~~Increased soil CO_2 emissions after basalt amendment were partly offset by biochar addition in an urban field experiment.~~

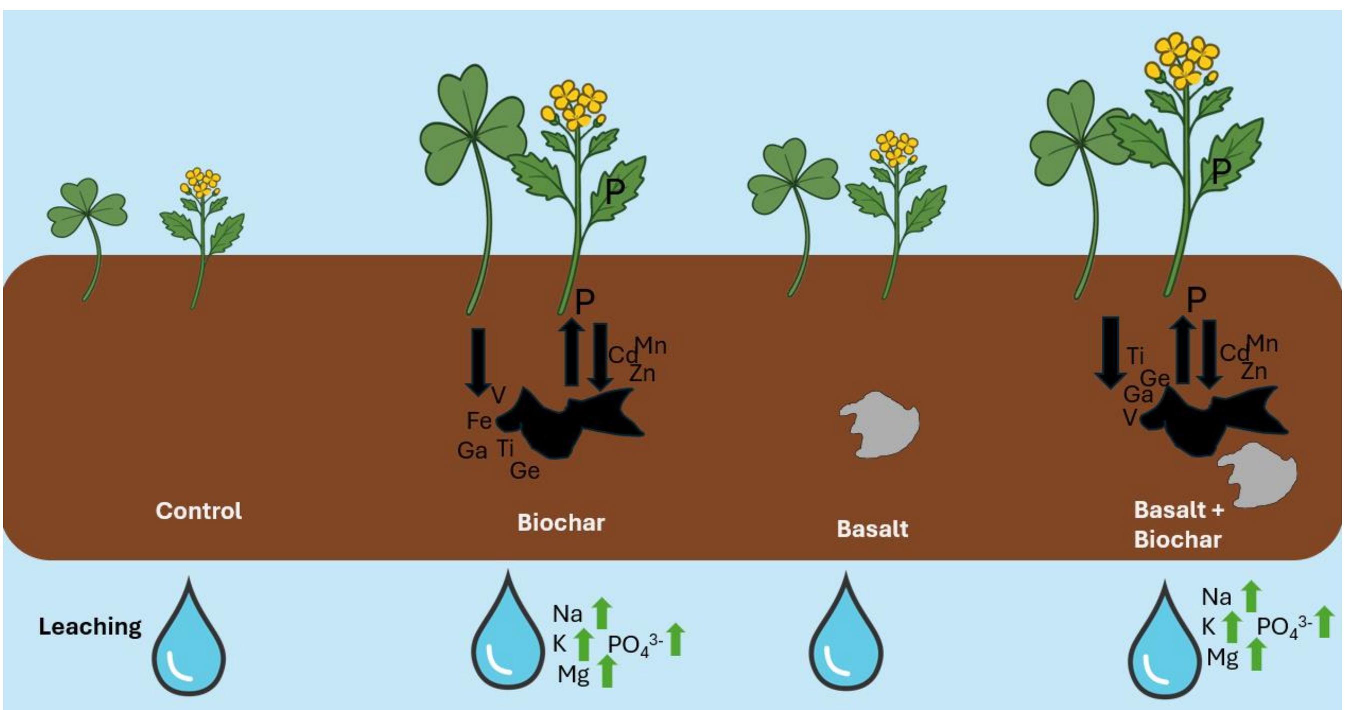
Effects of basalt and biochar addition on base cations and trace metals in plants and soil in an urban field trial

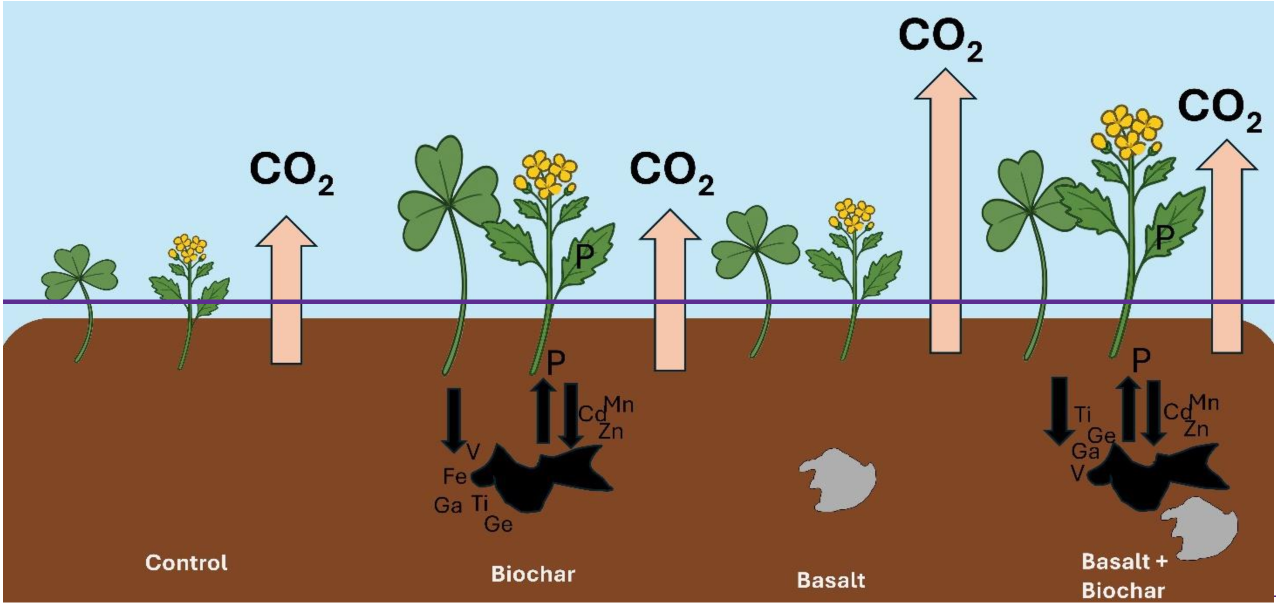
Arthur Vienne[1], Jennifer Newell[2], Jasper Roussard[1], Rory Doherty[2], Siobhan F. Cox[2], Gary Lyons[3], Sara Vicca[1]

[1] Biobased Sustainability Engineering (SUSTAIN), Department of Bioscience Engineering, University of Antwerp, Antwerp, Belgium
2 School of Natural and Built Environment, Queen's University Belfast, Belfast, UK.
[3] Agri-Environment Branch, Agri-Food and Biosciences Institute, Northern Ireland, UK

Correspondence to: Arthur Vienne (arthur.vienne@uantwerpen.be)

Graphical abstract





Abstract. Enhanced weathering (EW) and biochar amendment are proposed carbon dioxide removal (CDR) techniques with potential co-benefits for soil health and plant productivity. However, knowledge gaps remain regarding their impacts on soil carbon dynamics and heavy metal mobility. This study investigates the effects of basalt and biochar amendments on ~~soil CO_2 efflux (SCE),~~ soil base cation dynamics, biomass yield and ~~heavy~~ trace metal uptake in clover (*Trifolium pratense*) and mustard (*Brassica juncea*) field plots.

Basalt addition did not increase soil inorganic carbon ~~SIC~~, Tessier-extractable base cations, or dissolved inorganic carbon (DIC) in leachates, indicating no detectable inorganic C sequestration during the experiment. Either weathering of the relatively coarse basalt was limited, or weathering products were retained in soil pools inaccessible to the extraction scheme. Basalt increased Ni and Cr in the reducible soil fraction but did not elevate plant metal concentrations and even lowered Ni and Zn in leachates. Biochar ~~enhanced~~ increased plant biomass and reduced plant uptake of several trace metals in both mustard and clover plants, while basalt did not affect any of the 33 assessed elements in aboveground plant biomass. Co-application of basalt and biochar did not lead to observable rock weathering while also no synergistic gains in biomass, nor reductions in plant heavy metals were observed after co-amendment.

~~Despite potential CO_2 uptake through weathering, we found that basalt increased SCE in both crops, suggesting increases in soil organic matter (SOM) decomposition and/or rhizosphere respiration. While basalt alone increased CO_2 efflux, co-application with biochar tempered this response, potentially mitigating a basalt-induced priming of soil organic matter decomposition. Hence, co-application of biochar with basalt countered the basalt-induced rise in soil CO_2 emissions, while~~

~~biochar also reduced plant trace metal uptake, highlighting biochar's potential to mitigate both environmental and food safety risks.~~

1 Introduction

The accelerating impacts of climate change necessitate urgent action to mitigate rising atmospheric carbon dioxide (CO_2) concentrations (IPCC, 2021). Beyond emission reductions, carbon dioxide removal (CDR) technologies have emerged as critical tools for achieving net-zero climate goals (Fuss et al., 2018; Rogelj et al., 2018). There has been increasing interest in establishing CDR within existing infrastructure (Beesley & Hardman, 2024).

