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Let the dust settle: Impact of enhanced rock weathering on soil biological, physical, and geochemical fertility

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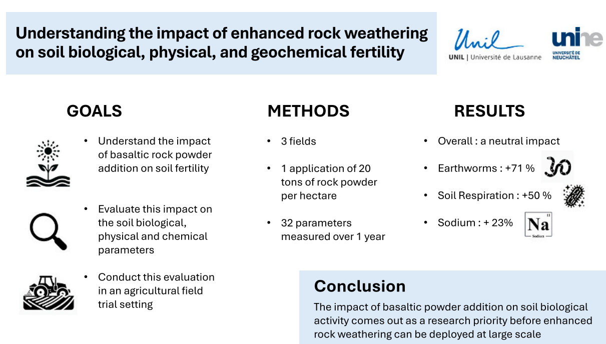
HIGHLIGHTS

- An integrative field trial on the impact of enhanced weathering on soil fertility
- Overall, a neutral to beneficial impact of basaltic rock powder application
- A stimulating impact on biological activity (+71 % earthworms, +50 % soil respiration)
- Higher soil respiration raising the question of potential C loss
- Higher Na concentration (+23 %) raising the question of soil sodification risk

GRAPHICAL ABSTRACT



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ABSTRACT

Terrestrial enhanced rock weathering (ERW) is a promising carbon dioxide removal technology that consists in applying ground silicate rock such as basalt on agricultural soils. On top of carbon sequestration, ERW has the potential to raise the soil pH and release nutrients, thereby improving soil fertility. Despite these possible co-benefits, concerns such as heavy metal pollution or soil structure damage have also been raised. To our knowledge, these contrasted potential effects of ERW on soil fertility have not yet been simultaneously investigated. This field trial aimed at assessing the impact of ERW on biological, physical, and chemical soil properties in a temperate agricultural context. To do so, three vineyard fields in Switzerland were selected for their distinct geochemical properties and were amended with basaltic rock powder at a dose of 20 tons per hectare (2 $kg.m^{-2}$). On each field, basaltic rock powder was either applied one year before the sampling campaign, one month before the sampling campaign, or not applied (control) for a total of 27 plots with 9 repetitions of each level. Overall, basaltic rock powder addition had a predominantly positive to neutral effect on soil fertility. Most soil properties showed no significant change either 1 month or 1 year post application. Nevertheless, our study highlighted a significant increase in earthworm abundance (+71 % on average), soil respiration (+50 %) and extractable sodium concentration (+23 %) as early as 1 month post application. The higher soil respiration raises the question of CO_2 losses from organic matter mineralization that could limit ERW's efficiency. The increase in sodium raises concerns about a sodification risk potentially damaging soil fertility. These elements now require

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further investigation before enhanced rock weathering can be considered a viable and secure carbon dioxide removal technology.

1. Introduction

Soil is one of the most fundamental and essential natural resources on Earth. With 95 % of food coming directly or indirectly from it, soils are the foundation of our agricultural systems and the primary guarantor of food security worldwide (FAO, 2022). Soil fertility is a critical concept commonly defined by the ability of soils to support plant growth and productivity (Patzel et al., 2000).

Soil fertility depends on many soil properties usually grouped into three categories or *pillars*, namely the biological, physical, and chemical pillars (Stenberg, 1998; Stockdale et al., 2002). The partitioning of soil fertility in tangible categories allows this otherwise broad concept to be effectively evaluated. The **biological** pillar covers soil organic matter (SOM) dynamics and the activity of macro-, meso-and micro-organisms, which all play a crucial role in the availability of soil nutrients and water and in the buildup and maintenance of soil structural quality (Huhta, 2007; Hartmann and Six, 2023). The **physical** pillar focuses on soil texture, structure, and bulk density influencing water and air exchanges, soil fauna development, root growth, nutrient access, and plant anchorage (Weil and Brady, 2017). The **chemical** pillar refers mainly to the abundance of plant nutrients and pollutants as well as to the soil properties like pH impacting their availability (Kabata-Pendias, 2010).

Worldwide, soil fertility is already considered as degraded due to unsustainable land use practices, deforestation, urbanization, and climate change (Foth and Ellis, 2018). In such a context, any technology that could impact soil fertility needs to be thoroughly evaluated before large scale deployment. Terrestrial enhanced rock weathering (ERW) is one of these technologies. This carbon dioxide removal technology aims at accelerating one of the most powerful regulating feedbacks of Earth's climate known as the *silicate-carbonate pump* (Urey, 1952; Walker et al., 1981; Kasting, 2019) by applying highly reactive silicate rock powders to soils. As silicate minerals dissolve in the soil solution, ERW sequesters CO_2 directly as alkalinity and carbonate minerals with a potential annual sequestration estimated between 0.2 and 4 Gt $CO_2.yr^{-1}$ (Lenton, 2010; Taylor et al., 2016; Beerling et al., 2018; Smith et al., 2020; Goll et al., 2021).

On top of directly sequestering CO_2, ERW is also promoted for its additional climate, food safety and soil cobenefits, namely for its potential to (1) decrease emissions of other greenhouse gases such as nitrous oxide (Chiaravalloti et al., 2023); (2) counter soil acidification and therefore increase some nutrients' availability while limiting the bioavailability of toxic elements (Anda et al., 2015); (3) release key plant nutrients such as phosphorus, potassium, and calcium (Anda et al., 2015; Lewis et al., 2021; Bi et al., 2024); and (4) boost primary productivity leading to an increase in plant biomass and possibly, carbon sequestration in the form of SOM accrual (Amann and Hartmann, 2019; de Oliveira Garcia et al., 2020).

ERW is, however, not devoid of potential adverse effects on the different pillars of soil fertility. The repeated addition of rock powder could for instance modify soil porosity through clogging and damage soil hydraulic properties (Andrews and Taylor, 2019; de Oliveira Garcia et al., 2020). As a result, air-soil gas exchange processes and water dynamics could be impacted, at least in the short term, as occasionally demonstrated when adding ground limestone to agricultural soils (Nunes et al., 2019; Bölscher et al., 2021). Regarding geochemistry, the silicate minerals that are currently considered for ERW contain toxic trace elements that could be released during weathering (Ten Berge et al., 2012). This could in turn impact the biological pillar of soil fertility by damaging crop health and soil biological activity with potential negative effects on nutrient cycling and bioturbation (Abdu et al., 2017). Mafic rocks such as basalts or basanites are currently considered as ideal candidates for ERW due to their high reactivity and relatively low heavy metal contents (Beerling et al., 2018; Amann et al., 2020). However, the recommended repeated applications still raise concerns about copper and nickel accumulation in soils (Dupla et al., 2023).

When evaluating the impact of ERW, past laboratory and field studies remained primarily focused on a single pillar of soil fertility. The emphasis was generally placed on soil chemistry (Gillman, 1980; Preuschen and Hampl, 1987; Ramezanian et al., 2013; Anda et al., 2015; de Vries et al., 2019; Vienne et al., 2022; Amoakwah et al., 2023; te Pas et al., 2023), with fewer efforts devoted to biology (Mersi et al., 1992; Carson et al., 2007; Li and Dong, 2013; Zhou et al., 2018) and even less to soil physics (Kahnt et al., 1986). This lack of multidimensional evaluation impaired our understanding of rock powder's impact on soil fertility as a whole, and possibly overlooked concomitant effects between the different pillars of soil fertility.

Our study aimed at determining the impacts of ERW on soil fertility from a combined biological, physical, and chemical perspective. To achieve this, the following goals were identified: 1) assess the potential changes in soil chemistry both in terms of soil pH, nutrient and heavy metal contents; 2) evaluate to which extent soil physical parameters such as soil texture and structure were impacted; and 3) investigate potential shifts in soil biological dynamics. To do so, three vineyard fields in Switzerland were selected for their distinct geochemical properties and were amended with basaltic rock powder that was either applied one year before the sampling campaign, one month before the sampling campaign, or not applied (control). Our analytical approach built on an expanded version of the *Biofunctool* framework specifically designed to evaluate the multifunctional impacts of land management practices (Thoumazeau et al., 2019). In total, 33 biological, physical and chemical fertility parameters were monitored.

We expected that the addition of basaltic rock powder would have an overall positive impact on soil fertility. Given the increases in pH and nutrient concentration that are commonly reported (see for instance (Gillman, 1980; Preuschen and Hampl, 1987; Ramezanian et al., 2013; Anda et al., 2015; de Vries et al., 2019; Vienne et al., 2022; Amoakwah et al., 2023; te Pas et al., 2023; Bi et al., 2024), we hypothesized that plots amended with rock powder would show a higher soil pH, base saturation, and phosphorus availability than the control plots. We did not expect strong adverse physical effects, because the amount of rock powder derived from a single application remains small compared to the bulk soil volume. On the other hand, we expected a possible inhibitory effect on surface soil organisms due to the textural properties of the fresh rock powder combined with an potential increase in heavy metal content or availability (Dupla et al., 2023).

With an overall neutral to beneficial impact, the addition of basaltic rock powder evaluated in this study corroborated most of these expectations. Our study revealed however that three consequences of ERW may have been overlooked, namely 1) a higher soil CO_2 respiration with an impact on net carbon dioxide removal that now remains to be quantified; 2) an increase in sodium concentration, which now needs to be investigated across various climates to assess potential sodication risks; and perhaps most surprisingly 3) a large increase in earthworms abundance in treated plots, with likely consequences for bioturbation and basalt powder incorporation into the soil's matrix.

