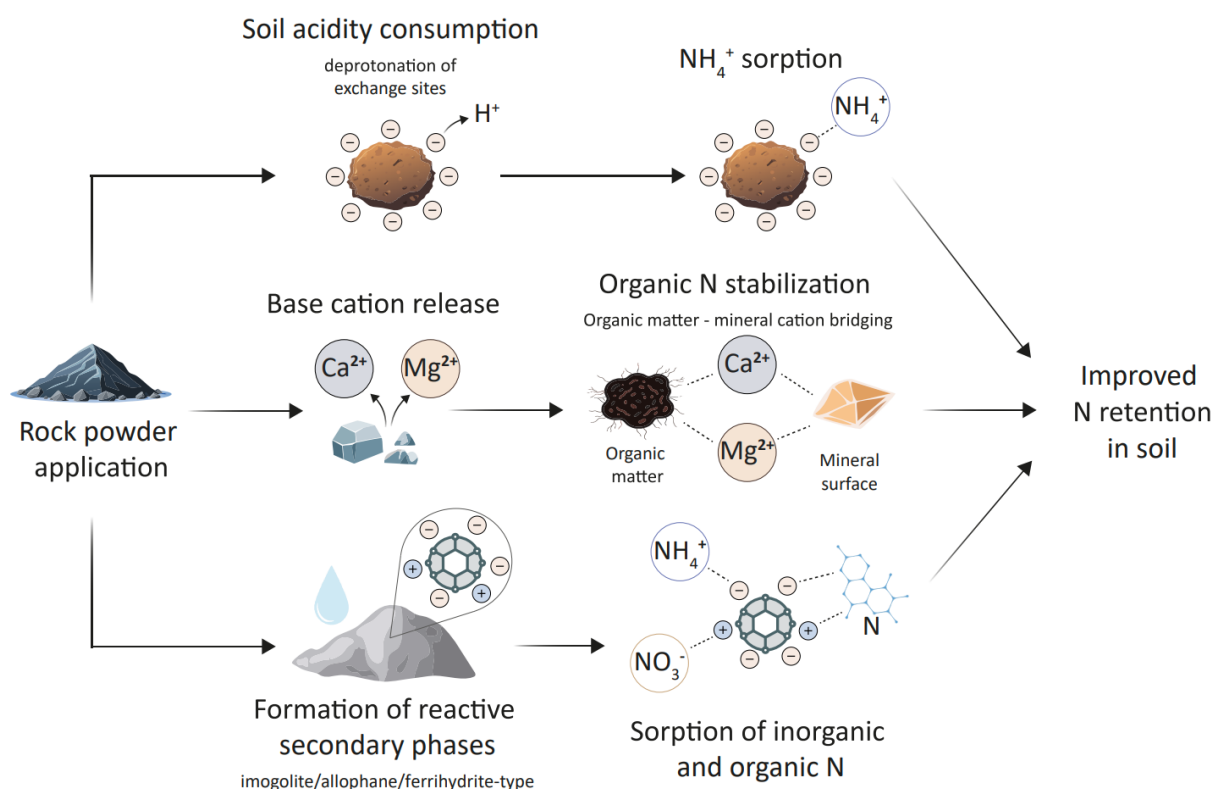


Fig 2. Conceptual pathways of ERW-associated N retention in soil. ERW-driven acidity consumption counters soil acidification, keeping organic and mineral exchange sites deprotonated and enhancing NH_4^+ retention. Another pathway is cation bridging, whereby divalent cations released through rock dissolution (Ca^{2+} , Mg^{2+}) bind soil organic matter to negatively charged mineral surfaces, physically and chemically stabilizing organic compounds against degradation. In parallel, silicate weathering can generate highly reactive amorphous secondary phases (e.g., imogolite, allophane-, and ferrihydrite-type minerals), whose high sorption capacity further enhances retention of both inorganic and organic N via direct mineral sorption and organic matter stabilization.

The Si increase observed here suggests that ERW could represent a globally relevant Si fertilization strategy. Si fertilization has long been recognized for its ability to enhance plant resistance to abiotic stresses such as drought and salinity and to biotic pressures including pests and diseases³⁹. For soybean and maize alone, Si fertilization has been shown to boost root and shoot growth traits and increase grain yield by 10 to 20%^{40,41}. By replenishing soil Si reserves, ERW could therefore strengthen plant resilience to stress and contribute to improving crop yields.

Unbalancing major element availability

Despite these benefits, ERW can also disturb elemental availability. This was observed with Ca or Mg suppression arising from elemental releases in unbalanced proportions. This phenomenon was especially visible with the peridotite feedstocks, which display a near-exclusive dominance of Mg over Ca (48% MgO vs. 0.3% CaO; see XRF results in Table S4). Their application drove a sharp decline in the soil Ca:Mg ratio from 31:1 in the control to 6:1 after treatment. Agronomically, Ca:Mg ratios below 10:1 are considered detrimental to forage productivity⁴². Exceeding this threshold after a single feedstock application suggests that, beyond toxic trace element concerns, Ca:Mg imbalance may pose an additional constraint on the use of olivine-rich feedstocks in ERW operations.

ERW also led to a decrease in potassium soil bioavailability. The most parsimonious explanation of this decrease is cation competition at soil exchange sites: the substantial release of Ca^{2+} , Mg^{2+} , and Na^{+} from fast-weathering silicate minerals in the feedstocks (Table S1) likely displaced K^{+} from exchangeable pools, a mechanism consistent with the K decline classically reported after liming⁴³. Under this scenario, K mobilized from exchange sites over the two years of the experiment was progressively taken up by plants or leached, explaining why the reduction detected in soil at the endpoint is markedly larger than the reduction measured in plant tissue. The very limited negative impact at the plant-level should not be read as reassurance, however. Continued crop removal through harvests and leaching could sustain lower plant-available K over time, particularly with K-poor feedstocks, with consequences for productivity and forage quality that would only become apparent beyond this trial's two-year window.

Na increase: beneficial or detrimental?

The strong and consistent increase in sodium content observed in our study likely reflects two mechanisms: desorption of native soil-exchangeable Na through competition with ERW-derived divalent cations (Ca^{2+} , Mg^{2+}), and weathering of Na-bearing minerals within the feedstocks themselves (natrite and trace halite in Concrete, nepheline and amphibole in Peridotite 1, and Ca-Na plagioclase, present in all feedstocks but abundant (>30%) only in Basalts 1-3, Table S1). This mineral-weathering contribution was further modulated by

feedstock specific surface area (SSA): Peridotite 1 ($3.2 \text{ m}^2 \text{ g}^{-1}$), for instance, was more reactive than Peridotite 2 ($1.9 \text{ m}^2 \text{ g}^{-1}$) (Table S3).

This change in Na does not raise toxicity issues on the short-term. In ERW-treated plants, Na concentrations ($0.5\text{-}0.7 \text{ g kg}^{-1}$) indeed remained far below the toxicity threshold reported for *Lolium perenne* (17 g Na kg^{-1})⁴⁴, suggesting no immediate agronomic concern. To the contrary, at such levels, Na could instead be beneficial to livestock. Higher forage sodium levels have indeed been linked to better digestibility along with improved mineral retention and nitrogen availability to the livestock^{45–47}.