Urban Nature-Based Solutions (NBS) are designed to protect and restore modified ecosystems to address multiple environmental and societal challenges, including climate resilience and human well-being (Cohen-Shacham et al., 2016). These NBS may comprise forested or agricultural systems, community gardens and allotments, wetland parks and lagoons, or building modifications such as green walls or roofing (Almassy & Maia, 2018). Urban sites are understudied, despite often reporting highly heterogeneous soils with considerable and variable potentially toxic element contamination, and thus variable potential response to CDR methods (Haque et al., 2021). Urban NBS implemented for CDR often focus on boosting plant biomass, and thus biological carbon capture.The second focus of urban NBSs is improving the commonly poor urban soil quality and C content (Buss et al., 2021; Farooqi et al., 2018; Taylor et al., 2021).

Two of such soil-based CDR techniques are enhanced weathering (EW) and soil biochar amendment. EW has garnered increasing attention due to its dual role in CO_2 removal and potential co-benefits for soil health and nutrient dynamics (Beerling et al., 2018, 2020; Haque et al., 2020a). EW involves the application of finely ground silicate or carbonate minerals to land, where they chemically react with CO_2 and water to increase dissolved inorganic C (DIC). Released base cations in soil water can also precipitate as solid carbonates, a second potential inorganic CDR pathway. Despite its potential, reported EW field studies remain scarce till date (Dupla et al., 2024; Haque et al., 2020b; Kantola et al., 2023; Larkin et al., 2022). In addition, there are concerns about the rate of basalt weathering and thus associated CDR rates (Power et al., 2025). Last, ~~heavy metal~~ potential contamination of~~with~~ the food chain by heavy metals may be a concern~~n issue~~, as basalt dust contains ~~significant traces of~~can contain trace metals such as Ni, Cr and Cu (Dupla et al., 2023).

A second soil-based CDR technique, biochar, is more established. As of 2025, biochar certificates dominate the voluntary C market for durable CDR credits (CDR.FYI, 2025). Biochar, the solid product yield of pyrolysis, is a stable form of C. Inertinite, the most stable form of biochar, even has a typical half life of 100 million years at 30°(Sanei et al., 2024). According to a recent analysis with 64 commercial biochar samples, 76% of samples consisted of pure inertinite, increasing the confidence for using biochar as a permanent CDR solution (Sanei et al., 2024). Additional advantages of biochar as a CDR technique include the generation of bio-energy in pyrolysis and adsorption of contaminants from (soil) water by biochar.

~~Increasing inorganic C is however not the only mechanism by which EW can affect C cycling. Soil organic C (SOC), the largest pool of C in many soils, may also be affected, but these effects have been rarely considered. Nonetheless, recent studies showed that SOC stocks can also be affected by EW (Klemme et al., 2022; Sokol et al., 2024; Steinwidder et al., 2025; Vienne et al., 2024). EW may both positively and negatively affect SOC stocks. For example, decomposition rates can rise when basalt increases pH of acidic soils, negatively impacting SOC (Klemme et al., 2022). In contrast, minerals can also adsorb dissolved organic C (DOC) from solution, thereby stabilizing SOC and forming mineral-associated organic matter (MAOM), increasing the permanence of SOC beyond decades (Lavallee et al., 2020).~~

~~Despite its potential, peer-reviewed EW field studies remain scarce till date (Dupla et al., 2024; Haque et al., 2020b; Kantola et al., 2023; Larkin et al., 2022). In addition, there are concerns about the rate of basalt weathering and thus associated CDR rates (Power et al., 2025). Another concern is the potential risk of SOC losses through EW (Klemme et al., 2022). Last, heavy metal contamination with the food chain may be an issue, as basalt dust contains significant traces of Ni, Cr and Cu (Dupla et al., 2023).~~

~~A second soil-based CDR technique, biochar, is more established. As of 2025, biochar certificates dominate the voluntary C market for durable CDR credits (CDR.FYI, 2025). Biochar, the solid product yield of pyrolysis, is a stable form of C. Inertinite, the most stable form of biochar, even has a typical half life of 100 million years at 30°(Sanei et al., 2024). According to a recent analysis with 64 commercial biochar samples, 76% of samples consisted of pure inertinite, increasing the confidence for using biochar as a permanent CDR solution (Sanei et al., 2024). Additional advantages of biochar as a CDR technique include the generation of bio-energy in pyrolysis and adsorption of contaminants from (soil) water by biochar.~~

Synergies between both EW and biochar ~~were~~have been postulated; Biochar has been~~was~~ hypothesized to increase weathering rates of EW and reduce accumulation of trace metals in soil waters (Amann & Hartmann, 2019). The latter is expected to follow from metal sorption to biochar, reducing cation concentrations in soil water. According to the principle of chemical equilibrium, more base cations can consequently dissolve into solution. ~~In conclusion, s~~This way, sorption of base cations by biochar may increase ~~the driving force to dissolve new base cations into solution~~rock dissolution. Nonetheless, in a mesocosm study, Honvault et al. (2024) did not detect any synergistic effects of biochar and basalt on CDR and therefore concluded that their effects were additive; however, data on this topic remain scarce.

~~Synergies between both EW and biochar were postulated; Biochar was hypothesized to increase weathering rates of EW and reduce accumulation of trace metals in soil waters (Amann & Hartmann, 2019). The latter is expected to follow from metal sorption to biochar, reducing cation concentrations in soil water, increasing the driving force to dissolve new base cations into~~

~~solution. If base cations scavenged by biochar would go to the exchangeable pool they can be redissolved later~~ Because sorbed base cations on biochar largely occupy exchange sites, they remain in the exchangeable pool and can re-dissolve later, which is desirable as this causes an increase of DIC in soil water. Likewise, trace metals added with basalt could be sorbed by biochar (in fractions with low bioavailability), which is especially relevant in urban, contaminated brownfield soils used for food production. Co-deployment of biochar and enhanced weathering could thus provide synergies for CDR and reduce the risk of ~~provide as a risk mitigation technique for~~ heavy metal contamination.

In ~~this study~~an urban agricultural field experiment, we tested whether co-applying basalt and biochar in urban plots yields synergies for enhanced weathering, inorganic C sequestration, and reduced plant metal uptake~~we therefore explore potential synergies of co-applying basalt and biochar in an urban agricultural setting.~~

~~We investigate synergies for both weathering, inorganic C sequestration and trace metal contamination~~. ~~We~~ To investigate weathering and inorganic C sequestration, we ~~assess~~ monitored base cations (in different soil pools and in leachates) and weathering products in soil ~~leachates in~~from field plots treated with basalt, biochar, or both.

~~-~~We also analyzed aboveground plant biomass and trace metals in plants. Specifically, we evaluated biomass yields and trace metal uptake in two crop species: clover (*Trifolium pratense*) and mustard (*Brassica juncea*). ~~Based on the abovementioned mechanism proposed by Amann & Hartmann (2019), w~~We hypothesized that biochar ~~enhances~~would enhance basalt weathering, ~~thereby reducing SCE~~ while simultaneously mitigating trace metal accumulation in plants through ~~after trace~~ ~~sorption in~~to low-bioavailability biochar fractions~~ with limited bio-availability~~.

~~soil CO_2 efflux (SCE) in field plots treated with basalt, biochar, or both, while examining the effects on trace metal dynamics and plant biomass.~~

~~Specifically, we evaluate biomass yields and trace metal uptake in two crop species: clover (*Trifolium pratense*) and mustard (*Brassica juncea*). Based on the abovementioned mechanism proposed by Amann & Hartmann (2019), we hypothesize that biochar enhances basalt weathering, thereby reducing SCE while simultaneously mitigating trace metal accumulation in plants after trace sorption in biochar fractions with limited bio-availability.~~

2 Methods

2.1 Site characteristics and timeline

The field experiment was undertaken at a prospective NBS site on the Lower Botanic Gardens in south Belfast, Northern Ireland, UK (54.57872, -5.93065) **(Figure 1).** The site measures ~3.2 hectares and is a public grass-turfed, tree-lined space in an urban residential area adjacent to the River Lagan. Underlying geology comprises Sherwood sandstone, glaciofluvial till, and estuarine alluvial silt deposits. Superficial geology comprises 2-3m of clay-sand and heterogenous historical industrial and residential waste infill (including brickworks, steelworks, bottle-works), and a ~0.4m surface layer of imported topsoil.