2. Methods

We investigated the impact of a single rock powder application at an equivalent rate of 20 $t.ha^{-1}$. Although substantial in practical terms, this rate remains at the lower end of the usually recommended rates varying between 10 and 100 $t.ha^{-1}$ (Renforth, 2012; Anda et al., 2015; Taylor et al., 2016; Beerling et al., 2018; Amann et al., 2020). Given the primary influence of pH on silicate weathering rates (Appelo and Postma, 2004), we selected three agricultural fields with different soil acidity: one slightly alkaline calcium carbonate-bearing soil (hereafter referred to as the *Carbonate* field) and two acidic soils containing mostly silicate minerals, one of them having received agricultural lime. For ease of reference, the limed and non-limed silicate fields will be hereafter referred to as the *Limed* and *Silicate* fields, respectively.

2.1. Site description

This study was conducted in western Switzerland (Fig. 1). The fields are located in Gorgier (Canton of Neuchâtel) and belong to the organic vineyard *Domaine des Coccinelles*. The climate is temperate oceanic (Cfb in Köppen classification) with a mean annual temperature of 10.8 °C and annual precipitation of 959 mm (reference period 1992–2022).

All fields lie on Quaternary moraines derived from sedimentary and crystalline rocks and formed during the last Würm glaciation (115′000–11′700 BP). Soil from the *Carbonate* field still contains primary carbonates derived from Urgonian limestone from the Barremian (129.4–125 Ma BP) and Aptian (125–113 Ma BP), while other soils are very low in carbonates. Calcium remains dominant on cation exchange sites in all soils while soil organic carbon (SOC) is almost similar (Table 1).

According to the World Reference Base for Soils Resources (WRB 4th edition 2022), these three vineyard soils belong to the Cambisol reference soil group. The *Carbonate* field is a Calcaric Hypereutric Cambisol (Loamic, Ochric), while the two other soils are Eutric Cambisol (Loamic, Ochric). All soils have a loamy texture (see Table S1 and Fig. S1 in Supplementary Material for additional details).

All fields are managed organically, meaning that no synthetic pesticides or mineral fertilizers have been applied since 1992. Grassed interrows are alternatively mowed or tilled every other year. Fields are fertilized with feather and bone meals (Labinor N10, Vitistim and Azoplum, Landor) which are equivalent to 28 kg $N.ha^{-1}.yr^{-1}$. Between 1996 and 2006, the *Limed* field received dolomitic limestone at an average annual dose of 100 $kg.ha^{-1}.year^{-1}$. Liming was discontinued in 2007. All fields received a compost application (5 $m^3.ha^{-1}$) in 2008.

2.2. Experimental and sampling design

Each field was split into 9 experimental plots of 3 × 3 m and distant from each other by at least 7 m. In each field, 3 plots did not receive any rock powder (*Control*), 3 plots received rock powder in 2021 one year before sampling (*Treatment + 1 year*), and three plots in September 2022 one month before sampling (*Treatment + 1 month*) (Fig. 2). Rock powder was hand broadcasted on the surface without any mechanical incorporation into the soil.

The sampling campaign was conducted between the 7th and the 14th of October 2022. Soil temperatures averaged 16 °C while air temperatures fluctuated between 12 °C and 26 °C for a 17.5 °C average over the campaign. The weather was mainly cloudy, with an 8 mm rain event on the 7th of October. To limit the influence of changing weather conditions, soil samples were collected across the three fields within the same

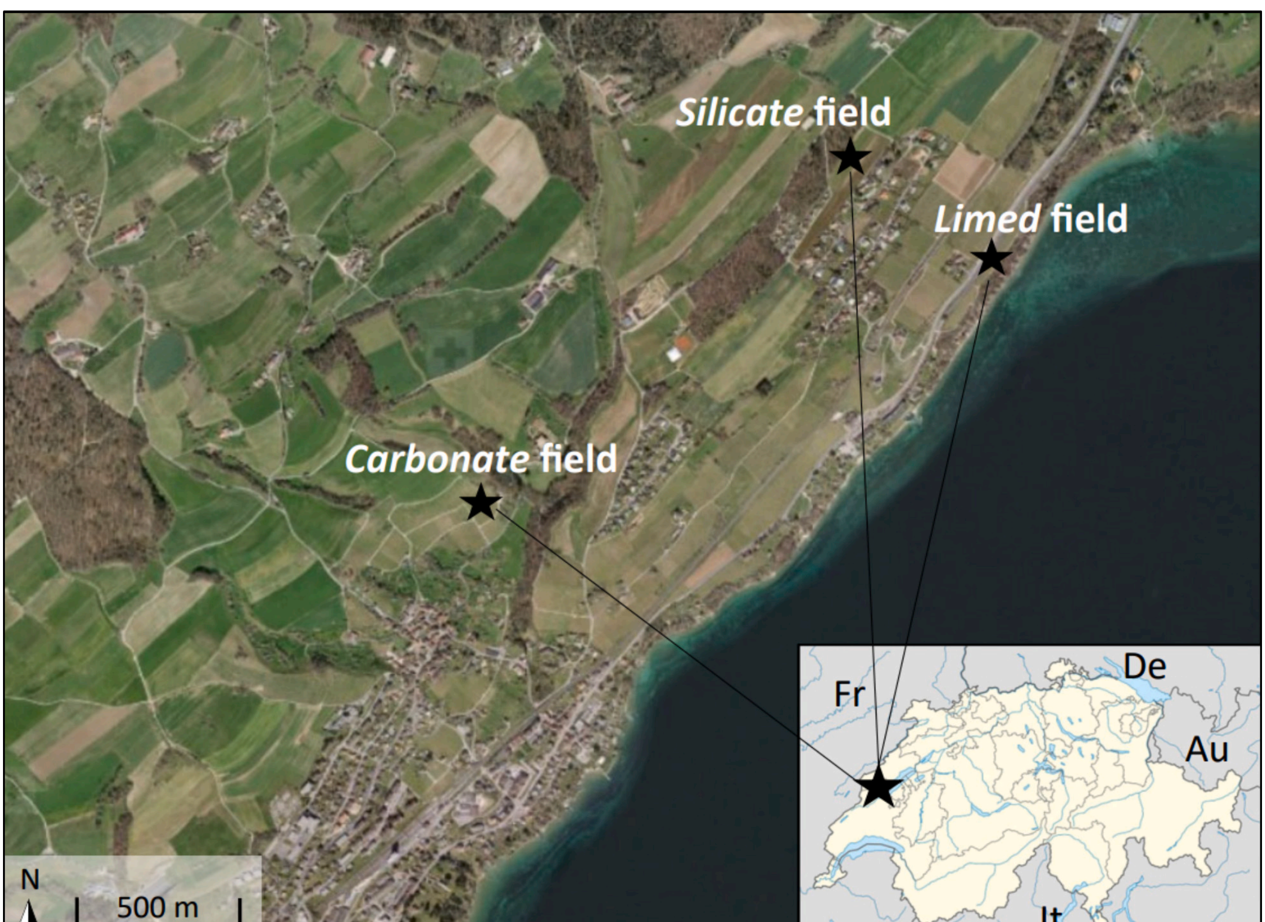

Fig. 1. Location of the three experimental fields on the northern shore of Lake Neuchâtel. (*Carbonate* field (altitude 499 m, slope 12 %, GPS coordinates 46°54′24.3749" N, 6°46′57.2628″ E), *Limed* field (altitude 440 m, slope 5 %, GPS coordinates 46°54′48.4841" N, 6°48′7.6028″ E) and *Silicate* field (altitude 532 m, slope 7 %, GPS coordinates 46°54′58.3474" N, 6°47′47.3471″ E) (Source: Esri (inset map), Swisstopo (aerial)).

Table 1
Select soil parameters of the three experimental fields before rock powder application. In each field, 3 plots (controls) were sampled with 7 soil cores (0–10 cm) composited per plot. For each parameter, the average value and the standard deviation are indicated (the mean values were only included for the cation saturations given that the standard errors were below 1 decimal unit).

Field	pH H_2O	$CaCO_3$ (%)	SOC (%)	NO_3 ($mg.kg^{-1}$)	PO_4 ($mg.kg^{-1}$)	Cation exchange capacity (CEC)					
						Total CEC ($cmol_c.kg^{-1}$)	Ca (%)	Mg (%)	K (%)	Na (%)	Al (%)
Carbonate	7.5 ± 0.1	13.8 ± 4.4	3.1 ± 0.5	6.4 ± 0.8	3.0 ± 0.4	29.7 ± 4.1	93.7	2.8	3.2	0.3	0.1
Limed	6.4 ± 0.2	1.8 ± 0.2	3.1 ± 0.6	14.7 ± 5.6	1.4 ± 1.1	31.5 ± 0.4	83.8	8.5	7.3	0.3	0.1
Silicate	6.2 ± 0.3	≤ 1.0	2.9 ± 0.3	9.0 ± 5.9	0.6 ± 0.1	22.4 ± 4.4	84.2	7.6	5.3	0.4	0.1