This reassurance is nevertheless conditional on the high-rainfall regime applied in this trial ($2,270 \text{ mm yr}^{-1}$, representing a tropical wet climate), which likely limited Na accumulation through continuous leaching. Under drier or more evaporation-dominated climates, where leaching is reduced and evapotranspiration concentrates salts in the root zone, the same feedstocks could plausibly drive Na towards levels relevant to plant salinity stress or soil sodicity²³ – a risk our design cannot rule out and that warrants dedicated testing across a gradient of water balances.

Concerning increase in plant Ni

The increase in plant Ni is of particular concern as the plant concentration in control plots (10 mg kg^{-1}) was already close to the critical agronomic threshold commonly associated with a yield reduction in *Lolium perenne* ($12\text{-}14 \text{ mg kg}^{-1}$)⁴⁸. The +35% increase in plant Ni observed under ERW pushed several feedstocks beyond this threshold (Basalts 1 and 3, Peridotites 1-2).

Additionally, Ni concentrations in soils stayed below 10 ppm for all feedstocks except for Peridotite 1-2 which increased to 60-70 ppm. These levels exceed environmental regulatory thresholds in many countries (e.g., Brazil, Canada, Germany, Russia; Table S4-S5)⁶. That these thresholds were exceeded after a single application suggests that Ni-rich ultramafic rocks such as peridotites may pose regulatory constraints for large-scale agricultural use⁴, irrespective of these feedstock's CO_2 removal potential and broader agronomic effects.

Promising yield gains

The +13% yield trend was uniform across all six feedstocks (Fig. 1B) and closely matches independent mesocosm evidence: basalt amendment of an alkaline soil (pH 8.1) under a temperate grassland system increased aboveground biomass by 14%⁴⁹. In absolute terms, the yields reported in our treatments ($1.9 \pm 0.1 \text{ t dry matter (DM) ha}^{-1} \text{ yr}^{-1}$ on average) compare favorably with those reported in other pot-based trials ($1.7 \pm 0.1 \text{ t DM ha}^{-1} \text{ yr}^{-1}$)⁵⁰. This result is even more notable given the sandy loam texture and low effective CEC of the soil used here, both of which typically constrain productivity⁵¹. Still, pot-derived yields cannot be directly

extrapolated to open-field conditions, as restricted root volume inherent in mesocosm experiments is known to limit both element foraging and total biomass accumulation⁵².

Because the tested feedstocks contain no N and negligible plant-available P, soluble N and P fertilizers were applied uniformly to all pots, including controls, ensuring that the observed yield gain reflects the amendments' liming and major and trace element supply effects rather than a masked fertilization artefact. Against this backdrop, the yield increase was accompanied by a modest decline in plant N ($-5\% \pm 1\%$) and P ($-6\% \pm 1\%$) tissue concentrations – a pattern consistent with the well-documented elemental dilution effect, whereby faster biomass accumulation outpaces element uptake on a per-unit-mass basis⁵³.

This yield gain is agronomically meaningful in the context of mounting pressure on forage systems. Rising population growth and increasing demand for animal protein have intensified forage shortages in many regions⁵⁴. In East Africa alone, an estimated 40% of annual feed demand currently goes unmet⁵⁵. Against this backdrop, an ERW-associated yield increase of this magnitude could represent a meaningful contribution to closing regional forage gaps.

Nutritional implications for plant quality

Since fat enhances metabolizable energy⁵⁶ and lignin limits cell wall digestibility⁵⁷, these two shifts point in the same direction: denser, more digestible biomass. Notably, all other measured forage-quality parameters (e.g., dry matter content, raw ash content, organic matter content) did not change significantly.

Forage fat content typically ranges between 1 and 5% DM, with *Lolium perenne* sitting at the lower end of this range^{58,59}. In our trial, control fat content (2.2% DM) already fell within this normal range, yet ERW feedstocks further increased it by up to 21% compared to control. Even modest lipid increases of this kind can raise metabolizable energy and feed conversion efficiency in ruminants⁵⁶, with potential to incrementally improve livestock productivity at scale.

The lignin response was proportionally larger. Control lignin content (8% DM) was markedly higher than the 2-4% DM typically reported for *Lolium perenne*⁶⁰, likely reflecting element limitation, a mechanism previously reported for Italian ryegrass under similar conditions⁶¹. This elevated baseline may explain why silicate feedstocks reduced lignin content by up to 54%: plants under beneficial-element constraints, particularly Si, invest disproportionately in structural, lignified tissue^{62,63}, an allocation that ERW's Si supply likely reversed⁶⁴. Because lignin is a primary determinant of cell wall digestibility in ruminants⁵⁷, reductions of this magnitude could translate into higher milk and meat yields in regions where livestock productivity is limited by forage quality rather than quantity.

If confirmed at scale, the benefits described above position ERW as a potential lever for global food security. Realizing this potential will, however, require careful feedstock selection, as the

lower K bioavailability and the sodium and potentially toxic trace metal accumulations observed with certain rock sources underscore the need to match feedstock composition to soil and regulatory contexts. Field-scale validations assessing a wide-range of ERW feedstocks across soils, climates and crops are now needed to further refine these findings.

Methods

Experimental design

The ERW feedstocks were evaluated in a controlled mesocosm experiment conducted in Fürth, Germany over 2 years between 2023 and 2025. Each treatment was established with four independent replicates in a fully randomized block design.

Each mesocosm consisted of two stacked 10 L lysimeters (diameter 25.6 cm; height 26.3 cm) with the lower bucket collecting leachate. The upper bucket contained a root fleece and a 3 cm layer of washed quartz sand to promote homogeneous drainage and pre-filtration of leachate. Above this layer, 10 cm of unamended soil was overlain by 15 cm of soil mixed with an ERW feedstock equivalent to 40 t ha⁻¹ (206 g per pot). Each mesocosm received 20 earthworms (equal mixture of *Eisenia foetida*, *Dendrobena veneta* and *Lumbricus terrestris*, Regenwuermer.de) to promote bioturbation. Each pot was sown with 3 g of perennial ryegrass (*Lolium perenne*) seeds, evenly distributed at the surface.

Mesocosms were constantly maintained above 19°C, with an average temperature of 23°C (Fig. S1). Irrigation water was supplied from a rainwater cistern and was delivered through automated irrigation rings (Netafim NetBow, 12 cm diameter) four times per day to reach an average irrigation rate of 2270 mm yr⁻¹. Pots were fertigated twice in 2023 (28/08 and 21/09) with a soluble mineral NPK fertilizer (8-8-6, Wuxal Super, Aglukon) for a total equivalent of 133 kg N ha⁻¹, 58 kg P ha⁻¹ and 83 kg K ha⁻¹.