Figure 1: Experiment location in Belfast, Northern Ireland, UK.

Figure created using © Google Earth imagery. Imagery © 2025 Google.

At the day of amendment grass was stripped, and basalt and biochar were mixed in the upper 5 cm of soil. Amendment of the clover plots occurred on May 16th 2023, while adjacent mustard plots received basalt on November 20th 2023. For both crops, four treatments were established: besides a control (C), basalt (B), basalt and biochar (BBi) and biochar (Bi) treatments were considered. Clover plots were 1.5m x 2m and arranged in a fixed order. Mustard plots were 1m x 1m and arranged in a fixed order as per the clover plots (**Figure 2**). Basalt treatments received an equivalent of 40 t basalt ha-1 while biochar was added at an application rate of 33 t ha-1, in range with typical application rates utilized in research (Anthony et al., 2025; Boito et al., 2025; Liu et al., 2013; Steinwidder et al., 2025). Permanent TOMST temperature and soil water content (SWC) sensors were installed at each plot, and SWC and temperature at a depth of -6cm, +2cm, and +15cm were monitored.~~from the soil surface were recorded at the time of SCE measurement.~~

~~Basalt treatments received an equivalent of 40 t basalt ha-1. Biochar was added at an application rate of 33 t ha-1.~~ Clover plots were seeded with *Trifolium pratense* at 4.5 g/m^2, while Mustard plots were seeded

-with *Brassica juncea* at 2.0 g/m^2. Seeding took place just after adding soil amendments.

Figure 2: Schematic overview of (A) clover plots and (B) mustard plots with treatments, plot numbers, plot sizes and spacing between plots. (C) Picture of amendment of the clover field plots. The stripped grass plots, yellow mixer to homogenize soils, white TMS TOMST temperature and soil moisture sensors can be identified.

2.2 Soil, basalt and biochar properties

A Paleogene basalt from the upper basalt formation in Northern Ireland was sourced from a local quarry. Basalt elemental composition was characterized using XRF, while basalt mineralogy was also measured using XRD (**Table 1**). Biochar was produced from dried and pelletized solid fraction of digestate from an anaerobic digester at AFBI Hillsborough. Digestate pellets were pyrolysed using a Biomacon C100–F Pyrolysis Boiler (R&S Biomass Equipment Ltd, Newtownstewart, NI) at a feed rate of 21 kg $h^{-}1$ and pyrolysis chamber temperature of 675 ± 5 °C. Laboratory characterisation of the digestate Biochar was undertaken by a commercial accredited laboratory (Eurofins Umwelt Gmbh, Germany) (**Table 1**). The studied soil was an alkaline soil (pH=8.22±0.5) with a -SOC content of 6.38±4.74 (**Table 2**).

2.3 Soil sampling and measurements

Soils of clover plots were sampled on 19/5/2023 for the initial sample, and on 12/11/2024 for the final sample (**Supplementary Table 1**). The upper 5 cm of soil (amendment depth) was sampled using a kopecky ring (5 cm diameter). Loss on ignition (LOI) was for clover planted plots. Soil organic carbon (SOC) was determined through LOI: approximately 1 g of dry sample was weighed using an analytical balance. Next, this sample was heated from 105 to 550 °C for 1 hour and maintained at 550°C for 4 hours in a Nabertherm Economy Muffle Furnace. After overnight cooling to 105°C, the sample was weighed again on an analytical balance. Assuming a C percentage of 58% (Van Bemmelen, 1890), the weight loss (which represents soil organic matter (SOM) was converted into SOC.

Soil-bound cations were extracted twice using the sequential extraction scheme of Tessier et al. (1979). In this sequential leaching protocol, we distinguish (base) cations in four different consecutive fractions: the exchangeable, carbonate-, (hydr)oxide- and SOM-associated fractions. In the exchangeable soil pool, cations are bound to negatively charged surfaces of clay minerals or SOM and can be extracted with a weak salt solution (e.g. 1M $BaCl_2$). The carbonate pool consists of minerals such as $CaCO_3$, with its carbon typically reported as soil inorganic carbon (SIC). Quantifying carbonate-associated base cations can help circumvent common challenges related to carbon heterogeneity and the detection of relatively small SIC shifts (Kelland et al., 2020). Carbonates are extracted with acidic acetate solutions. In the reducible soil pool, base cations are linked to Fe- and Mn-(hydr)oxides and are extracted with 0.04M $NH_2OH.HCl$ in 25% acetic acid. Finally, in the oxidizable pool, cations are associated by stronger bounds to SOM or sulfides and are extracted with acidic H_2O_2 solutions. Tessier's sequential extractions were also used in ~~other~~ recent EW studies~~research~~ (Boito et al., 2025; Niron et al., 2024; Steinwidder et al., 2025; Vienne, 2025). The Tessier protocol was slightly modified, as for the exchangeable extraction, 10 mL 1 M NH_4-acetate was used rather than the more toxic $BaCl_2$. In addition, Na acetate was replaced by a volumetric mixture of (1 mL: 4 mL: 5 mL of 3 M NH_4-acetate: H_2O:1 M acetic acid) respectively to allow for Na analysis. In the four different soil fractions, elements were quantified using ICP-OES (iCAP 6300 duo, Thermo Scientific). In the soil sample taken immediately after amendment, Na, K, Mg, Ca, Fe, Al, Si, Ni, Cr, Zn, Cu and Pb were quantified in all fractions. For base cations, Al, Fe and Si these extractions were repeated in the final sampled soil samples of clover planted plots. Similar as in Larkin et al. (2022), SIC was quantified from base cations in these acetate leaching extracts, assuming 0.5 mol of solid carbonate-C per mol of base cation charge.

Table 1: Biochar ((chemical composition) and basalt (chemical composition and particle size distribution) characteristics.

Biochar characteristics		**Basalt characteristics**	
Feedstock	Digestate	Na_2O	2.11%w/w
pH (1g:2.5mL H2O)	10.47	MgO	4.82%w/w
Bulk Density	475 kg/m^3	Al_2O_3	14.7%w/w
Specific surface (BET)	463.68 m^2/g	SiO_2	55.52%w/w
Ash content	42.3%w/w	P_2O_5	0.17%w/w
Total carbon	55.4%w/w	SO_3	0.17%w/w
Organic carbon	54.9%w/w	K_2O	2.81%w/w
Total nitrogen	11.1 g/kg	CaO	3.01%w/w
Na_2O	21.8 g/kg	TiO_2	0.74%w/w
MgO	28.2 g/kg	Mn_2O_3	0.11%w/w
SiO_2	158 g/kg	Fe_2O_3	6.69%w/w
P_2O_5	40.6 g/kg	BaO	0.05%w/w
SO_3	14.4 g/kg	Loss on Ignition	8.5%w/w
K_2O	41.6 g/kg	Albite	62.1%w/w
CaO	69.9 g/kg	Pyroxene	31.4%w/w
Fe_2O_3	11.7 g/kg	Olivine	6.2%w/w
		Montmorillonite	1.2%w/w
		Size fraction	**% of particles**
		>2 mm	27.63
		500 µm – 2 mm	42.19
		355 – 500 µm	5.48
		63- 355 µm	16.76
		< 63 µm	6.94

2.4 Soil leaching test

Leaching tests were conducted on soils from the clover plots. To assess potential elemental losses from the topsoil and evaluate basalt weathering and biochar effects on element mobility, we determined the capacity of the soil to leach cations and other elements using a standardized soil leaching protocol. Measurements were made on soil sampled immediately after biochar and/or basalt amendment and after 550 days. Soils for this leaching test came from the plots amended with cloverWe determined the capacity of the soil to leach elements and DIC by utilizing a soil leaching protocol. We did this both for the initial soil sample (sampled just after biochar and/or basalt amendment) and for a soil sample taken after 550 days. In this protocol, we leach 1 kopecky ring of soil (5 cm height, 5 cm and diameter) with an 150 mL of rain water (collected in Antwerp, Belgium) to obtain at least 100 mL leachate water. This amount is roughly equivalent to the infiltration taking place in the field site over 81 days (estimate based on open source weather data). The exact dry soil mass per kopecky ring was noted down and natural rainwater was collected in Wilrijk, Antwerp. After obtaining 100 mL leachate, sufficient for all executed analysis, we determined DIC, electrical conductivity (EC), dissolved nitrogen (N), phosphate and the following elements (K, Na, Ca, Mg, Al, Fe, Si, Ni, Cr, Zn, Cu). Elements, N and phosphate were measured only on leachates of the initially sampled soils, while EC, DIC and pH were measured also on the soil sampled after 550 days. Leachate samples were filtered through a 0.45 µm PET filter. DIC was measured using a FormacsHT with LAS sampler (Skalar - NLD). pH and EC were measured with a Hanna Instruments (HI6522-02) analyzer. Dissolved elements were measured through ICP-OES (iCAP 6300 duo, Thermo Scientific). Before analysis, ICP samples were conserved using 1.5 mL (HNO3 69%) per 30 mL sample. The elemental composition of the input water can be found in Table S4. All concentrations were multiplied with leachate volumes and divided by the mass of leached soil to convert units from mg L^{-1} to µg element g^{-1} soil.