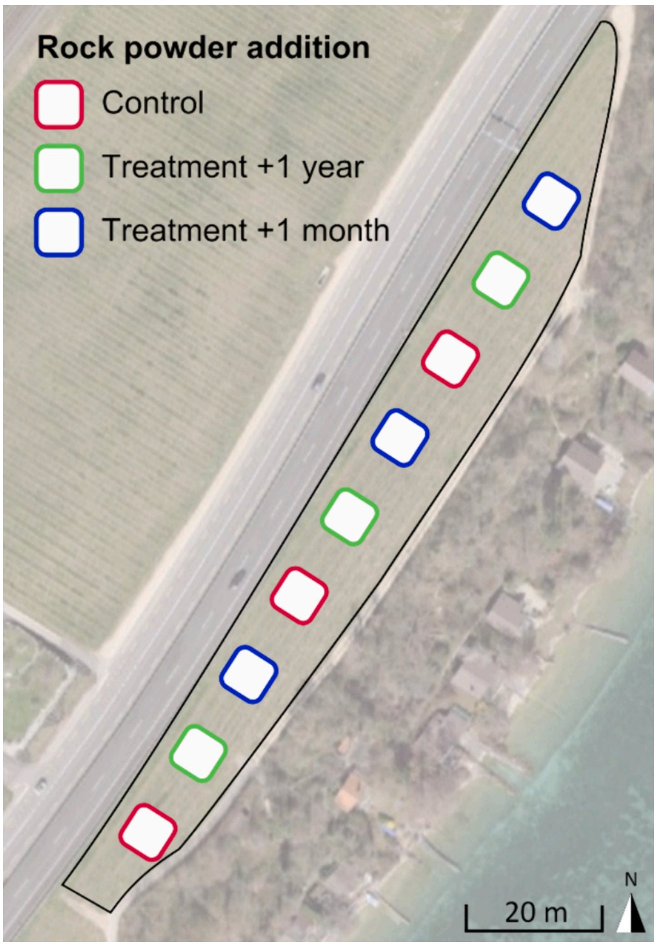

Fig. 2. Experimental design for the limed field. Basaltic rock powder was either applied one year before the sampling campaign (Treatment +1 year, green), one month before the sampling campaign (Treatment +1 month, blue) or not applied (Control, red). The same pattern was applied to the two other fields, for a total of 27 plots with 9 repetitions of each level.

day for each parameter and within 3 h for the most sensitive parameters (e.g. NO_3). Every parameter was measured based on a composite sample made of 7 soil cores on each plot. Unless stated otherwise, soil cores were extracted in the upper 0–10 cm layer after clearing surface vegetation.

2.3. Feedstock description

The basaltic rock used in the experiment (commercial name 'Eifelgold', RPBL company) originates from Hohenfels-Essingen, Germany. For grainsize analysis, soil particles were first dispersed with sodium hexametaphosphate 40 g/L and then left on an orbital shaker for 24 h before analysis on a LS 13320, Beckman Coulter. The analyzer pump ran at 80 % (about 9500 mL min^{-1}), with samples lightly sonicated in both the auto-sampler and analyzer (4/8 setting; approx. 2 J mL^{-1}) prior to measurement. It used the default optical model (Fraunhofer.rf780d) in auto-dilution mode and took measurements at a 12 % obscuration level. The USDA grain size upper limits (2 µm for clay, 50 µm for silt and 2 mm for sand) were chosen to calculate textural fractions (%). The rock powder's specific surface area (SSA) was calculated using N_2 adsorption-desorption (TriStar II Plus, Micromeritics) isotherms in combination with the Brunauer–Emmett–Teller (BET) equation (Brunauer et al., 1938). Abrasion pH was measured potentiometrically using a glass-body combination electrode (Thermo Scientific Orion ROSS Probe) using a rock powder to distilled water ratio of 1:2 following standard procedure by Grant (1969). Amorphous glass content was estimated semi-quantitatively as the surface ratio of glass vs crystalline fractions of five thin sections of Eiffelgold basaltic rock based on petrographic observations using a polarizing microscope (BX61, Olympus) and on electronic observation using a field emission electron probe micro-analyzer (JXA-8350F, JEOL). Mineralogical composition was determined via powder X-ray diffraction (XRD) on ground samples prepared according to Klug and Alexander (1974). 800 g of ground rock powder were pressed in a powder holder before being analyzed using Cu Kα radiation at 45 kV/40 mA with a 13 s counting time per 0.02° for 2 θ in the 1–65° range. Samples were rotated at a range of 1°.min^{-1} with an acquisition step size of 0.03–0.05° 2 θ (ARL X'TRA, Thermo). The bulk mineralogy of samples was then quantified using external standards (Adatte et al., 1996). Elemental analysis was conducted via X-Ray Fluorescence (XRF) spectroscopy (AXIOS^{mAX}, PANalytical) using fused disks made of 1.2 g of calcinated rock powder and 6 g of dilithium tetraborate for major and minor elements. For trace elements, XRF analyses were performed on pressed pellets of 12 g of sample mixed with 3 g of Hoechst wax C micropowder (Merck Milipore). Calibrations were based on synthetic geological reference materials and international silicate rock reference materials according to Foley et al. (2023).

Grainsize analysis showed that 80 % of the rock powder is below 52 µm with a silt loam texture (Table S1 and Fig. S1). Its specific surface area is 6.74 +/− 0.10 $m^2.g^{-1}$ which lies in the upper-end of ERW feedstocks (Anda et al., 2015; Lewis et al., 2021) and its abrasion pH is 10. Mineralogical analyses indicate that 'Eifelgold' is a basaltic rock classified as basanite according to the total alkali silica (TAS) classification of volcanic rocks (Le Maitre et al., 2002), dominated by pyroxenes, and devoid of any secondary calcite. Mineralogical and elemental compositions are summed up in Table 2.

2.4. Soil fertility parameters

The high number of parameters associated with the integrative approach implied that the selected methods had to be robust, sensitive as well as time- and cost-effective. We built on the *Biofunctool* framework specifically designed to evaluate the multifunctional impacts of land management practices in the field (Thoumazeau et al., 2019). *Biofunctool* consists of indicators that evaluate organic carbon dynamics, soil structuration and nutrient cycling. These indicators were completed by the assessment of soil parameters known to be essential drivers of soil fertility (e.g., pH, nutrient content, cation exchange capacity) (Weil and Brady, 2017) and of soil parameters that are specifically relevant in the ERW context (e.g., heavy metal content and availability) (Dupla et al.,

Table 2
Rock powder elemental and mineralogical compositions. Minerals % are expressed on a crystalline fraction basis.

Major and minor elements	Content (%) XRF analysis	Trace element	Content (ppm) XRF analysis	Mineralogical family	Mineral	Content (%) XRD analysis
SiO_2	44.1	Ba	1068	Pyroxene	Augite	48.4
Al_2O_3	14.4	Co	44	Olivine	Forsterite (Fo_{75})	19.8
CaO	11.6	Cr	147	Plagioclase	Labradorite (An_{55})	10.0
Fe_2O_3	11.2	Cu	56	Feldspathoid	Leucite	9.1
MgO	8.8	Mn	1390	Fe-Ti Oxide[1]	Hematite, Ilmenite	10.3
K_2O	3.5	Ni	98	Mica	Phlogopite	2.5
Na_2O	3.1	Sr	776	**Total mineralogical content**		**100.1**
TiO_2	2.7	V	305			
P_2O_5	0.6	Zn	75	Estimated amorphous/glass content		5–10

[1] The oxide category can contain traces of other *minerals such as* magnetite (Fe_3O_4), rutile (TiO_2), and perovskite ($CaTiO_3$).

2023). Regarding specifically the biological indicators, we completed the *Biofunctool* set with measures of SOC content and stability given their essential impact on to soil biotic and abiotic properties like water and nutrient retention, resistance against compaction and erosion (Loveland and Webb, 2003; King et al., 2020). Finally, while *Biofunctool* indicators already include measures of microbial and mesofauna activity, we added at the macrofauna scale an abundance measure of earthworms that are considered the primary ecosystem engineers in temperature climates (Syers and Springett, 1984; Tomati and Galli, 1995; Kooch and Jalilvand, 2008; Le Bayon et al., 2017). Each indicator and its associated method are detailed below (see Table 3 for a methodological summary).

a. First fertility pillar: organic matter dynamics and biological activity

The biological impact of ERW was assessed by looking at whether rock powder addition had led to changes in the abundance and stability of SOM and in the biological activity of soil organisms at the microbial, meso- and macrofauna levels. Soil organic C content and thermostability were measured using Rock-Eval pyrolysis according to Sebag et al. (2016). The relative importance of thermally labile and highly thermostable organic matter fractions was calculated using Rock-Eval indices, respectively named I and R, based on the approach proposed by Sebag et al. (2016). Total nitrogen content was quantified by automated dry combustion to calculate the C:N ratio used here as a proxy of SOM degradability (Bengtsson et al., 2003). Soil organic C labile fraction was further quantified by measuring the permanganate oxidizable carbon (POXC) content (Culman et al., 2012). Microbial soil activity was measured via basal heterotrophic respiration (Stone et al., 2016), hereafter referred to as soil respiration. The mesofauna activity was assessed using the bait lamina method (Törne, 1990; Kratz, 1998; Griffiths et al., 2016). We completed the assessment at the macrofauna level by extracting earthworms using the combined mustard flour and hand sorting procedure (Lawrence and Bowers, 2002).