Soil description

The soil used in the experiment is Eutric Cambisol (Loamic, Aric) according to the FAO World Reference Base⁶⁵. Soil was sampled in Fürth, Germany (49.48747° N, 10.94914° E) from a former cropland field that was conventionally managed until 2014 and that has since been converted to permanent grassland without fertilization or organic amendments. The initial soil has a circumneutral pH (pH H₂O 7.2), with only trace of inorganic carbon (TIC 0.1%). Its total organic carbon content is 1.0%. It has a sandy loam texture according to the USDA textural classes⁶⁶ and a low effective cation exchange capacity (10.2 meq 100g⁻¹). Mineralogically, it is dominated by quartz (66.2%) and K-feldspars (20.7%; Table S1), while its elemental composition is dominated by Si, Al, and K (Table S2).

The mineralogy of the soil and feedstocks was determined by bulk XRD. Samples were dried at 40 °C, homogenized, wet-milled in alcohol and dried to minimize preferred orientation, then analyzed on a Bruker D8 Advance (XE-T detector, Cu-K α radiation). Phases were identified and quantified by Rietveld refinement.

Feedstock description

The feedstocks used in this experiment comprised one industrial material (Concrete) and five igneous silicate rocks currently used in enhanced rock weathering operations worldwide. These materials were provided by ERW companies under confidentiality agreements; supplier identities and source locations are therefore not disclosed. The industrial feedstock consisted of crushed cement concrete dominated by carbonate minerals, primarily calcite and dolomite. Three silicate feedstocks were mafic volcanic rocks (Basalt 1-3) dominated by plagioclase and pyroxene. Two additional silicate feedstocks were slightly serpentinized ultramafic rocks (Peridotite 1-2) dominated by olivine and serpentine (see SI for additional elemental and mineralogical information).

Soil analysis

Soil samples were collected from the upper 15 cm at the end of the experiment, homogenized, oven-dried at 40 °C, and sieved to <2 mm. To preserve undisturbed control mesocosms for a follow-up study, only two of the four control replicates were sampled. Soil pH was determined in 1:5 soil-to-solution ratios using 0.01 M CaCl₂ and nanopure water, following horizontal shaking for 10 min and 24 h equilibration, with a Metrohm 713 pH meter (6.0262.100 electrode)⁶⁷.

Bioavailable elements were extracted using Mehlich-3 solution (0.2 M CH₃COOH, 0.25 M NH₄NO₃, 0.015 M NH₄F, 0.013 M HNO₃, 0.001 M EDTA; pH $\approx$ 2.3) with 2 g soil and 20 mL solution, shaken for 5 min at 120 rpm, settled 5 min, and vacuum-filtered (0.5 μ m)^{68,69}. Because Mehlich-3 cannot fully mobilize P in the presence of high soluble Si⁷⁰, P bioavailability is not reported here. Total element contents (Al, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Si, and Zn) were determined via aqua regia digestion (1 g soil, 2 mL H₂O, 6 mL HCl, 2 mL HNO₃, 120 °C, 150 min), diluted to 50 mL, and filtered through 20 μ m paper⁷¹, before being measured by ICP-OES (Agilent 5100, Santa Clara, CA, USA).

Soil organic carbon (SOC) was quantified by dry combustion (~400 mg soil) using a SoliTOC Cube Analyzer as the sum of TOC 400 and ROC fractions, calibrated with reference materials (recoveries 100.7-101.7%). Total nitrogen was determined by dry combustion (CN928, LECO; ~500 mg soil) with EDTA reference calibration (>98% recovery). Effective cation exchange capacity (CEC) was determined using the unbuffered BaCl₂ method, whereby 20 mL of 0.1 M BaCl₂ was added to 3 g soil, shaken for 1 h at 120 rpm, settled 5 min, and vacuum-filtered (0.45 μ m)⁷². Exchangeable cations (Ca, Mg, K, Na, Al) were then quantified by ICP-OES

(Agilent 5100, Santa Clara, CA, USA) and CEC calculated as the sum of charge-equivalent cation concentrations.

Forage biomass analysis

Aboveground biomass was sampled every 3-6 weeks, depending on plant growth rates, throughout the experimental period. Samples were dried at 55 °C for 48 h then ground to pass through a 1-mm screen sieve using a centrifugal mill (ZM 1, Retsch GmbH, Haan, Germany). For each replicate pot, all harvested samples were combined into a single biomass sample. Samples were analyzed for elemental content, dry matter (DM), ash, organic matter (OM), neutral detergent fiber (NDF), acid detergent fiber (ADF), nitrogen, ether extract, starch, crude fiber, and gross energy according to the official methods of analysis⁷³ and performed in duplicate as described by Birkinshaw et al.⁷⁴.

Elemental contents were determined by fully dissolving samples in a HF:HNO₃ mixture (0.02g sample, 0.1 ml HF, 0.9 ml HNO₃). Following dilution and addition of an internal In standard, the digested samples were analyzed using an Element XR high-resolution ICP-MS. Total ash was determined using a thermogravimetric device (TGA-701, Leco; AOAC official method 942.5). Bomb calorimetry (C7000, IKA-Werke) was used to determine the gross energy of the dietary components. Nitrogen in forage samples was analyzed by a carbon/nitrogen analyzer (TruMac CN, Leco; AOAC official method 968.06). Crude protein in forage samples was calculated as N × 6.25. Ether extract was determined using a Soxhlet extractor (Extraction System B-811, Büchi; AOAC official method 963.15), and a Fibertherm FT 12 (Gerhardt GmbH and Co. KG, Königswinter, Germany) to determine ash-corrected detergent fiber fractions. Heat-stable α -amylase (Sigma-Aldrich, St. Louis, MO) was used with neutral detergent fiber (AOAC official method 2002.04) and acid detergent fiber (AOAC official method 973.18) analysis. Acid detergent lignin was determined from the acid detergent fiber residue following digestion with 72% sulfuric acid according to AOAC official method 973.18.

Data analysis

Statistical analyses were performed in R (v4.6.1) in two steps on soil and crop variables (Fig. S2-S7). First, to test the overall effect of ERW, each response variable was analyzed with a linear mixed-effects model including treatment (ERW vs. control) as a fixed effect and ERW feedstocks as a random effect, fitted with the lme4 package⁷⁵. P-values were derived using Satterthwaite's approximation for degrees of freedom⁷⁶ to maintain nominal Type I error rates and limit anti-conservative bias⁷⁷.

Second, to resolve feedstock-specific effects, linear models with pre-specified contrasts were fitted to compare each feedstock treatment against the control⁷⁸. Differences between treatments and control were assessed using Holm-adjusted p-values to correct for multiple

comparisons⁷⁹. For the soil sample, the control sample size was smaller but the use of pre-specified contrasts and Holm-adjusted p-values for multiple comparisons ensured robust inference⁷⁸. The normality and homogeneity of variance of the model residuals were assessed both visually and using the Shapiro-Wilk⁸⁰ and Levene⁸¹ tests, respectively. Where necessary, Box-Cox transformation was applied to meet these assumptions⁸².