Soil CO_2 efflux (SCE) was measured in the center of each plot using the WMA-4 portable CO_2 Gas Analyzer (PP Systems). Gas collection chambers were created using air-tight PVC casing (8 cm high, 10 cm diameter) with flexible gas tube connectors. Gas collection chambers were inserted into the centre of each plot to 5 cm depth and CO_2 measurements were observed at 0-minutes and 60-minutes, with the difference as representative SCE over 1 hour. SCE measurements were taken for up to one calendar year for mustard-seeded plots (21/11/2023-12/11/2024); and clover-seeded plots (20/12/2023-12/11/2024). Mustard-seeded plot SCE was measured for 10 consecutive days immediately after soil amendment, followed by 5-day intervals for 20 days, then at 14-day intervals until the end of the experiment. Clover-seeded plot SCE was measured at 14-day intervals. On sampling dates, all measurements were taken between 9:00-12:00 local time.

Table 2: Background soil characteristics.

Texture (clay: silt: sand %)*~~type~~	Loamy soil (0.07: 20.82: 79.13) ~~Clayey Sand~~				
Property	**Unit**	***Max***	***Min***	***Median***	***Mean + - standard deviation***
pH		9.00	7	8.4	8.22±0.5
Organic matter	%	8.2	0.3	2.5	2.80±1.84
SOC	%	21.6	2.2	5	6.38±4.74
Nitrogen	%	0.6	<0.01	0.39	0.37±0.13
As	mg/kg	93	3.6	11.5	15.54±16.45
Cd	mg/kg	2.67	0.34	0.52	0.62±0.46
Cr(III)	mg/kg	57.7	23.9	37.25	38.89±8.27
Cr(VI)	mg/kg	<0.3	<0.3	<0.3	All <LOD
Cu	mg/kg	294	32	82	88.00±54.31
Pb	mg/kg	851	63	166	222.25±184.19
Hg	mg/kg	2.84	0.12	0.4	0.57±0.55
Ni	mg/kg	127	41	62	66.96±21.65
Se	mg/kg	1.33	0.52	0.7	0.75±0.25
Zn	mg/kg	997	89.4	169	208.26±172.10

* Textures were derived from the control soil particle size distribution, measured using a mastersizer 2000 with a Hydro 2000G sample dispersion unit.

2.6~~5~~ Plant measurements

Mustard was planted on 20/11/2023 and harvested after 182 days (7/5/2024), and after 364 days (12/11/2024). Clover was planted in May 2023, and harvested after 172 days (13/11/2023), and after 354 days (7/5/2024). At the time of harvest, a 50 cm² square in the NW corner (at 6 months) or SE corner (at 12 months) of each clover and mustard plot was isolated using a tape measure. All plant matter was removed from ~5mm above the soil surface (Griffin et al., 2017; Laird et al., 2017). Plants were oven dried at 65°C for 72 hours. Plants were then weighed to derive biomass dry weight and ground to analyze plant elemental concentrations, which were quantified using ICP-MS (iCAP TQ ICP-MS, Thermo Scientific, US). The analyzed plant elements were: Ag, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Ga, Ge, Li, Mg, Mn, Mo, Ni, P, Pb, Rb, Re, S, Se, Si, Sr, Ta, Ti, Tl, U, V, W, and Zn.

2.7~~6~~ Data analysis

For ~~analyses~~measurements that were not repeated in time (i.e., biomass and plant elemental concentrations, leachate elements), we applied a multiple linear regression and a two-way anova using the lm and aov function in R and assessed the basalt, biochar and the basalt x biochar interaction effect. For measurements that were repeated in time (LOI and elemental soil data from sequential extractions and leachate pH, EC and DIC), a mixed linear model was constructed with basalt, biochar, time and their interactions as fixed factors and plot number as a random factor using the lmer function from the lme4 package, after which a multiple anova was done using the anova function from the car library in R. ~~. I~~If the interaction effects (biochar x basalt, basalt x time or biochar x time) were not significant, a new model without the non-significant interaction effect was ~~selected~~applied. ~~For analyses that were not repeated in time (i.e., biomass and plant elemental concentrations), we applied a multiple linear regression using the lm function in R and assessed the basalt, biochar and the basalt x biochar interaction effect.~~ All analyses were executed in R studio (R-4.0.5) and a significance threshold of 0.05 was used.

~~For SCE, soil temperature and crop type were included as a co-variate as well and interactions between crop type and amendments were tested for. When not statistically significant, interaction effects were removed from the models. The multicollinearity assumption for interaction effects was verified using the vif function and evaluation of including interaction effects in the selected model was done by assessing whether the variance inflation factor of variables was below three (Zuur et al., 2010). The vif of all significant interaction effects was below this threshold. Because the SCE model had a positive skew, SCE was log10 transformed to get normally distributed model residuals.~~

~~For analyses that were not repeated in time (i.e., biomass and plant elemental concentrations), we applied a multiple linear regression using the lm function in R and assessed the basalt, biochar and the basalt x biochar interaction effect. All analyses were executed in R studio (R-4.0.5) and a significance threshold of 0.05 was used.~~

3 Results

3.1 Soil base cations and trace metals

Basalt significantly increased soil exchangeable Ca (+12%~~, p=0.046~~) and reducible Mg (+91%)~~%, p = 0.02)~~(**Figure 3**). The increase in exchangeable Ca and reducible Mg was however already detected in soils sampled just after basalt amendment. We did not detect increases in base cations in time in any of the four extracted soil pools (no positive basalt:time interaction effects were found) (**Figure 3**).Hence, basalt did also not increase carbonate cations ~~or~~ and ~~hence~~ SIC in time.

Biochar significantly increased base cations in the exchangeable pool (+320% ~~(p<0.01)~~, +674% ~~(p=0.02)~~, +31% ~~(p=0.02))~~ for K, Na and Mg respectively~~,)~~**Figure 3)**. The biochar-stimulated exchange of K and Na decreased in time (**Figure 3A and**

3B). With biochar amendment, all base cations also increased significantly in the carbonate pool (+343% ~~(p=0.03)~~, 184%, 103% and 110% ~~(p=0.03), (p=0.04), (p=0.02)~~ for K, Na, Ca and Mg respectively, **Table S3**). Again for Na, this increase decreased with time (p<0.01). We found no significant basalt x biochar interaction effects for any of the investigated base cations.

Si, Al and Fe distribution in soils can give further insights on the mobility of cations. Si increased in the reducible soil pool (+25%, **Table S3**) and remained unchanged in other pools. Al was the only element for which a basalt:biochar interaction effect was observed (**Table S3**); ~~E~~Eexchangeable Al increased after co-application of basalt and biochar (+232%, **Table S3**). Basalt amendment ~~caused~~ decreased~~s in~~ Al and Fe (-22% and -92% respectively, **Table S3**) in the carbonate soil pool and in the oxidizable pool (Fe: - 18%, Al: -14%, **Table S3).** In the reducible pool, Fe did significantly increase (+36%, **Table S3**) and also Al tended to increase in the reducible soil pool (p=0.10, +27%). Reducible Al and Fe in the basalt ~~amended plots~~treatment, however, significantly decreased in time (**Fig. S8, Table S3**).

For soil trace metals, we found that basalt significantly increased reducible Ni and Cr (+62% -and~~and Cr~~+45% respectively, **Table S2**) and oxidizable Ni (+18%, **Table S2**), while biochar decreased exchangeable Ni (-41%, **Table S2**). We found no statistically significant basalt x biochar interaction effects for Ni or Cr. No significant effects of basalt, biochar or their interaction were found for Cu, Zn and Pb in any of the soil fractions (**Supplementary Table 2**).