More specifically, for Rock-Eval pyrolysis, soil samples were oven-dried at 105 °C for 48 h, sieved to 2 mm before being ground to 20 μm using a planetary miller. Samples were first subject to pyrolysis (initial temperature: 200 °C, final temperature: 650 °C, heating rate: +30 °C.min^{-1}) and were then oxidized from 300 °C to 850 °C at +20 °C.min^{-1}. All Rock-Eval analyses were performed on a RE6 pyrolizer ("Turbo" model, Vinci Technologies®). SOC content was obtained as the sum of pyrolyzed and oxidized carbon using the SOTHIS correction to discard inorganic carbon (Hazera et al., 2023). For CHN elemental analysis, 10 mg of ground soil samples placed in tin capsules were subjected to complete combustion (1800 °C for 3 s) and quantification of elemental N by thermal conductivity (Flash EA 1112 nitrogen and carbon analyzer, Thermo Scientific). Permanganate oxidizable C was extracted using 0.02 M $KMnO_4$ based on the method adapted from Weil et al. (2003) (details available at lter.kbs.msu.edu/protocols/133). Soil basal heterotrophic respiration was assessed after 24 h and 48 h via using the *SituResp* method (Thoumazeau et al., 2017). Briefly, soil samples were incubated with a pH-sensitive gel at room temperature with differences in absorbance being measured at 570 nm at each time step. Samples were then incubated for an extended period (5 months) to confirm short-term trends. For the bait lamina method, 8 bait laminas filled with organic substrate (70 wt% cellulose powder and 30 wt% bran flakes, Terra Protecta) were placed 30 cm apart and at 8 cm depth on each plot. After 9 days, the laminas were collected, and an organic matter degradation score was calculated based on the number of empty

Table 3
Summary of the fertility parameters measured in this study together with their respective method and references.

Soil biological parameters			Soil physical parameters			Soil chemical parameters		
Parameter	Method	Reference	Parameter	Method	Reference	Parameter	Method	Reference
Earthworm abundance	Mustard extraction + hand-sorting	Lawrence and Bowers, 2002; Zaborski, 2003	Soil texture	Laser diffraction	Agrawal et al., 1991	pH H_2O	1:2.5 pH H_2O	Thomas, 1996
OM degradation	Bait lamina*	Törne, 1990; Kratz, 1998	Dry bulk density	Core	International Organization for Standardization (ISO), 2017	Carbonate content	Rock-Eval	Jiang et al., 2017
Soil respiration	SituResp*	Thoumazeau et al., 2017	Soil structural quality	VESS*	Ball et al., 2007; Guimarães et al., 2011	Cation exchange capacity	1 M NH_4Cl extraction	Shuman and Duncan, 1990
Soil organic carbon content	Rock-Eval	Disnar et al., 2003	Aggregate water stability	Slake test*	Herrick et al., 2001	Extractable elements	Exchangeable (1 M KCl and 1 M NH_4Cl extractions)	Keeney and Nelson, 1983; Shuman and Duncan, 1990
Labile carbon pool	POXC*	Weil et al., 2003	Water infiltration rate	Beerkan*	Braud et al., 2005; Lassabatère et al., 2006		Mehlich 3	(Mehlich, 1984)
C/N ratio	SOC and total N content	Bengtsson et al., 2003					0.01 M $CaCl_2$ extraction	(Quevauviller, 1998)

*Methods contained in the *Biofunctool* soil quality assessment framework (Thoumazeau et al., 2019).

holes on each lamina. Earthworm biomass was measured using one mustard flour extraction by plot followed by hand sorting a 30x30x30 cm soil volume to recover residual individuals (Lawrence and Bowers, 2002).

b. Second fertility pillar: soil physical parameters

To measure ERW's potential impact on the physical pillar of soil fertility, we combined the measurement of soil texture and bulk density with integrative physical indicators such as structural quality, water infiltration and aggregate stability. Soil texture was measured using laser diffraction particle size analysis (Agrawal et al., 1991). Soil bulk density measurements relied on the core cylinder method (International Organization for Standardization (ISO), 2017). Structural quality was assessed using the Visual Evaluation of Soil Structure (VESS) (Ball et al., 2007; Guimarães et al., 2011) which is a standardized version of the spade test that proved able to identify differences in structure, resulting from differences in soil management (Guimarães et al., 2013). Water infiltration was measured as a proxy of soil poral connectivity (Di Prima et al., 2017; Angulo-Jaramillo et al., 2019) using the single ring infiltrometer Beerkan method (Braud et al., 2005). Aggregate stability, which is widely recognized as a key indicator of the soil's overall ability to resist to stresses like erosion and tillage (Amézketa, 1999), was assessed using a standardized version of the slake test (Herrick et al., 2001).

More specifically, particle size analysis by laser diffraction required first to digest SOM using 10 % hydrogen peroxide while buffering the pH at 7 using NaOH at 0.1 M to avoid mineral weathering. Soil particles were submitted to the same treatment described above for the rock powder grainsize analysis. Bulk density ($g.cm^{-3}$) was measured by extracting soil cylinders at 5 cm soil depth using the core cylinder method (International Organization for Standardization (ISO), 2017). Samples were dried at 105 °C for 48 h and sieved at 2 mm. Bulk density was calculated based on the mass of dried sample after exclusion of the coarse fraction (> 2 mm) both from mass and volume measurements assuming a 2.65 $g.cm^{-3}$ particle density. The VESS approach consisted in extracting an undisturbed slice of soil from the 0–15 cm top layer using a spade and manually breaking it up along the fracture planes. Soil aggregates were then evaluated according to their size, shape, porosity, root density and resistance to break up. Based on a standardized marking scale (available at https://www.sruc.ac.uk/media/xbrfn4x3/vess-colour-chart.pdf), structural quality score ranges from 1 (optimal) to 5 (poor) (Ball et al., 2007; Guimarães et al., 2011). As for the Beerkan method, a 20 cm wide ring was inserted in the soil at 5 cm depth. A 310 mL water volume (corresponding to a 1 cm water layer) was then gently poured in the ring followed by another volume as soon as the first one had fully infiltrated. The infiltration time ($s.L^{-1}$) of each water volume was individually measured until reaching a steady state. Saturated hydraulic conductivity ($mL.min^{-1}$) was then deduced from the results following Braud et al. (2005). Soil aggregate stability was measured on 9 aggregates (6–8 mm) sampled at the soil surface (0–2 cm) and 9 other aggregates (same diameter) at 8–10 cm depth (Herrick et al., 2001). Aggregates were immersed in water and allowed to slake for 5 min before a series of 5 sieving-immersion moves. A stability score ranging from 0 (instantaneous dispersion after immersion) to 6 (at least 75 % of the aggregate is intact after the final sieving-immersion step) was then attributed to each aggregate. This score was then averaged for the 9 aggregates at each depth.

c. Third fertility pillar: soil chemical parameters

To assess ERW's impact on soil chemistry, we investigated (1) differences in soil pH and calcium carbonate mineral content as a measure of potential alkalinity changes, and (2) cation exchange capacity (CEC), as well as concentrations of extractable macronutrients and of potential toxic trace elements specifically contained in basaltic rocks (Dupla et al., 2023) as a measure of soil chemical fertility. We assessed nutrient bioavailability using a range of classical extractions. Exchangeable element concentrations were measured using a 1 M KCl extraction for nitrates ($NO_{3\ exch}$) and phosphates ($PO_{4\ exch}$) (Keeney and Nelson, 1983) and using the 1 M NH_4Cl extraction for base cations (Ca_{exch}, Mg_{exch}, K_{exch}, Na_{exch}), total salt-extractable P_{exch} and Al_{exch} (Keeney and Nelson, 1983; Maynard et al., 2008). It should be noted that, like most standard CEC extractants, NH_4 can cause the partial dissolution of finely divided secondary carbonates (Dohrmann, 2006). This should however not be an issue here because there was not a quantitative fraction of pedogenic carbonates in our soils, and the analysis is used comparatively. NO_3 was the only N form that was analyzed as it is the dominant N form in well-aerated soils with low acidity levels (Hachiya and Sakakibara, 2017). A universal Mehlich 3 (M3) extraction was used for all the elements known to be successfully analyzed via M3, namely P_{M3}, K_{M3}, Ca_{M3}, Mg_{M3}, Al_{M3}, Na_{M3}, Cu_{M3}, and Zn_{M3} (Mehlich, 1984; Ziadi and Tran, 2008). For the other trace elements namely Cr_{CaCl2}, Ni_{CaCl2} and V_{CaCl2}, we used a 0.01 M $CaCl_2$ extraction, which, despite a lower ionic strength, is reliable for toxic trace elements bioavailability assessment (Quevauviller, 1998; Hendershot et al., 2008).

More specifically, soil active acidity (pH H_2O) was measured potentiometrically on a 1:2.5 soil:solution ratio using a combination electrode (Orion 8172BNWP ROSS Sure-Flow, Thermo Scientific) (Thomas, 1996). The soil carbonate content (%) was calculated based on the total mineral carbon (MinC) from the Rock-Eval analysis (Jiang et al., 2017). Cation exchange capacity (CEC) was calculated as the sum of the base cations (calcium, magnesium, potassium, sodium) and aluminum ($cmol_c.kg^{-1}$) extracted using an unbuffered 1 M NH_4Cl solution (Shuman and Duncan, 1990). $NO_{3\ exch}$ and $PO_{4\ exch}$ concentrations ($mg.kg^{-1}$) were measured with a sequential analyzer (Smartchem 200, AMS Alliance). The other element concentrations ($mg.kg^{-1}$) were measured via inductively coupled plasma optical emission spectroscopy (ICP-OES) (Optima 8300, PerkinElmer).