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Supplementary material

Of the article entitled

Systematic comparison of major enhanced rock weathering feedstocks highlights agronomic benefits and trade-offs

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Feedstock information

The six investigated feedstocks comprise three basaltic rocks (Basalt 1-3), two peridotites (Peridotite 1-2), and one concrete-derived material (Concrete).

Basalt 1 and Basalt 3 are composed primarily of plagioclase, clinopyroxene, alkali feldspar, Fe-Ti oxides, and minor olivine (1.3 and 1.2%). Basalt 2 presents a less evolved composition with no alkali feldspar but substantial olivine (6.1%). All three basalts contain significant amounts of secondary mineral phases such as 2:1 layer silicates (likely smectite group minerals), chlorite, and, in the case of Basalt 2 and Basalt 3, trace carbonates, indicating varying degrees of metamorphic and/or supergene alteration. The two peridotite feedstocks are dominated by olivine (60.8% and 81.6%) but display partial serpentinization with 16.8% and 9.1% serpentine minerals and 4.7% and 0.8% talc in Peridotite 1 and Peridotite 2, respectively. The Concrete material is characterized by a carbonate-rich assemblage dominated by calcite, accompanied by quartz, feldspar phases, and minor secondary minerals and oxides (Table S1).

In terms of grainsize and specific surface area (SSA), Concrete is 2-10 times coarser than the other feedstocks but presents a SSA ($19.5 \text{ m}^2 \text{ g}^{-1}$) that is 3-10 times higher due to its structural porosity (Table S3). The two peridotites are fine-grained ($d_{90} < 50 \text{ }\mu\text{m}$) and 2–10 times finer than the three basalts; among the latter, Basalt 2 is 3–4 times finer than Basalt 1 and Basalt 3.

Detailed mineralogical composition (Table S1), elemental composition (Table S2), and grain-size distribution and specific surface area (SSA) (Table S3) are available in Supplementary information.

Table S1. Mineralogical composition of the initial soil and of the ERW feedstocks measured by X-ray diffraction (XRD).

Mineral	Soil	Concrete	Basalt 1	Basalt 2	Basalt 3	Peridotite 1	Peridotite 2
SILICATES							
Quartz	66.2	16.9	6.2	2.4	2.7	0.7	0.7
Cristobalite					2.0		
Tridymite					1.9		
K-feldspar	20.7	0.4	5.5		13.7		
Plagioclase	2.4	1.7	33.8	58.6	38.1	1.2	0.7
Clinopyroxene			17.4	10.9	20.6	0.6	0.9
Orthopyroxene			3.5	7.0	3.7	3.1	3.4
Amphibole			1.5			2.2	0.7
Olivine			1.3	6.1	1.2	60.8	81.6
Nepheline					1.3	0.5	
Beta C2S (Larnite)		0.4					
C3S		0.4					
2:1 layer silicates	8.9	2.5	23.3	12.1	6.1	0.6	
Chlorite		0.3	1.2	1.3		4.4	
Kaolinite	1.1		0.7			2.7	0.8
Serpentine						16.8	9.1
Talc				0.3		4.7	0.8
CARBONATES							
Calcite	0.2	61.2					
Dolomite/Ankerite		9.3		0.6	0.9	0.3	0.2
Hydrotalcite		0.5				0.5	0.3
Natrite		1.7					
PHOSPHATES							
Apatite		0.9	0.5		1.5		
SULPHATES							
Gypsum		0.9					
Ettringite/Aft		0.9					
HALIDES							
Halite		0.2					
OXIDES/HYDROXIDES							
Rutile/Anatase	0.2						
Hematite			0.2				
Spinel-type minerals			2.8	0.4	2.1	0.4	0.8
Ilmenite			2.1	0.3	4.4	0.3	
Portlandite		0.4					
Srebrodolskite		0.3					

Table S2. Elemental composition of the initial soil and ERW feedstocks measured by X-ray fluorescence (XRF).

Detection limits (DL) are provided for each parameter (bdl: below detection limit). Loss on Ignition (LOI) was determined through heating at 1000 degrees C for 2 hours.

Element	Unit	DL	Soil	Concrete	Basalt 1	Basalt 2	Basalt 3	Peridotite 1	Peridotite 2
SiO ₂	%	0.01	81.44	18.53	49.73	47.93	49.62	41.73	41.56
Al ₂ O ₃	%	0.01	7.27	1.93	13.3	18.79	12.38	0.84	0.42
Fe ₂ O ₃	%	0.01	2.02	1.11	13.4	8.31	15.15	6.92	8.49
MnO	%	0.005	0.11	0.05	0.189	0.127	0.207	0.095	0.118
MgO	%	0.01	0.37	2.81	5.74	8.38	4.04	45.76	47.49
CaO	%	0.01	0.51	40.86	8.18	10.87	7.9	0.23	0.3
Na ₂ O	%	0.01	0.49	0.11	2.67	2.19	2.64	0.11	0.1
K ₂ O	%	0.01	3.96	0.3	1.41	0.37	1.55	0.08	0.03
TiO ₂	%	0.01	0.23	0.1	2.35	0.36	3.72	0.01	0.03
P ₂ O ₅	%	0.01	0.20	0.04	0.28	0.12	0.47	bdl	0.01
LOI	%	0.01	3.39	34.4	3.14	3.06	1.69	3.82	1
Cr	ppm	68	68	bdl	137	342	bdl	2463	3216
Co	ppm	37	bdl	bdl	44	44	44	104	126
Cu	ppm	40	bdl	bdl	40	88	40	bdl	bdl
Ni	ppm	24	bdl	bdl	39	157	bdl	2601	2915
V	ppm	17	17	39	336	106	403	bdl	bdl

Table S3. Grainsize and surface area of the ERW feedstocks. Particle size distribution measured by laser diffraction.

Results are shown as mean, mode, and percentile values d10, d50, d60, d90. BET specific surface area determined by N₂ adsorption.

Analysis	Unit	Parameter	Concrete	Basalt 1	Basalt 2	Basalt 3	Peridotite 1	Peridotite 2
Grainsize	µm	Mean	285.5	128.7	36.5	130.8	21.2	17.5
	µm	Std. dev.	251.1	130.1	41.5	129.2	16.2	13.2
	µm	Mode	454.6	244.9	53.3	235.04	26.4	23.4
	µm	d10	18.2	4.5	3.2	10.9	4.1	3.4
	µm	d50	233.8	77.8	20.6	85.0	17.5	14.5
	µm	d60	319.6	149.5	29.9	122.8	22.1	18.5
	µm	d90	643.5	319.1	93.3	322.8	44.3	36.4
Specific surface area	m ² /g	BET area	19.5	2.4	6.7	6.5	3.2	1.9