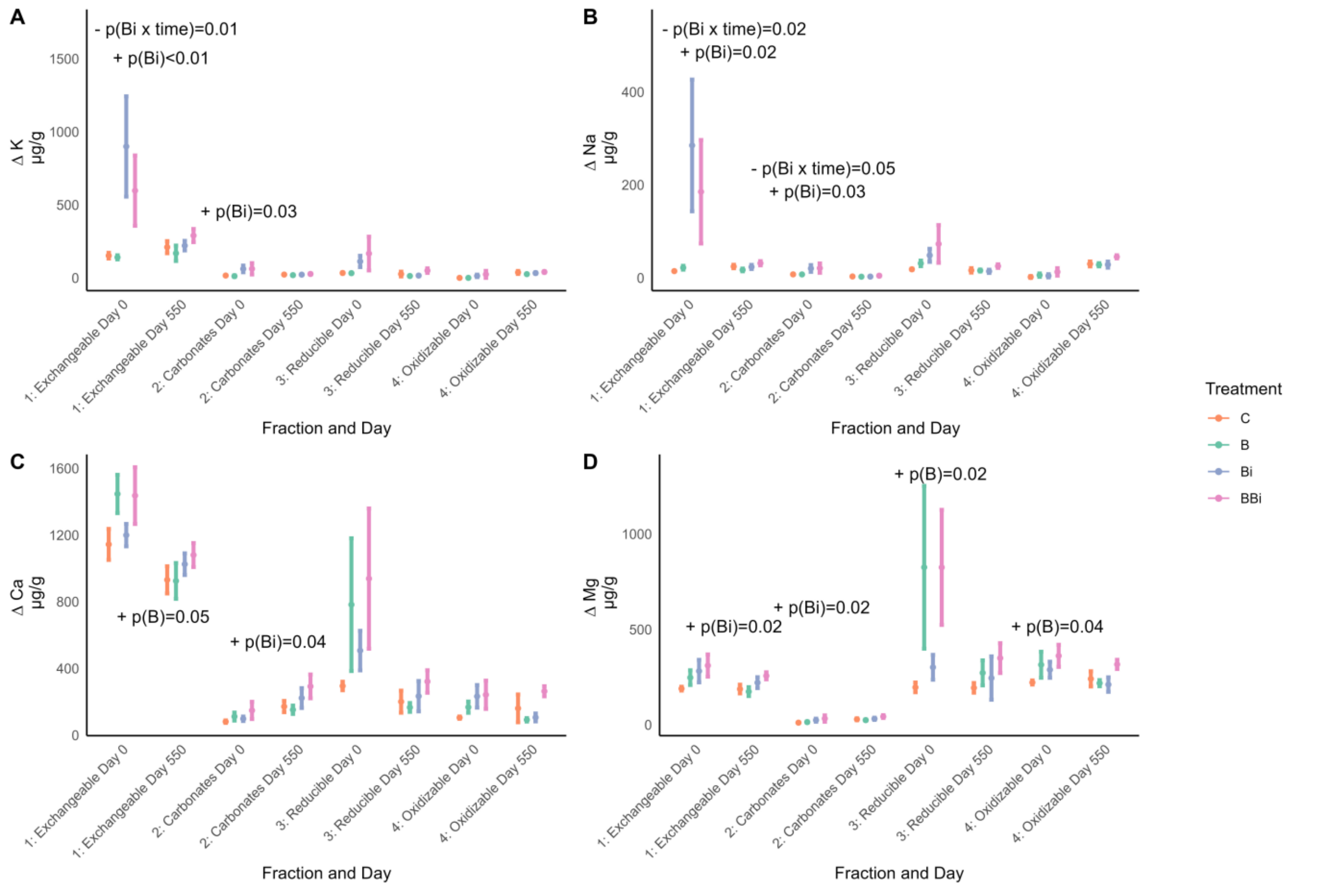


Figure 3: Changes in (A) K, (B) Na, (C) Ca and (D) Mg in µg element/g soil for different soil fractions in clover plots, relative to control soil for different sampling times (initial = directly after amendment and last = after 550 days). Dots and error bars represent averages and standard errors. P values for basalt and biochar effects (p(B) and p(Bi)) are annotated on the plots.

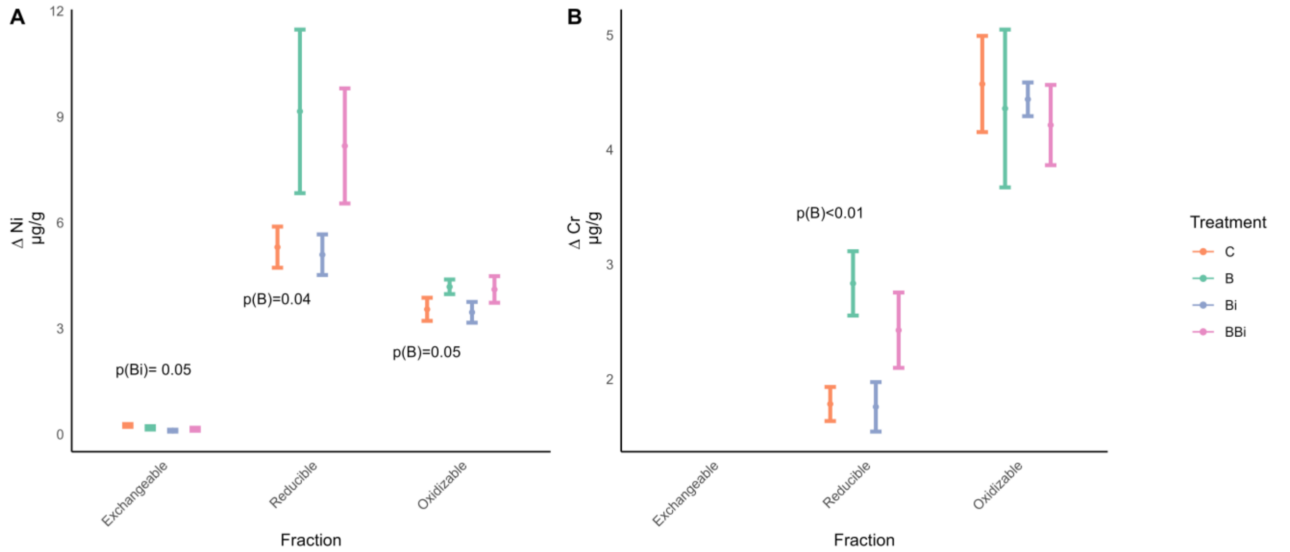


Figure 4: Delta in elements relative to control soils of Ni and Cr for the 4 different considered soil fractions. These soil elements were extracted after initial soil sampling in clover ~~planted~~ plots. P(B) and p(Bi) are p values for basalt and biochar, respectively. Carbonate-Ni and -Cr and exchangeable Cr were all below detection limits and are not shown in this plot.

3.2 Soil leachates

Basalt did not increase any of the measured elements in soil leachates (**Figure 5**). In contrast, basalt even tended to decrease leachate Ni (p=0.06, -29%, **Figure 5**) and Zn (p=0.08,-35%, **Figure 5**). Also pH, DIC and EC were not significantly affected by basalt (**Fig. S14**). Biochar significantly increased Na, K, Mg and P in leachates (+348%, +241%, +84% and +283% respectively, **Figure 5**).) ~~Pa~~nd these increases were also reflected in a significant rise in ~~electric conductivity~~EC (+93%, **Fig. S14**). We did not find significant basalt x biochar interaction effects on leachate concentrations of any of these elements, nor on DIC, EC and pH. (**Fig. S14**).