2.5. Statistical analysis

Primary data treatment and displays were performed in R version 4.2.2 (R Development Core Team, 2022). No outlier was excluded given that all outlying values remained in environmentally realistic ranges. Data exploration included conducting a principal component analysis (PCA) based on the correlation matrix using the PCA() function from the package FactoMineR v1.42 (see Table S2 for correlation matrix). Results were represented using biplots on which we added 95 % confidence ellipses for each field (*Carbonate*, *Limed*, *Silicate*) based on Euclidian distances (Wold et al., 1987). The overall impact of rock powder addition on the fertility pillars was displayed using radar charts (package fmsb v0.7.5) where each mean value is represented with a dot. The inner line represents the lowest possible value, i.e. the value corresponding to the poorest score (e.g., 5 for a VESS score) for variables measured on an ordinal scale or 0 for all the variables measured on an interval or ratio scale (e.g., rate, content, or concentration). The outside line corresponds to the best measured score or to the highest measured value for all continuous variables.

The effect of rock powder addition on each fertility variable was assessed using linear models implemented in SAS/STAT software, version 9.4 (SAS Institute Inc). First, we set up a two-way analysis of variance (ANOVA) to test for the effects of treatment and field. The treatment x field interaction term was initially systematically included. However, the interaction was never below the significance threshold ($\alpha = 0.05$) for any of the tested fertility variable. It was therefore discarded from subsequent models. When required, data transformation was conducted until the normality of residues and the homoscedasticity assumptions were met (Box and Cox, 1964). The significance of the overall model and of each predictor were tested using an F-test (Table S5). For each soil fertility variable that proved to be significantly impacted by rock powder addition, a *t*-test was used to compare means and a strip plot was produced with significant differences marked using compact letter display (Piepho, 2004).

Second, we further explored the predictors of responsive soil fertility variables using general linear mixed models (Bolker et al., 2009). Field was set as a random effect and fixed effects included rock powder treatment and any continuous variables likely to impact the response. The main theoretical drivers of each fertility variable were included. The dataset, as well as additional details on the statistical approach and the modeling results, can be found in Supplementary Material.

3. Results

3.1. Field influence on soil fertility parameters

The three fields displayed significantly distinct biological, physical and chemical traits. Following PCA, the first principal component highlights the opposition between carbonate and silicate soil environments with chemical parameters like pH, carbonate content, and Ca vs Al concentrations having some of the highest eigenvalues (Fig. 3). The second principal component bears biophysical parameters such as soil structural quality and organic matter maturation which distance the *Silicate* and *Limed* fields without, however, completely separating them.

Most of the evaluated soil fertility parameters were significantly different between fields (Table 4, see Table S3 for complete results field by field). Most notably, compared with the *Limed* and *Silicate* fields, the *Carbonate* field had almost twice as much Ca_{M3} and a carbonate content an order of magnitude higher. Its Cu_{M3} concentration was 36 times higher, while Mg_{M3} and Al_{M3} concentrations were around half those of the other fields. The *Silicate* field tended to have opposite characteristics with higher SOM degradation scores (bait lamina), silt and clay contents and Al_{M3} for instance. Most notably, the average earthworm abundance was 1.8 and 15 times higher than those of the *Limed* and *Carbonate* fields, respectively. The *Limed* field displayed intermediate results for most other parameters with the exception of a more thermally labile SOM (I Index), more K_{M3}, and a lower soil structural quality (VESS).

3.2. Basaltic rock powder influence on soil fertility parameters

a. Biological activity and organic matter dynamics

Overall, rock powder addition had a neutral to stimulating effect on biological fertility parameters (Fig. 4 and Table S5). Earthworm abundance and soil respiration were the only parameters significantly impacted by rock powder addition, with all the others resulting in non-significant differences. Earthworm abundance (individuals.m^{-2}) was strongly impacted (+71 % average increase between 1-month-old treatment and control) (Fig. 5A). The potential impact of the main theoretical drivers of earthworm abundance (soil texture, SOC content, pH, soil structural quality, soil bulk density, toxic trace elements) (Hendrix et al., 1992; Nuutinen et al., 1998; Iordache and Borza, 2010; Phillips et al., 2021) was assessed in a general linear mixed model. On top of the rock powder effects, only copper content was found to have a significantly negative effect on earthworm abundance (Section S3 in Supplementary Material).

Soil respiration was the other parameter significantly impacted by rock powder addition. On average, in the plots that had received rock powder for 1 month, soil respiration was 20.4 % higher than in control plots 24 h after the beginning of the incubation, +11 % higher after 48 h and even +51 % higher 5 months (Fig. 5B). The theoretical predictors of soil respiration (SOC, pH, water content, nutrients, toxic trace elements) (Davidson et al., 1998; Savin et al., 2001; Stell et al., 2021) were tested in a general linear mixed model and only rock powder addition came back as significant (Section S3).

b. Soil physical parameters

Rock powder addition did not significantly influence soil physical parameters (Fig. 6 and Table S5). Although we could witness an average

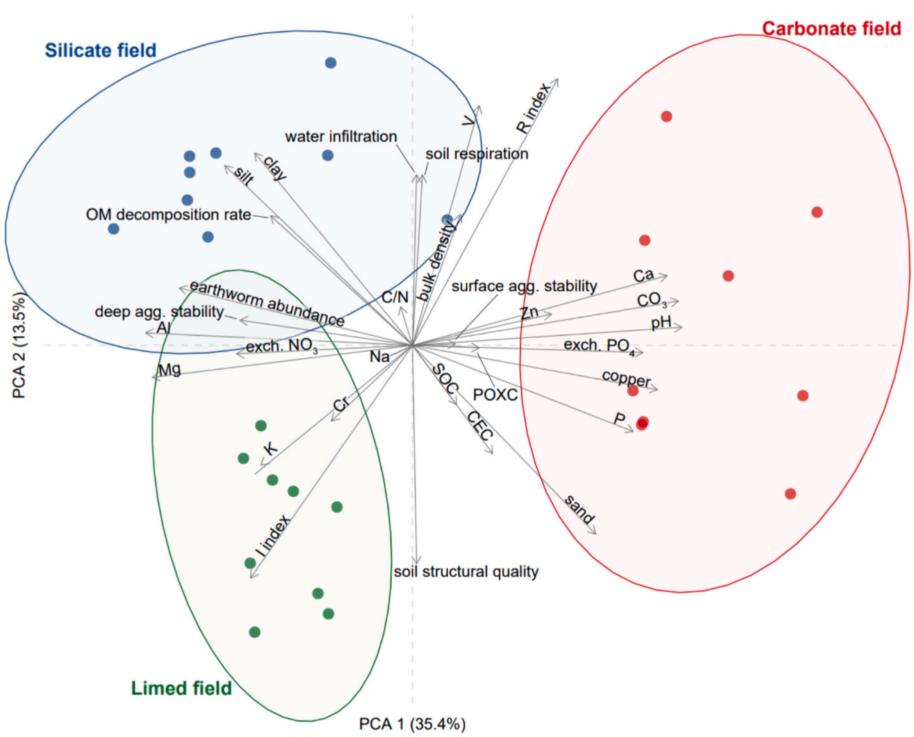

Fig. 3. Biplot showing the results of a principal component analysis (PCA) of soil fertility parameters. The input data is the complete dataset for all treatments. The first two principal components (PCA 1 and PCA 2) are the two dashed axes. The share of explained variance by each PCA is given in brackets. Each arrow represents a loading vector, indicating the magnitude and direction of a fertility parameter's contribution to the component. Each dot represents a plot from the *Carbonate* field (blue), *Silicate* field (red) or *Limed* field (green). Each ellipse encloses the region that contains plots from each field, with a 95 % confidence level.

Table 4

Influence of basaltic rock powder application (rock) and field type (field) on soil fertility variables using general linear modeling (GLM). Variables were ranked per significance level within each soil fertility category. Variables were transformed whenever linear model assumptions were not met. Significance differences are highlighted in bold.

	Soil Variables	Overall p-values (Pr > F)			Adj. R^2
		GLM	Rock	Field	
Biological fertility	Earthworm abundance	**< 0.001**	**0.029**	**< 0.001**	0.76
	Immature OM (I index)	**< 0.001**	0.794	**< 0.001**	0.63
	Mature OM (R index)	**< 0.001**	0.812	**< 0.001**	0.58
	Soil respiration (+3 m)	**< 0.001**	**< 0.001**	0.243	0.57
	OM degradation score	**0.002**	0.251	**< 0.001**	0.52
	Labile OC content	0.230	0.397	0.148	0.22
	SOC content	0.568	0.637	0.370	0.12
	C/N ratio	0.878	0.646	0.867	0.05
Physical fertility	Soil structural quality (VESS score)	**< 0.001**	0.344	**< 0.001**	0.57
	Silt content	**0.001**	0.744	**< 0.001**	0.54
	Sand content	**0.002**	0.904	**< 0.001**	0.51
	Clay content	**0.020**	0.971	**0.004**	0.40
	Deep aggregate water stability	**0.040**	0.503	**0.013**	0.35
	Water infiltration rate	0.3178	0.602	0.161	0.19
	Surface Aggregate stability	0.666	0.555	0.559	0.10
	Soil bulk density	0.738	0.635	0.595	0.08
Geo-chemical fertility	Cu_{M3}	**< 0.001**	0.836	**< 0.001**	0.99
	Carbonate content	**< 0.001**	0.923	**< 0.001**	0.97
	Al_{M3}	**< 0.001**	0.090	**< 0.001**	0.92
	pH H_2O	**< 0.001**	0.454	**< 0.001**	0.83
	Ca_{M3}	**< 0.001**	0.712	**< 0.001**	0.82
	P_{M3}	**< 0.001**	0.126	**< 0.001**	0.81
	Mg_{M3}	**< 0.001**	0.355	**< 0.001**	0.69
	$PO_{4\ exch}$	**< 0.001**	0.680	**< 0.001**	0.75
	Na_{M3}	**< 0.001**	**< 0.001**	0.511	0.79
	Ni_{CaCl2}	**< 0.001**	0.778	**< 0.001**	0.69
	V_{CaCl2}	**0.004**	0.863	**< 0.001**	0.49
	$NO_{3\ exch}$	**0.017**	0.386	**0.006**	0.41
	Zn_{M3}	**0.026**	0.172	**0.017**	0.38
	K_{M3}	0.077	0.767	0.021	0.31
	Cr_{CaCl2}	0.118	0.540	0.047	0.27
	Cation Exchange Capacity	0.280	0.365	0.213	0.20

decrease in water infiltration rates between the control and the 1-month-old application (−5 % across all fields and − 49 % for the *Carbonate* field), this decrease remained within natural variability within each field.

c. Soil chemical parameters

Rock powder addition did not have any significant impact on pH, nutrients and on most trace elements (Fig. 7 and Table S5) but increased significantly extractable sodium concentration (+22.8 % on average between 1-month-old treatment and control) (Fig. 8). Elemental concentrations are detailed in Table S6 and Fig. S3.