Environmental conditions

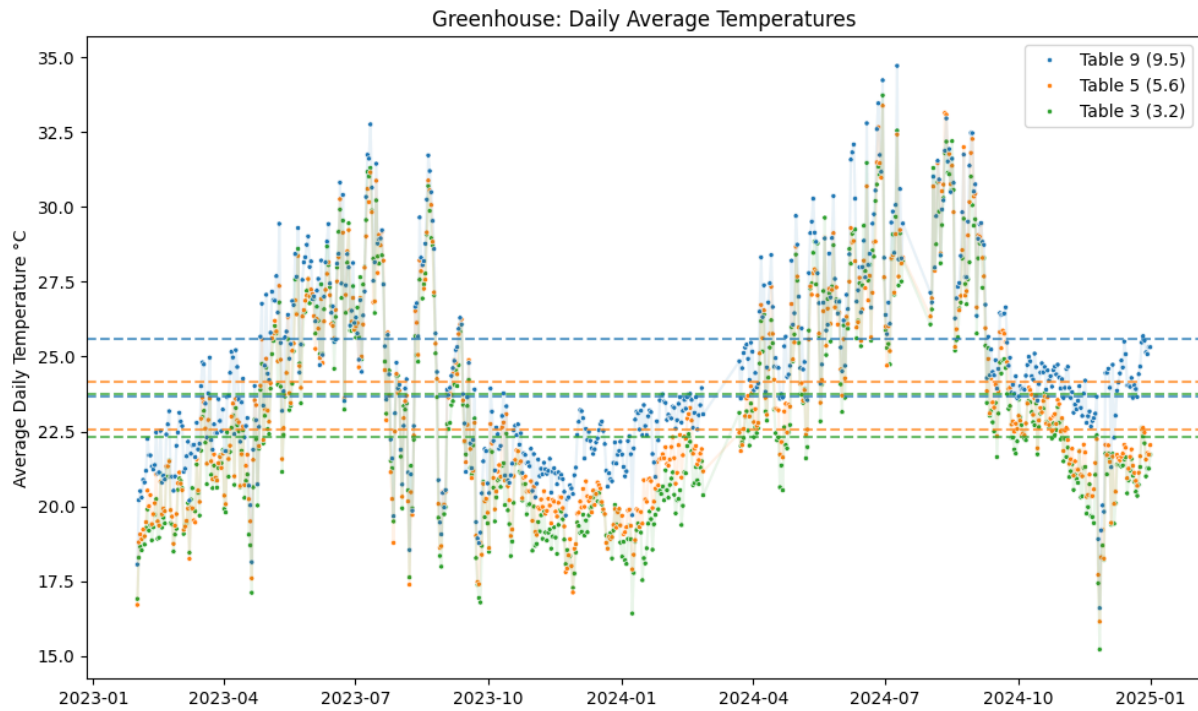


Fig S1. Greenhouse soil temperature conditions. Daily soil temperatures (°C) monitored from mesocosm tables (3, 5, 9) distributed throughout the greenhouse.

ERW impact on soil and forage properties

ERW vs Control: Linear mixed model (ERW feedstocks as random effect). **P = 0.015**.
Each feedstock vs Control (below): Linear model with pre-specified contrasts. $P(\text{model}) < 0.001$.
Control (n = 2), Feedstocks (n = 4). Holm-adjusted difference significance relative to Control:
* P < 0.05, ** P < 0.01, *** P < 0.001, **** P < 0.0001

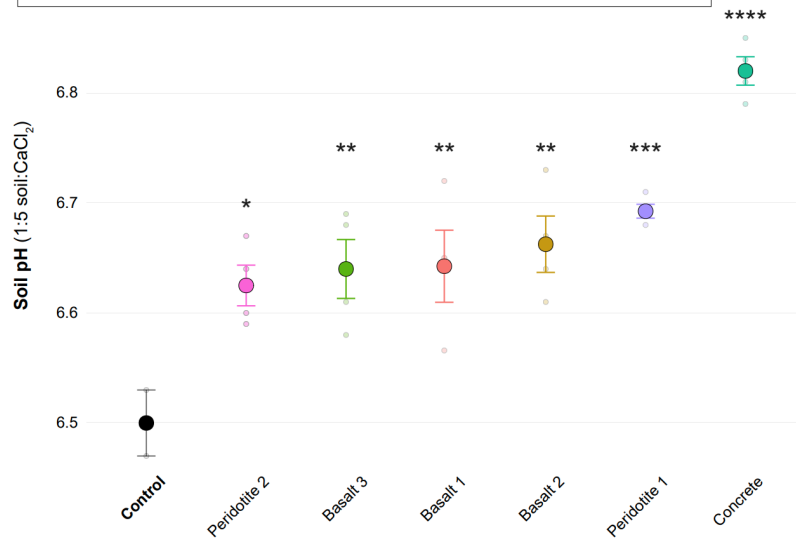
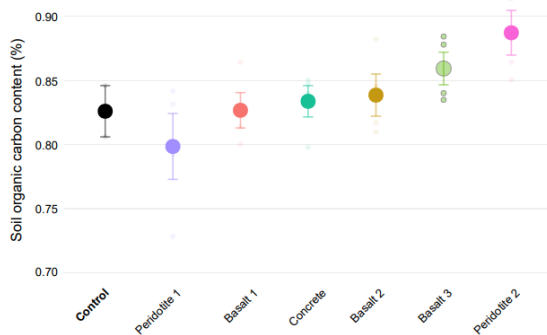


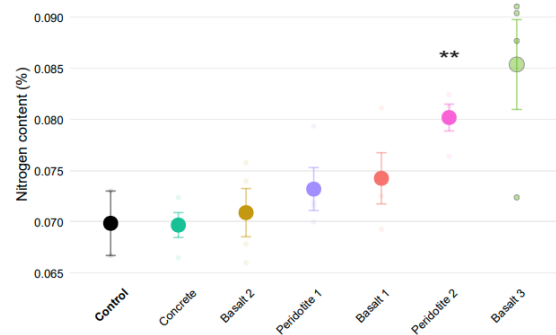
Fig S2. ERW-induced change in soil pH. Impact of rock powder addition (40 t ha⁻¹) on soil pH, 2 years post application. Points show individual replicate measurements, large circles indicate treatment means and error bars represent ± SEM.

ERW vs Control: Linear mixed model (ERW feedstocks as random effect). $P(\text{SOC}) = 0.67$, $P(\text{N}) = 0.17$, $P(\text{P}) = 0.75$, **$P(\text{Si}) = 0.01$** .
Each feedstock vs Control (below): Linear model with pre-specified contrasts. $P(\text{SOC}) = 0.02$, $P(\text{N}) = 0.001$, $P(\text{bioP}) = 0.07$, $P(\text{bioSi}) < 0.0001$.
Control (n = 2), Feedstocks (n = 4). Holm-adjusted difference significance relative to Control:
* P < 0.05, ** P < 0.01, *** P < 0.001, **** P < 0.0001