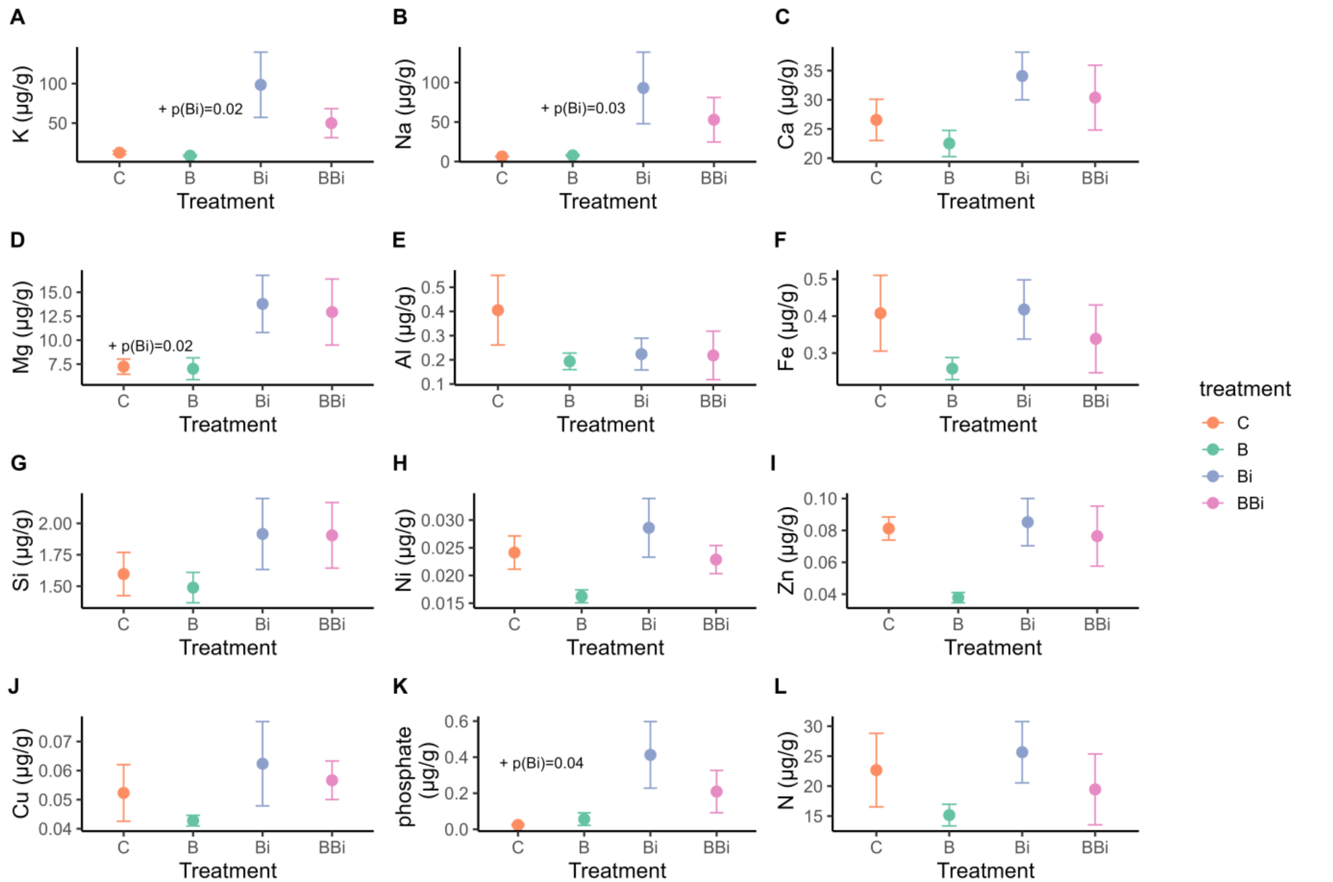


Figure 5: Results from the soil ~~water~~ leaching test for ~~soil~~ samples taken instantly after ~~soil~~basalt and biochar amendments. Dots and error bars represent averages and standard errors of the mean.

3.3~~2~~ Plant biomass

Basalt amendment did not significantly influence clover or mustard ~~yield~~biomass, although a tendency towards higher biomass (p=0.07, +31%, **Figure 6**)~~)~~ was observed for mustard. Biochar did significantly increase biomass of both crops (mustard: +110% and clover: +19%, **Figure 6**). No significant basalt x biochar interaction effects on biomass were observed (**Figure 6~~5~~**). While clover yield significantly decreased in time, mustard yield increased slightly, yet significantly in time for all treatments.

3.4~~3~~ Plant Trace metals

While basalt significantly increased reducible Ni and Cr in soils (**Figure 4**), we did not observe increases for these elements and any of the other 33 assessed elements in aboveground biomass (**Figure 7~~6~~** and **Supplementary Figures 1-6**), neither for ~~both~~ clover, nor for ~~and~~ mustard plants. In clover plants, Ti, V, Fe, Ga and Ge significantly decreased after biochar amendment (with -60%, -61%, -63%, -63%, -57% respectively, **Figure 7**). In mustard plants, biochar decreased concentrations of Mn, Zn and Cd (-48%, -32% and -63% respectively, **Figure 7**). In contrast, biochar increased P (+30%, **Figure 7**) in mustard plants.~~In clover plants, Ti, V, Fe and Ge significantly decreased after biochar amendment. In mustard plants, biochar decreased concentrations of Mn, Zn and Cd. In contrast, biochar increased P in mustard plants.~~

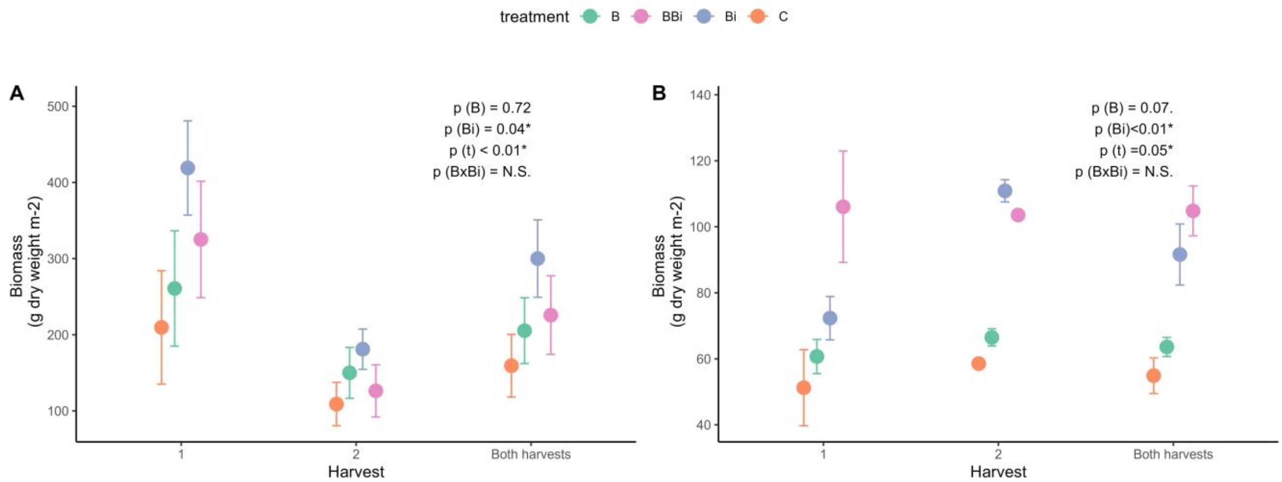


Figure 6~~5~~: Aboveground dry biomass in function of time after amendment for (A) clover and (B) mustard plots. "N.S." = Not significant, this is indicated when the interaction effect was tested for but was not statistically significant. p(B), p(Bi), p(t) and p(BxBi) represent p values of basalt, biochar, time and basalt x biochar effects. Dots and error bars represent mean biomass +- the standard error of the mean.