4. Discussion

4.1. Field effect

For most soil fertility parameters, it should first be noted that significant differences appeared primarily between fields rather than between rock powder application levels. The *Carbonate*, *Silicate* and *Limed* fields were indeed chosen to represent three typical geochemical environments ranging from moderately acidic to more alkaline. These environments are known to influence soil fertility (Gray et al., 2016) and rock powder application did not erase this influence. Additionally, the fact that the measured soil fertility parameters were significantly different between fields confirms the sensitivity of the selected methods. This reinforces the reliability of the trends found between rock powder applications, which will be discussed in the subsequent sections. Finally, no significant statistical interaction between fields and soil parameters could be identified in any of the linear models. The three fields can therefore be interpreted as a biogeochemical continuum which facilitates the detection of any potential effect associated with rock dust addition.

4.2. Basaltic rock powder effect

Rock powder addition resulted in an overall neutral to beneficial impact on soil fertility. Most soil parameters remained unaffected by rock powder addition which can be seen as an encouraging signal toward a large-scale deployment of ERW.

a. A short-term response spike

Among the 32 investigated fertility parameters, only three were significantly affected by rock powder addition: earthworm abundance, soil respiration and sodium concentration. In all these cases, these parameters were the highest after 1 month of application and decreased significantly after 1 year. This short-term spike followed by a return to normal can probably be explained by the initial weathering of the most reactive minerals and phases and by a progressive attenuation of the signal as seen in the sodium spike detailed below and as confirmed in other experiments led by the Carbon Drawdown Initiative (www.carbon-drawdown.de) using the same feedstock (Hammes et al., 2023). Arguably, the powder was also progressively incorporated, at least in part, into the soil matrix with rain and through bioturbation beyond the sampling depth (0–10 cm), thereby making the detection of an ERW signal increasingly difficult. If applications were to be annually repeated as advocated in most ERW scenarios (Renforth, 2012; Anda et al., 2015; Taylor et al., 2016; Beerling et al., 2018), the short-term effects measured in our study would probably add up although specific trials are now needed to grasp the scale of these changes.

b. A sodium spike

Among all chemical parameters, sodium concentration was the only one emerging as significantly impacted by rock powder addition. To our knowledge, this field trial is the first one reporting such an increase in soils in an ERW context. This result is nevertheless coherent with the findings from Swoboda et al. (2021), who measured a + 533 % sodium increase in a 46-day incubation experiment using the same 'Eifelgold' rock powder mixed with cattle slurry. Based on the feedstock's mineralogical analysis (Table 2), sodium arguably comes from the weathering of basaltic glass and plagioclase mineral labradorite ($Na_{0.45}Ca_{0.55}Al_{1.6}Si_{2.4}O_8$) (Harley and Gilkes, 2000), each representing around 10 % of the basanite rock used in this study. Although labradorite is two to three orders of magnitude less reactive than glass (Brantley and Olsen, 2013), labradorite is known for being present at the nano- and micro-scale in the groundmass of basanite (e.g., Brown and Carmichael, 1969; Keil et al., 1972; Hofmeister and Rossman, 1985). At this scale, basanite's high specific surface area favors its rapid weathering arguably explaining why sodium was detected in the soil solution within the first month. A similar spike could, however, not be detected for calcium, despite its presence in basaltic glass and labradorite, nor for other plant macronutrients such as potassium and magnesium. This situation could be explained by the intensity of nutrient cycling, with fluxes of biological uptake and mineralization typically orders of magnitudes higher

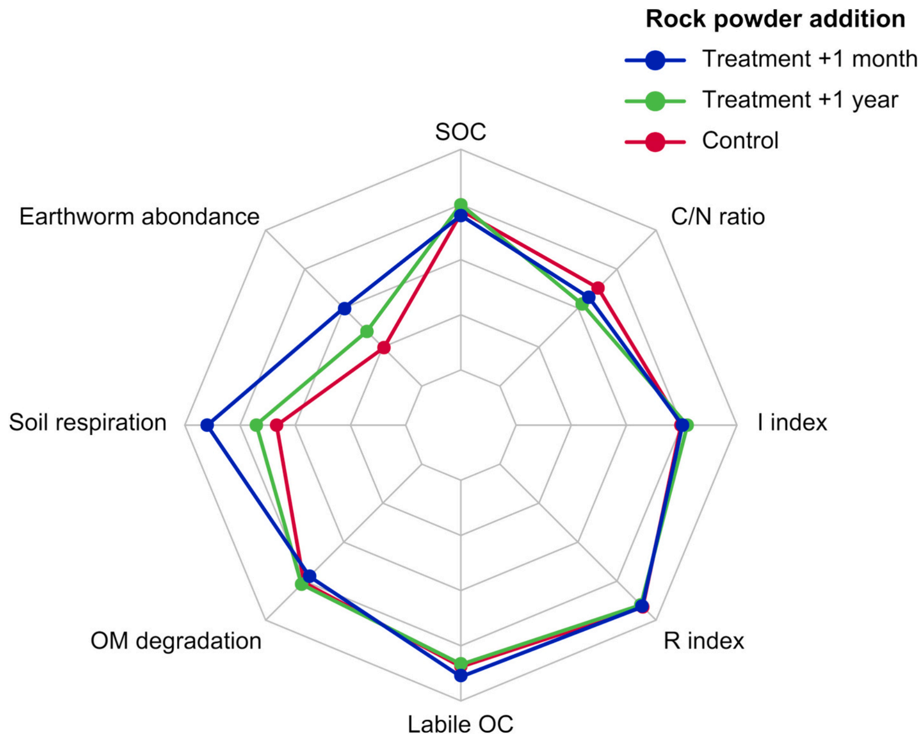

Fig. 4. Evolution of biological fertility parameters following basaltic rock powder addition after 1 month (Treatment +1 month, blue) and 1 year (Treatment +1 year, green) versus no application (Control, red). For each parameter, the dot corresponds to the mean value for all fields, the inner grey line is the lowest possible value (e.g., minimum score or null value/content), and the outside line corresponds to the highest measured value.

than mineral weathering fluxes (Likens et al., 1994; Jobbágy and Jackson, 2001; Peters et al., 2004; Kertesz and Frossard, 2015). Natural variability may also have blurred weak signals as in the case of phosphorus. Given the basalt and plots properties, the increase resulting from the 20 t.ha^{-1} basalt addition happened to be in the same order of magnitude as P variability across plots even when considering total elemental concentrations using XRF (Table S4).

The sodium signal is a positive signal for ERW's kinetics. Sodium is a standard marker of silicate weathering often used, for instance, to distinguished carbonate- from silicate-draining rivers (Gaillardet et al., 1999). After only one month of application, a significantly higher sodium concentration in the three monitored fields therefore constitutes a strong indication of mineral weathering. Given that the CO_2 sequestration potential of ERW directly depends on the rock powder's ability to weather, detecting such a fast geochemical signal indicates that at least part of the carbon dioxide removal happened within the first few weeks.

Sodium accumulation, known as *sodification*, is, however, harmful to both soil structure and soil organisms (Subbarao et al., 2003). To evaluate this sodification risk, we calculated the exchangeable sodium percentage (ESP), which is the share of sodium on the CEC (Gupta and Sharma, 1990). The average ESP across all fields went from 0.4 % for the control to 0.9 % after 1 month of application and 0.5 % after 1 year. Although the impact of rock powder is visible (and statistically significant), this increase in ESP remained far below the 15 % ESP threshold, beyond which sodification is usually considered problematic (Sparks, 1995). Additionally, the fact that the ESP almost halved between 1 month and 1 year of application indicated a minimal sodification risk for temperate climates. Sodium has indeed a very low affinity for exchange sites making it especially prone to leaching (Essington, 2015). Any additional sodium is expected to be leached in climates with positive water balance where rainfall exceeds evapotranspiration. The question becomes, however, much more relevant in arid and semi-arid zones. In such climates, using sodium-rich silicate minerals could potentially aggravate soil sodification which is already a major threat to soil fertility (Singh, 2021). ERW field trials across climates are now needed to evaluate this risk and assess, where necessary, whether sodium-poor feedstocks could be used as alternatives.

c. A stimulating impact on earthworm abundance

Although the impact of earthworms on ERW has begun to be assessed (Lian et al., 2019; Vienne et al., 2023), our study is the first one to report a positive effect of basaltic rock powder addition on earthworms. Given the central role of earthworms as fertility drivers in temperate climates (Syers and Springett, 1984; Tomati and Galli, 1995; Kooch and Jalilvand, 2008; Le Bayon et al., 2017, 2021), this finding constitutes a potentially major co-benefit for ERW.