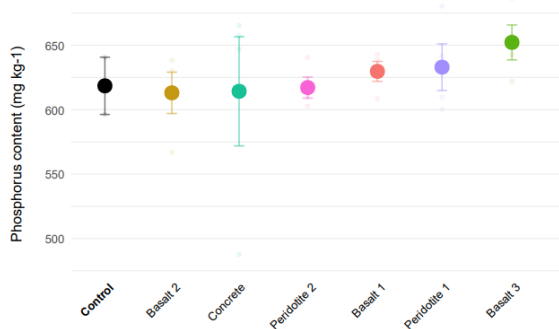
A) Soil organic carbon



B) Nitrogen



C) Phosphorus



D) Silicon

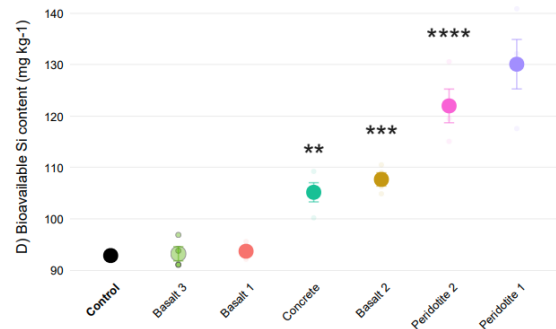


Fig S3. Impact of ERW on SOC, N, P and Si soil contents. Impact of rock powder addition (40 t ha⁻¹) on soil organic carbon (SOC), total nitrogen and bioavailable silicon (Mehlich-3 extractable), 2 years post application.

ERW vs Control: Linear mixed model (ERW feedstocks as random effect). $P(\text{Ca}) = 0.63$, $P(\text{Mg}) = 0.037$, $P(\text{K}) = 0.032$, $P(\text{Na}) = 0.36$.
Each feedstock vs Control (below): Linear model with pre-specified contrasts. $P(\text{Ca}) = 0.02$, $P(\text{Mg}) = 0.001$, $P(\text{K}) = 0.07$, $P(\text{Na}) < 0.0001$.
Control (n = 2), Feedstocks (n = 4). Holm-adjusted difference significance relative to Control:
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$.

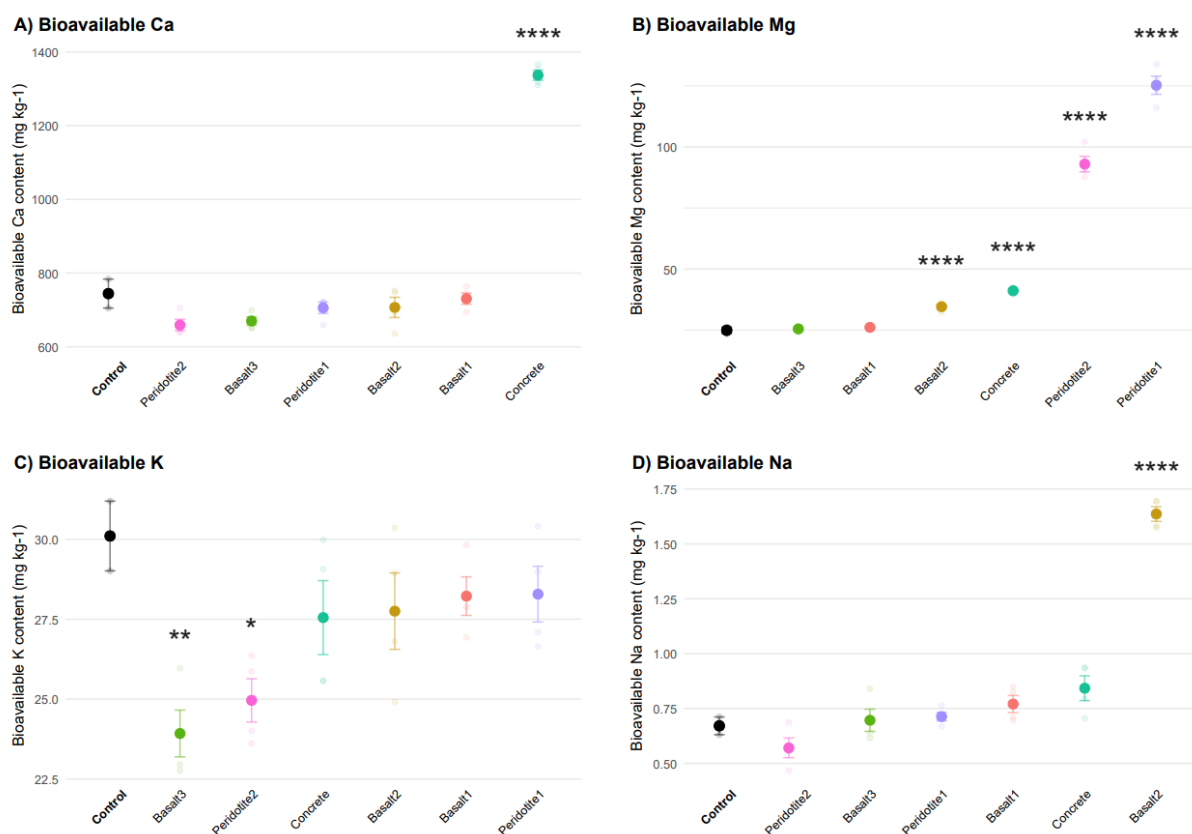


Fig S4. Impact of ERW on base cation bioavailability in soil. Impact of rock powder addition (40 t ha⁻¹) on bioavailable (Mehlich-3 extractable) Ca, Mg, K and Na content, 2 years post application.

ERW vs Control: Linear mixed model (ERW feedstocks as random effect).
 $P(\text{Si}) = 0.076$, $P(\text{Ca}) = 0.54$, $P(\text{Mg}) = 0.65$, $P(\text{K}) = 0.56$, $P(\text{Na}) = 0.059$, $P(\text{P}) = 0.058$, **$P(\text{Co}) = 0.024$** , $P(\text{Cr}) = 0.19$, $P(\text{Cu}) = 0.75$, $P(\text{Mn}) = 0.47$, **$P(\text{Ni}) = 0.028$** , $P(\text{Zn}) = 0.45$.
Each feedstock vs Control (below): Linear model with pre-specified contrasts. Linear model with pre-specified contrasts:
 $P(\text{Si}) = 0.03$, $P(\text{Ca}) = 0.01$, $P(\text{Mg}) < 0.0001$, $P(\text{K}) = 0.20$, $P(\text{Na}) = 0.02$, $P(\text{P}) = 0.001$, $P(\text{Co}) = 0.001$, $P(\text{Cr}) = 0.003$, $P(\text{Cu}) = 0.09$, $P(\text{Mn}) = 0.10$, $P(\text{Ni}) < 0.0001$, $P(\text{Zn}) < 0.0001$.
Control (n = 4), Feedstocks (n = 4), Holm-adjusted difference significance relative to Control: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$