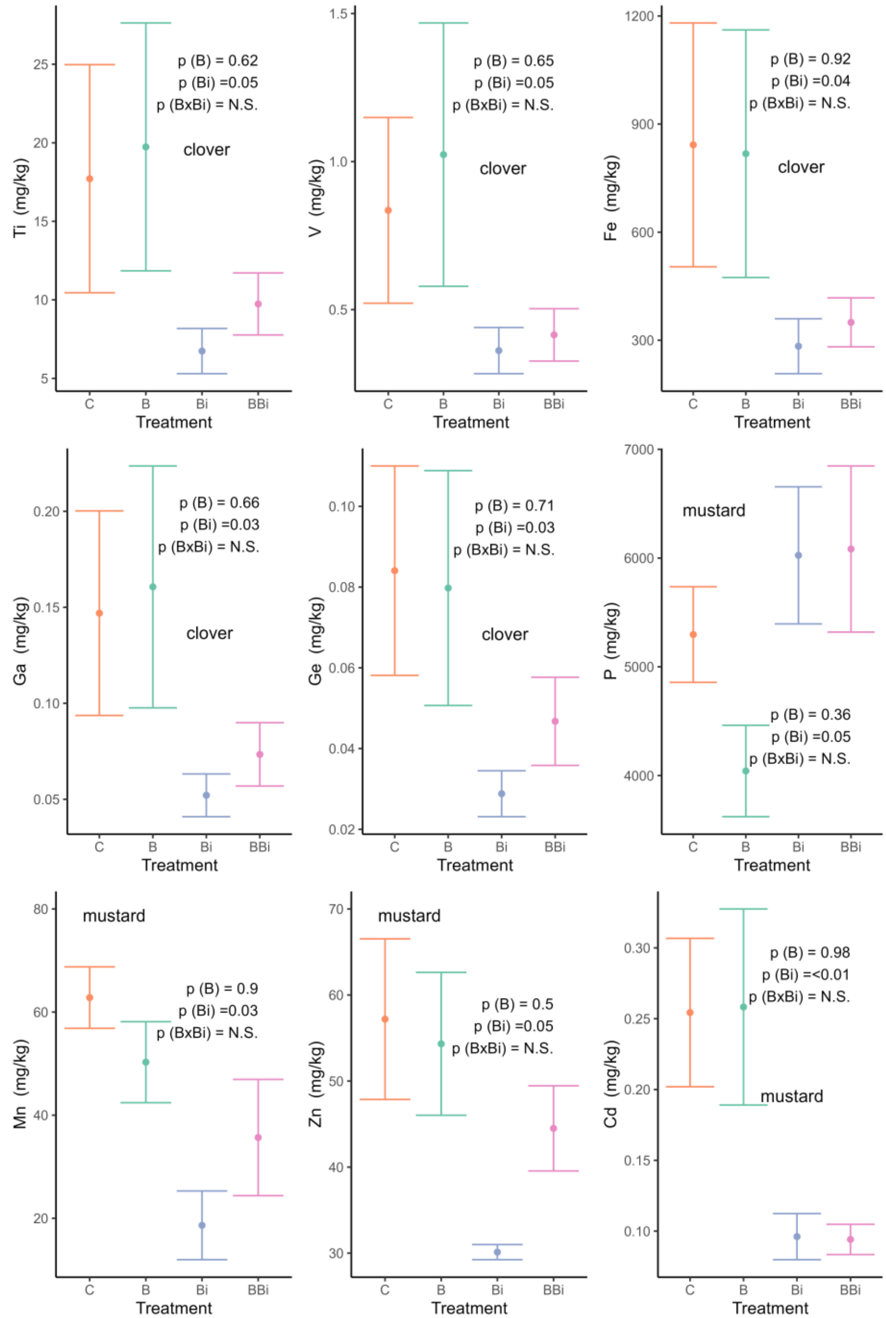


Figure 76: Elements in clover or mustard plants for different treatments. Error bars represent averages +- standard errors. Only elements with significant changes are shown here. For all plant (trace) elements, we refer to **Supplementary Figure 1-6**.

3.4 Soil CO_2 emissions

Amendment with only basalt increased SCE significantly while we did not observe a significant crop effect observed (**Figure 7**). The biochar-only treatment also tended to increase SCE relative to the control. Interestingly, co-application of biochar with basalt significantly decreased the basalt induced increase in SCE (significant, negative basalt x biochar interaction effect on SCE).

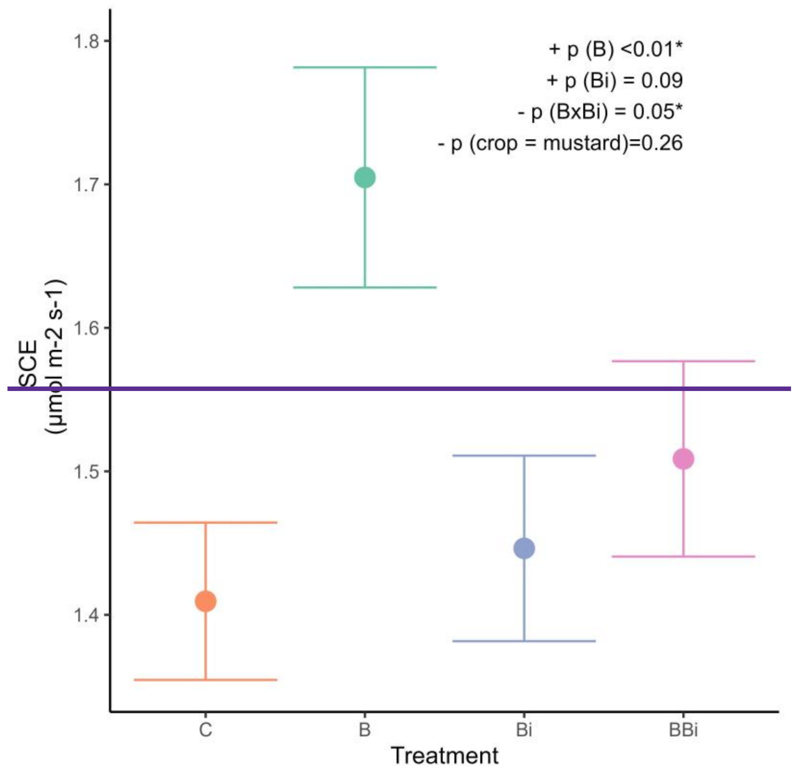


Figure 7: SCE in function of treatment. p(B), p(Bi) and p(BxBi) and p(crop) are p values from the basalt, biochar and basalt x biochar interaction and crop effects respectively. A (+/-) sign before the p value indicates a positive/negative effect on SCE. Dots and error bars represent the mean SCE +- the standard error of the mean for all measurements taken between 20/12/2023-12/11/2024 for both clover and between 21/11/2023-12/11/2024 for mustard plots. Temporal dynamics for the SCE of both crops are presented in Supplementary Figure 12.

4 Discussion

4.1 Effects on inorganic CDR and soil chemistry

While initially after basalt amendment, a peak of exchangeable Ca and reducible Mg was observed in top soil (0-5 cm), these element pools decreased in time. We did not observe accumulation of base cations in any of the other extracting soil pools, including the carbonate pool 550 days after the start of the experiment. ~~Hence, in our experiment, we found no~~The lack of an increase in base cations in the carbonate fraction ~~and hence conclude no increases~~indicates that ~~in~~ soil carbonates or SIC did not increase. ~~The A~~The decreases in~~of~~ base cations in extracted fractions of the topsoil ~~soil pools~~ over time ~~may~~ can indicate that positively charged base cations, along with negatively charged bicarbonate, leached into deeper soil layers. Nonetheless, ~~in our leachates from the~~the leaching test with topsoil samples ~~5cm deep soil cores, none~~ showed no increase in leaching of ~~the investigated~~ base cations or~~, nor~~ DIC ~~increased significantly~~.

Hence, the absence of an accumulation of base cations in any of the four extracted soil pools ~~and~~as well as in the leachates ~~can reflect~~implies either no detectable basalt weathering within 550 days or redistribution of released base cations such as Ca into secondary minerals or strongly bound pools not accessible by the Tessier extraction scheme. Limited weathering may have occurred as the utilized basalt had a relatively coarse particle size. Moreover, 62% of the basalt was identified to be albite, a mineral with a low weathering rate (approximately 10^-12 mol/m²/s at pH 8, ~~(~~(Palandri & Kharaka, 2004)) and the 31% pyroxene minerals present also have a relatively low weathering rate at pH 8 (augite for example also dissolves at a rate of ~10^-12 mol/m²/s at pH 8). Nonetheless, there was also 6% olivine present in the rock feedstock, for which we expect a weathering rate of ~10^-10 at this pH. We cannot exclude the possibility that leaching of air-dried topsoil as done here underestimates field leaching (e.g., via preferential flows and limited cation extraction efficiency in air-dried topsoil). In addition, base cations may have been scavenged by newly formed clay minerals. Ca could for example have precipitated as Ca-montmorillonite, making it unextractable with the Tessier protocol, even if weathering occurred. In other words, secondary oxides and clays may have formed but gone undetected if they were retained in a residual soil fraction resistant to extraction ~~by the Tessier sequential scheme~~ (Steinwidder et al., 2025). Clay-like material (including precursor clay minerals and protoclays) were previously identified in natural Northern-Irish basalts similar to the one used in this experiment (Cox et al., 2017). Recent studies have suggested the potentially significant production of secondary minerals and associated degassing of bicarbonate (Iff et al., 2024; Niron et al., 2024; Steinwidder et al., 2025; Vienne et al., 2025).

~~Although no inorganic CDR was detected here,~~ Importantly, basalt application did not increase concentrations of trace metals in the most bio-available soil pool, ~~being~~ i.e., the exchangeable pool, and even decreased Zn and Ni leaching ~~from the top soil here~~in our leaching test.

On the other hand~~Instead,~~ elevated levels of Ni and Cr were observed in the oxidizable and reducible pools, which are less bioavailable soil fractions (Al-Mur, 2020), suggesting limited mobility and uptake risk. Specifically, Ni showed significant accumulation in both the reducible fraction and the oxidizable fraction associated with ~~soil organic matter (~~SOM~~)~~, while Cr increases were confined to the reducible ~~fraction~~pool. The tendency for lower Ni in leachates from basalt amended soils support that Ni was immobilized in the reducible pool (and potentially other soil pools not targeted by the extraction).