The increase in earthworm abundance can be due to earthworm reproduction being stimulated and/or to earthworms being attracted in the treated plots. The second option is more likely given that rock powder application also increased earthworm biomass (Fig. S2). If the increase in abundance had been due to newborn worms, it would have resulted in almost no difference in total mass (Gerard, 1967; Fernandez et al., 2010).

On the contrary, the hypothesis that the surrounding earthworms were attracted to the treated plot could be explained by biogeochemical phenomena. These organisms are indeed known to exhibit active orientation and movement toward microorganism-dense areas (Zirbes et al., 2011). In our study, the significantly higher soil respiration associated with rock powder addition indicates a higher microbial activity (further described in the section below). This increased activity may have played a determining role in attracting surrounding earthworms to the treated plots. Nevertheless, both hypotheses remain now to be tested in dedicated experiments. For instance, comparing the earthworm density in the treated plots and the surroundings of these plots could clarify the extent of this potential earthworm migration. Similarly, incubation experiments could contribute to quantifying the impact of basalt on earthworm reproduction rates.

d. An increase in soil respiration

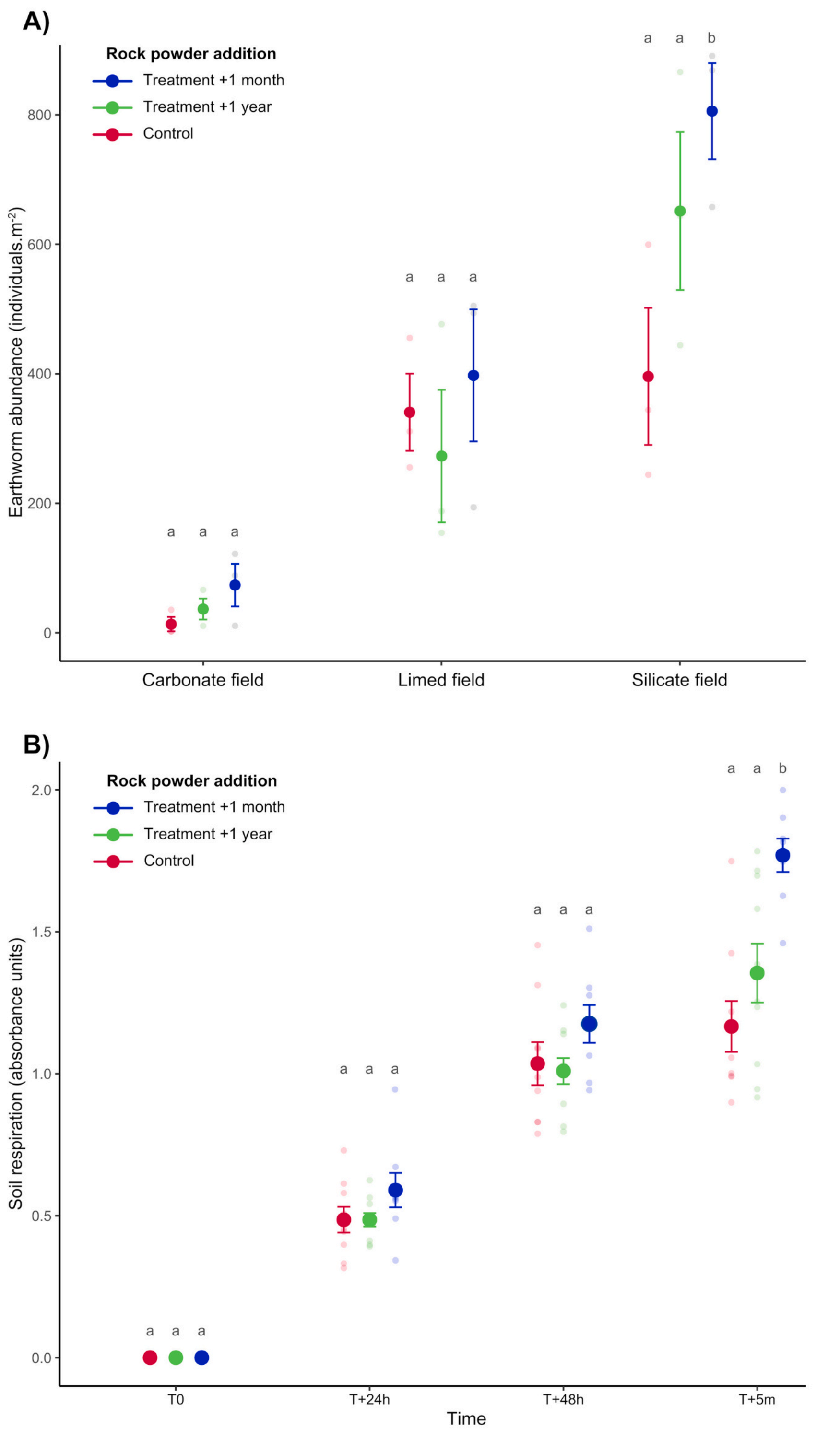

Fig. 5. Impact of basaltic rock powder addition on earthworm abundance (individuals.m^{-2}) (A) and soil respiration (B) after 1 month (blue), 1 year (green) vs control (red). Each deep color dot corresponds to the mean value, faded dots are individual results, and error bars correspond to the standard error of the mean. Within each group, a different letter corresponds to a significant difference at the $\alpha = 0.05$ level. Significance levels are the results of the inferential models described in the Methods section.

Mechanistically, the higher soil respiration measured in our study is not straightforward to explain as the main drivers of soil respiration (temperature, moisture, pH, SOC content and nutrient availability) (Ryan and Law, 2005) remained stable. Since soil respiration is linked to SOM mineralization, a possible explanation could be that SOC stock may have started to decrease without this change being detectable yet (Schlesinger and Andrews, 2000). Indeed, changes in SOC stocks are known to require years, if not decades, to be detected after the introduction of new farming practices (Christensen and Johnston, 1997).

Although the SituResp method used in this experiment is not designed to precisely quantify the additional amount of CO_2 being released (Thoumazeau et al., 2017), results from other experiments may

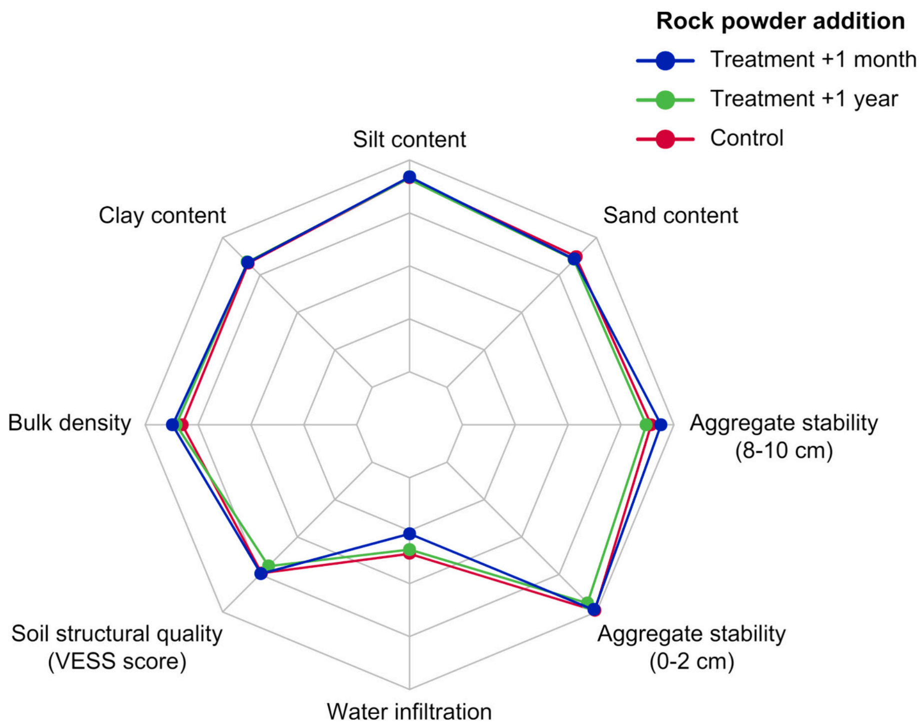

Fig. 6. Impact of basaltic rock powder on soil physical parameters after 1 month (Treatment +1 month, blue) and 1 year (Treatment +1 year, green) versus no application (Control, red). For each parameter, the dot corresponds to the mean value for all fields, the inner grey line is the lowest possible value (e.g., minimum score or null value/content), and the outside line corresponds to the highest measured value.