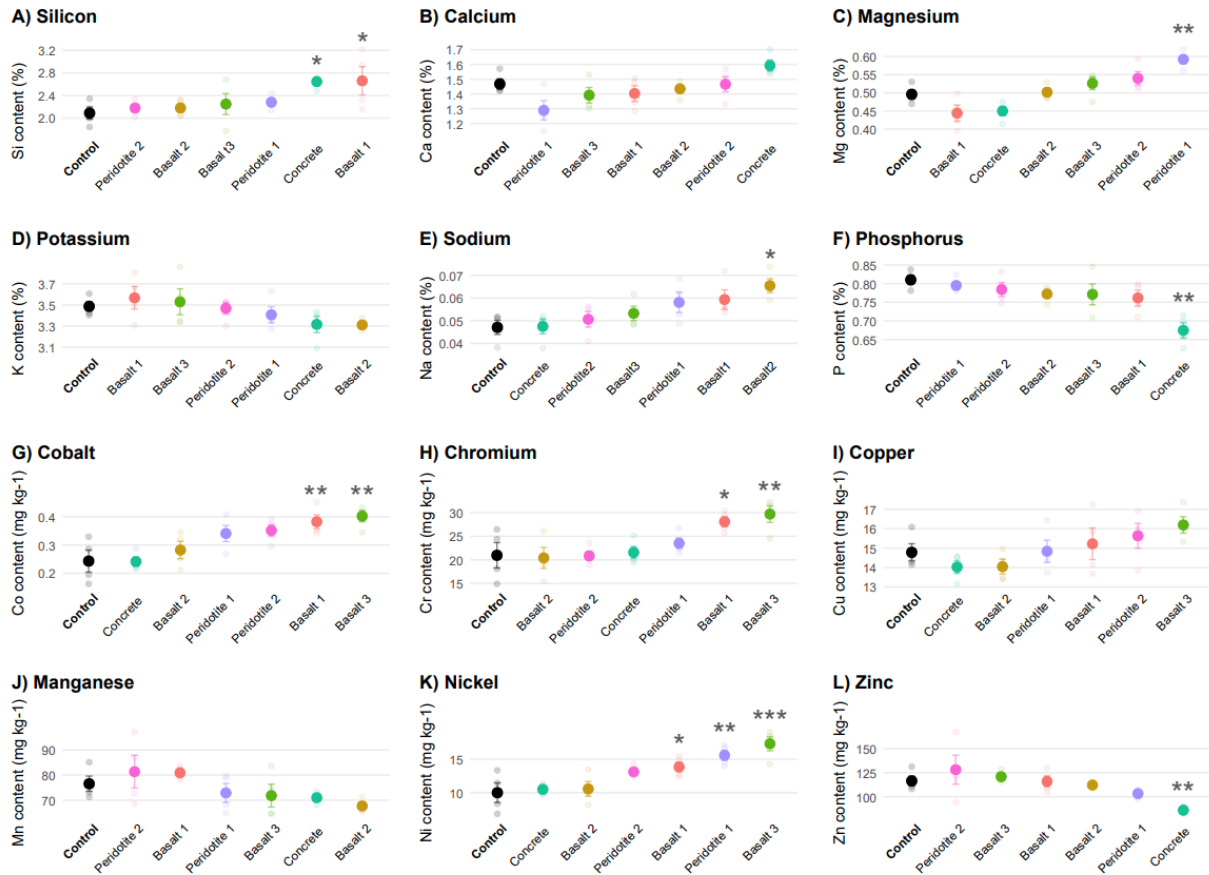


Fig S5. Impact of ERW on forage elemental composition. Impact of rock powder addition (40 t ha⁻¹) on Si, Ca, Mg, K, Na, P, Co, Cr, Cu, Mn, Ni and Zn, 2 years post application.

ERW vs Control: Linear mixed model (ERW feedstocks as random effect). $P(\text{Co}) = 0.11$, $P(\text{Cr}) = 0.045$, $P(\text{Cu}) = 0.025$, $P(\text{Mn}) = 0.078$, $P(\text{Ni}) = 0.12$, $P(\text{Zn}) = 0.56$.
Each feedstock vs Control (below): Linear model with pre-specified contrasts. $P(\text{Co}) < 0.0001$, $P(\text{Cr}) < 0.0001$, $P(\text{Cu}) = 0.006$, $P(\text{Mn}) = 0.002$, $P(\text{Ni}) < 0.0001$, $P(\text{Zn}) = 0.001$.
Control (n = 2), Feedstocks (n = 4), Holm-adjusted difference significance relative to Control: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$.

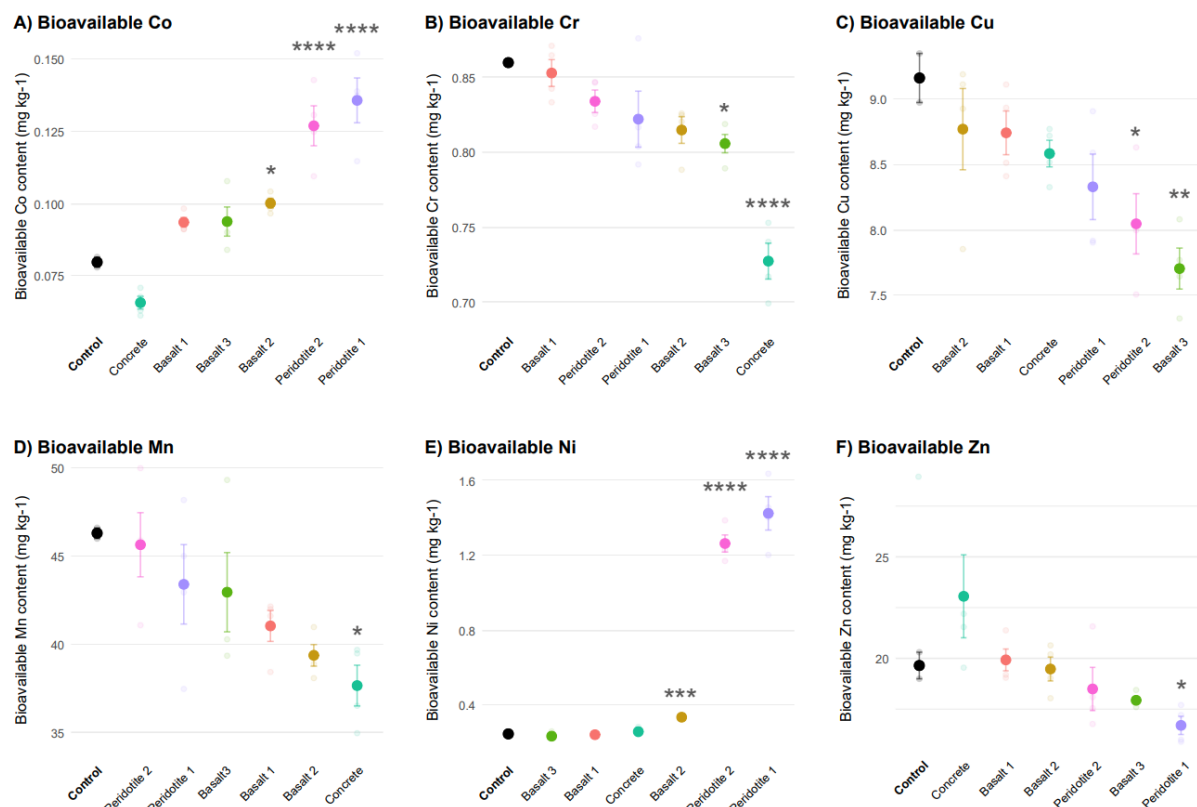


Fig S6. ERW's impact on potentially toxic trace element bioavailability in soil. Impact of rock powder addition (40 t ha⁻¹) on bioavailable (Mehlich-3 extractable) elemental concentrations of Co, Cr, Cu, Mn, Ni and Zn, 2 years post application.

ERW vs Control: Linear mixed model (ERW feedstocks as random effect). $P(\text{Fat}) = 0.024$, $P(\text{Yield}) = 0.034$, $P(\text{Lignin}) = 0.012$, $P(\text{Hemi.}) = 0.54$, $P(\text{Cell.}) = 0.037$, $P(\text{Prot.}) = 0.037$.
Each feedstock vs Control (below): Linear model with pre-specified contrasts.
 $P(\text{Fat}) < 0.0001$, $P(\text{Yield}) = 0.50$, $P(\text{Lignin}) < 0.0001$, $P(\text{Hemicellulose}) < 0.0001$, $P(\text{Cellulose}) = 0.01$, $P(\text{Protein}) = 0.48$.
Control (n = 4), Feedstocks (n = 4). Holm-adjusted difference significance relative to Control: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$.

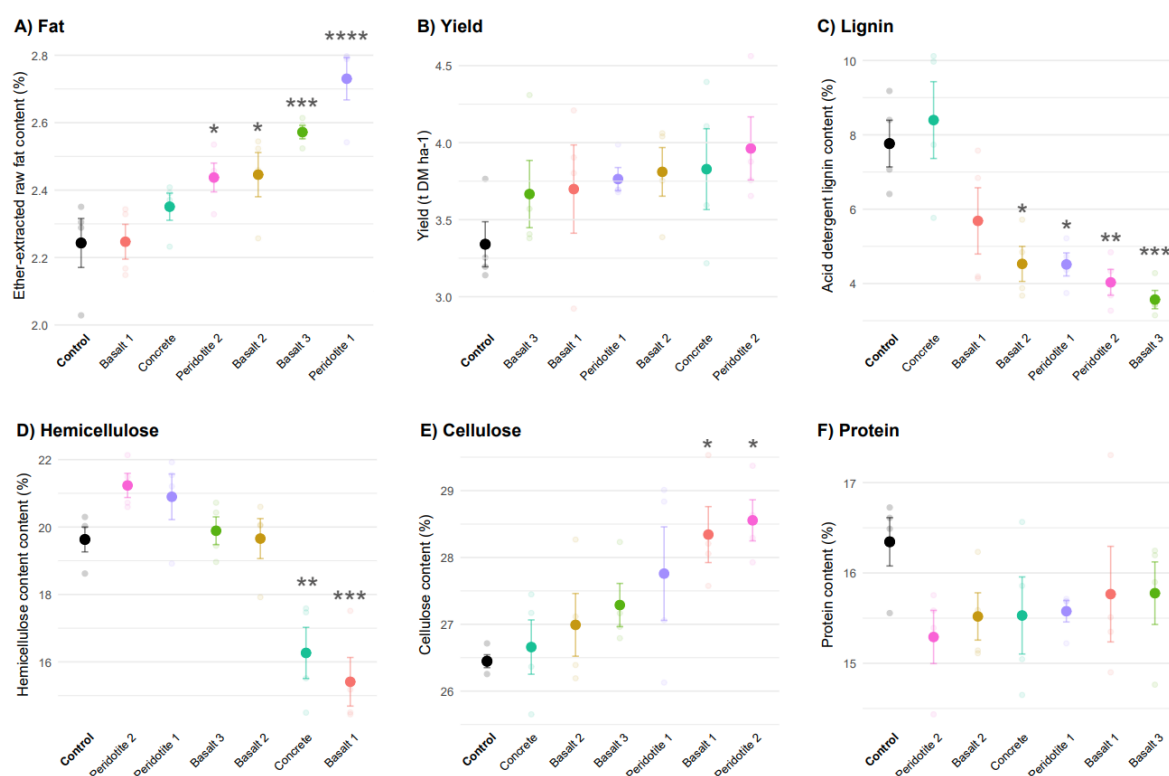


Fig S7. Impact of ERW on forage nutritional profile. Impact of rock powder addition (40 t ha⁻¹) on crop yield, raw fat content, lignin, hemicellulose, cellulose and protein contents, 2 years post application.

Table S4. Potentially toxic elements content. Aqua regia extractable content of trace elements in soils (mg kg⁻¹ ± standard error).

Feedstock	Co	Cr	Cu	Mn	Ni	Pb	Zn
	mg kg ⁻¹						
Control	3 ±0,1	38,5 ±1,1	36,7 ±0,8	810,9 ±9,3	6,8 ±0,2	61,9 ±3,2	96,5 ±2,5
Concrete	2,8 ±0,2	36,8 ±2,5	36 ±2,5	805,1 ±55	6,7 ±0,5	58,7 ±3,2	110,5 ±11,7
Basalt1	3,5 ±0,1	38,1 ±0,3	37,3 ±0,5	814,1 ±5,9	7,7 ±0,4	61,6 ±0,4	102,8 ±1,3
Basalt2	3,6 ±0,1	37,1 ±1,1	38,2 ±1	839,3 ±23,8	9,7 ±0,3	68,2 ±8,5	101,9 ±3,1
Basalt3	3,6 ±0,1	37,1 ±0,7	36,8 ±0,4	830 ±23,3	6,9 ±0,1	61,1 ±0,8	99,3 ±1,7
Peridotite1	4,6 ±0,4	43 ±1,6	35,6 ±1,5	831,6 ±12,8	60,1 ±2,3	60,8 ±1,9	80 ±5
Peridotite2	5,5 ±0,1	38,1 ±0,5	35 ±0,5	846,2 ±20,6	72,5 ±1,7	61,4 ±1	91,2 ±0,2

Table S5. Potentially toxic trace elements limits in soils. Upper allowed values for total content of trace elements (TE) in soils in five national regulation systems applied to the textural class (sandy loam) and pH value (pH H₂O 7.2) of the soil used in this study.

	Brazil	Canada	China	Germany	Russia
Value type	Prevention Values	Agricultural Soil Quality Guidelines	Risk screening values (for agricultural land excluding paddy fields and orchards)	Precautionary values	Tentative Permissible Concentrations
Regulation	CONAMA Resolução n° 420/2009	Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health	GB 15618-2018 Soil Environmental Quality - Risk Control Standard for Soil Contamination of Agricultural Land	Federal Soil Protection and Contaminated Sites Ordinance (Bundesbodenschutzverordnung)	SanPiN 1.2.3685–21 Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans
Cr (mg kg⁻¹)	75	64	200	60	-
Cu (mg kg⁻¹)	60	63	100	40	33
Ni (mg kg⁻¹)	30	45	100	50	20
Zn (mg kg⁻¹)	300	250	250	150	55