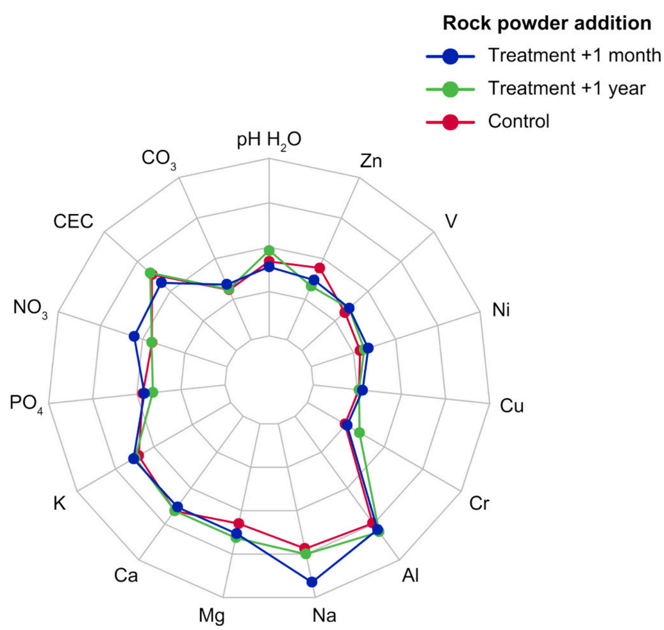

Fig. 7. Impact of basaltic rock powder addition on soil main chemical parameters including pH, carbonate content, nutrient and trace element bioavailability using NH_4Cl for the effective cation exchange capacity (CEC), KCl for NO_3 and PO_4, Mehlich III for Al, Ca, Cu, K, Mg, Na and Zn and $CaCl_2$ for Cr, Ni and V. Rock powder was either applied for 1 month (Treatment +1 month, blue), 1 year (Treatment +1 year, green) or not applied (Control, red). For each parameter, the dot corresponds to the mean value for all fields, the inner grey line is the lowest possible value (e.g., minimum score or null value/concentration), and the outside line corresponds to the highest measured value. For soil pH, the inner grey line corresponds to the lowest measured pH.

provide some insight into the magnitude of the phenomenon. In a 46-day incubation experiment, Swoboda et al. (2021) applied the same 'Eifelgold' powder to cattle slurry at a 5 % *w*/w dose and found an increase in SOM decomposition with higher cumulative CO_2 and total greenhouse gas emissions (+9 % and a + 161 %, respectively). In another trial, Mersi et al. (1992) found that the addition of 4.7 t.ha^{-1} of a basic silicate rock powder mixture (basalt, diabase, bentonite) had increased soil respiration by 33 % and microbial biomass by 35 %. In an incubation experiment evaluating the impact of olivine on sandy podzols (pH 3.6), Dietzen et al. (2018) also observed that the CO_2 sequestration gains were totally compensated by a 60–70 % increase in soil respiration. These results are all the more important as the annual CO_2 fluxes associated with soil respiration are 1 to 3 orders of magnitude higher than the CO_2 capture usually expected from ERW (Reay and Grace, 2007; Strefler et al., 2018; Goll et al., 2021). The additional CO_2 emissions that necessarily result from soil respiration could indeed offset some of the C sequestration targeted by ERW and may, in the worst-case scenario, even lead to an overall carbon emitting operation. To date, most ERW models do not take soil respiration into account (Andrews and Taylor, 2019). The few that considered it either assumed that respiration remained constant (Cipolla et al., 2021) or even that it decreased with ERW (Goll et al., 2021).

Two phenomena could, however, attenuate these supplementary CO_2 emissions. First, the boost in fertility that ERW should deliver in the long run, especially in highly weathered soils, should result in a higher primary productivity, which in turn should increase SOM content (Wiesmeier et al., 2019). Second, the incongruent dissolution reaction behind silicate weathering should logically increase the amount of secondary phases (e.g., allophane and imogolite) and minerals (e.g., clays) (Wilson, 2004). This reactive material is known to favor mineral-associations with SOM, one of the main drivers behind SOM stabilization and carbon sequestration (Lehmann and Kleber, 2015; Cotrufo et al., 2019). In the longer run, ERW could therefore potentially offset the increase in soil respiration via higher organic C stocks. These hypotheses remain now to be tested.

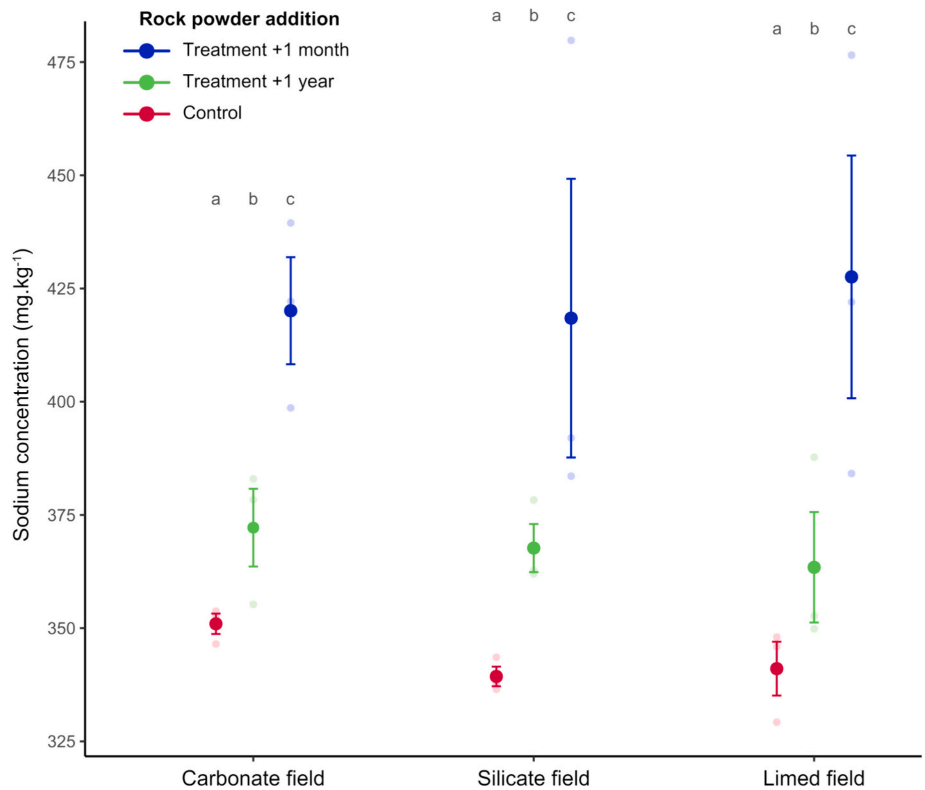

Fig. 8. Impact of basaltic rock powder addition on bioavailable sodium concentration (mg.kg^{-1}) after Mehlich III extraction. Rock powder was either applied for 1 month (Treatment +1 month, blue), 1 year (Treatment +1 year, green) or not applied (Control, green). Each deep color dot corresponds to the mean concentration, faded dots are individual results, and bars represent standard error of the mean. Within each group, a different letter corresponds to a significantly different concentration at the α = 0.05 level. Significance levels are the results of the inferential models described in the Methods section.

4.3. Perspectives

This study was designed as integrative. The high number of investigated parameters (32) obliged us to limit the number of fields (3) and repetitions (27 plots in total) with unavoidable consequences on statistical power. This also forced us to select only one application rate and two time intervals (1 month and 1 year) to assess ERW's overall impact. Any change that may have happened within the first days/weeks (e.g. a nutrient flush) and then dampened (via leaching for instance) or changes that would have required more than a year to happen (e.g., a change in SOC content) were therefore missed in our trial. In the future, monitoring these changes more finely will help, for instance, to better understand the significant increase in earthworm abundance associated with rock powder addition.

For a few methods, proxies of the fundamental parameters had to be chosen for time and cost reasons. Meso- and micro-fauna activities were for instance assessed via soil respiration and SOM degradation, respectively, which remain both first-order approximations of the true parameters. Given the increase in soil respiration and its potential implication on ERW's carbon sequestration budget, microbial dynamics should now be more closely investigated.

Finally, despite soil differences, the climatic and agricultural context was also almost identical for all experimental fields. On top of a similar temperate climate, the three fields were subject to the same rock powder and the same organic farming practices. If these similarities contributed to restrain environmental variability, the potential impact of this environment on our results remains a blind spot. An illustration of this point is copper which is considered as one of the potentially toxic trace elements that could accumulate the most in soils as a consequence of ERW (Dupla et al., 2023). In vineyards, copper has been used as a fungicide since the 19th century and has, therefore, already heavily accumulated in soils (Fagnano et al., 2020). In the control plots, the *Carbonate* and *Limed* fields displayed, for instance, an average copper concentration of 359 and 96 ppm (Table S6) which is 9.2 and 2.4 times respectively higher than in natural soils (Kabata-Pendias, 2010). This already copper-rich environment arguably mitigated any potential copper impact from ERW on soil organisms. Similarly, evaluating the impact of different feedstocks and/or different grain sizes would help to better constrain the extent of their overall impact on soil fertility.

Despite its limitations, this field trial has arguably opened research avenues. More than ever, field-based studies are now needed to evaluate ERW's impact on soil fertility across various climates, farming practices and crops with the impacts on soil organisms, hydraulic conductivity, and sodium accumulation emerging as priority research areas.

5. Conclusion

Overall, basaltic rock powder addition resulted in a neutral to beneficial impact on soil fertility. Most biological, physical, and chemical parameters remained unaffected after 1 month and even 1 year of application, with significant differences appearing primarily between fields rather than between rock powder treatments. This multi-site field trial highlighted, however, an increase in soil respiration and sodium concentration which, despite being encouraging signs of short-term weathering kinetics, should be further investigated before ERW can be deployed as both an efficient and safe carbon dioxide removal technology.

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CRediT authorship contribution statement

Xavier Dupla: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Romane Claustre:** Writing – original draft, Investigation, Formal analysis, Data curation. **Emma Bonvin:** Writing – original draft, Investigation, Formal analysis, Data curation. **Iris Graf:** Writing – original draft, Investigation, Data curation. **Renée-Claire Le Bayon:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Stéphanie Grand:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Research data is available in Supplementary Material.

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Appendix A. Supplementary data

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