~~This distribution indicates that the added metals were largely sequestered in more stable pools, reducing their immediate bioavailability to plants.~~ Chromium in soils is predominantly present as Cr(III), which has a strong tendency to adsorb or co-precipitate with iron oxides, especially at alkaline pH (van Raffe et al., 2025). In natural basaltic soils, Fe-oxides are known to be the main Cr scavengers (Sun et al., 2022). Acidity and organic acids can however promote leaching of these Fe-Cr-oxides and formation of oxidized Cr. In natural basaltic soils, the availability of Cr in the soil was extremely low due to the high stability of Cr bound to Fe-oxides.

Similarly, Ni also associates with Fe oxides (Xu et al., 2007), but is likely to have a relatively higher tendency to leach from these oxides compared to Cr due to its different chemical behavior. Ni(II) has a smaller charge compared to tri- or hexavalent Cr and ability to react with organic ligands~~matter~~ increases its mobility (Barałkiewicz & Siepak, 1999). The higher accumulation of Ni in the oxidizable ~~SOM~~ fraction following basalt addition thus likely reflects this affinity for organic complexes, while Cr remained~~s~~ predominantly in the reducible ~~Fe-oxide~~ fraction indicative of its immobilization in Fe-Cr-oxides. -A similar effect was ~~seen~~reported ~~in studies of~~for soils overlying the Antrim basalts (similar to the basalt used in this study) in Northern Ireland (Cox et al., 2013, 2017). ~~This~~These distributions indicate ~~s~~ that the added metals were largely sequestered in more stable pools, reducing their immediate bioavailability to plants.

Biochar alone increased EC, K and Na in leachates, increased K, Na, and Mg in the exchangeable soil fraction, and K, Na, and Ca in the carbonate fraction. The latter increase in carbonate base cations is consistent with previous findings, as biochar is known to increase base cation exchange and promote the formation of ~~secondary~~ SIC ~~inorganic carbon (SIC)~~ (Amann & Hartmann, 2019; Dong et al., 2019). We presume that biochar caused trace elements to shift towards fractions that are chemically stable, immobile and biologically inert (Al-Mur, 2020). The only trace metal that was significantly affected by biochar in our sequential extractions was Ni, which significantly decreased in the exchangeable soil fraction.

We hypothesized that biochar would increase basalt weathering and retain base cations in the exchangeable pool. In contrast with our hypothesis there were no synergistic basalt x biochar interaction effects for any of the base cations, neither in the ~~and~~ soil fractions, -nor in the leachates ~~nor in leachates~~. Similarly, the trace metals did not show a significant basalt x biochar interaction effect for any of the soil pools and leachates.

In contrast with the hypothesis postulated by Amann & Hartmann (2019) and -i~~I~~n agreement with Honvault et al. (2024), this suggests that the effects of basalt and biochar on soil base cations are additive ~~and not~~rather than synergistic (~~Amann & Hartmann, 2019~~; Honvault et al., 2024). -The soil texture in the soil utilized by Honvault et al. (2024) was similar (sandy loam), yet we expect higher weathering in their study as pH (in KCl) was only 5 and 66% of their basalt had pyroxene mineralogy, with only 18% of albite. Nonetheless, the synergy on weathering was absent (Honvault et al., 2024). Besides this study, w~~W~~e are not aware of other studies that investigated the fate of weathering products in the soil after co-application of basalt and biochar, so more research is needed to confirm this finding.

4.2 Plant Biomass

Basalt did not significantly affect biomass and plant trace metal concentrations in our experiment. Unlike in studies in acidic agricultural soils (e.g.(Beerling et al., 2024)) we dide~~o~~ not observe a liming effect as the unamended control had already an alkaline pH (8.22 on average).

Biochar, on the other hand, significantly increased biomass of both clover and mustard plants. The 67% increase in mustard biomass after biochar amendment in our study positively correlated with Mo, P, Rb, Mg and S in aboveground biomass, while it negatively correlated with Cd, Mn, Tl, Zn and U in aboveground biomass (**Fig. S12**). The biomass increase may (in part) be due to a P-fertilization effect, as mustard biomass-P increased and our digestate-derived biochar had a relatively high P_2O_5 content (40.6 g/kg) and phosphates in biochar-leachates significantly increased. For clover, there was an inverse correlation between aboveground biomass Li, Co, V, Ge and Fe and aboveground biomass ~~itself~~. We expect that lower amounts of toxic trace metals were taken up by clover here. Nonetheless, we could not find robust models in which aboveground biomass was predicted by significant changes in aboveground biomass elements for both crops. It is possible that interactions with belowground nutrient dynamics, which were not captured in this study, played a role.

The positive effect of biochar on *Trifolium pratense* biomass is in line with recent literature. Chen et al. (2021) found increased growth after fertilization with biochar albeit only when nitrate was co-applied. After amending with 33 ton biochar ha^{-1}, our observed clover yield relative to unamended controls was on average 88%, similar to the biomass increase after amending 5% biochar (approximately 75 ton biochar ha^{-1}, assuming a bulk density of 1.5 kg L^{-1}) in Pb contaminated soils (Meng et al., 2023). ~~The 67% increase in mustard biomass after biochar amendment in our study may (in part) be due to a P-fertilization effect, as mustard biomass-P increased and our digestate-derived biochar had a relatively high P_2O_5 content (40.6 g/kg).~~

While biochar effectively stimulated biomass production, we did not observe any synergistic effect between basalt and biochar in promoting biomass production. Similarly, Honvault et al. (2024) reported no significant interaction when cultivating wheat, although they noted a positive trend in total plant biomass.

4.3 Trace metals in aboveground biomass

While we observed increases in reducible soil Ni and Cr after basalt amendment, we did not find higher concentrations of these metals in the plants after applying 40 t basalt ha^{-1}, presumably because of the low bioavailability of metals in the reducible soil fraction. With a higher application rate of 74 t basalt ha^{-1}, Honvault et al. (2024) did detect increases in wheat seed Ni to 5 mg kg^{-1}, yet below the toxicity level for sensitive species (10 mg kg-1 dw) (Yusuf et al., 2011). With maize however, no significant increases in trace metals were observed in plant parts after amendment with a basalt range (10-200 t ha^{-1}) (Rijnders et al., 2024).

While we only detected a decrease in exchangeable trace metals after biochar amendment for Ni, we found that multiple elements (V, Ti, Fe, Ga, Ge) decreased in aboveground clover biomass. This is in line with results of Pescatore et al. (2022), who found that biochar decreased several trace metals (Cr, Cu, Ni and Pb in this case) in the aboveground biomass of berseem clover. Also in mustard~~ aboveground biomass,~~ biochar decreased trace metals, in particular~~; Biochar decreased~~ Mn, Zn and Cd. This is~~in *Brassica juncea*,~~ in line with Zang et al. (2023) who found decreased Cd in mustard~~*Brassica juncea*~~ post biochar amendment. Similarly, Gonzaga et al. (2019), observed decreases in plant Cu with mustard ~~*Brassica juncea*~~ after biochar amendment.

~~Mechanistically, b~~Biochar can reduce plant metal uptake through increasing pH.~~;~~ ~~Typically, b~~Biochar is typically alkaline (our biochar had a pH of 10.47) and ~~therefore increa~~can thus immobilize~~ses~~ metals ~~in the form of~~ insoluble hydroxides and carbonates (Mei et al., 2025; Wang et al., 2022). In addition, the high surface area, porous structure and abundant functional groups (carboxyl, hydroxyl and phenoloic groups) can adsorb heavy metals (Viotti et al., 2024; Zhou et al., 2022).

Biochar reduced plant trace metal uptake, but no synergistic effect with basalt was observed. This aligns with the findings of Honvault et al. (2024), who observed no synergetic reduction in trace element uptake from basalt when co-applied with biochar. In our study, adding basalt on top of biochar did not further decrease trace metal uptake. Whereas Honvault et al. reported increased uptake with basalt under more acidic conditions, our alkaline soil likely already immobilized trace elements from basalt, and biochar did not modify this effect.~~.~~

We expect that the pH increase and sorption capacity of biochar were more important than the pH increase due of basalt addition, meaning that basalt ~~does~~ did not provide additional reductions in plant heavy metal uptake.

~~4.4 **Changes in SCE**~~

Contrary to our hypothesis, SCE increased in basalt amended soils relative to control soils (**Figure 7**). In general, SCE consists of rhizosphere respiration and soil organic matter decomposition, as well as CO_2 fluxes related to inorganic C processes. In general, CO_2 fluxes from organic cycling tend to be an order of magnitude higher than inorganic cycling (Clarkson et al., 2023; Weil & Brady, 2016). Although DIC leaching was not quantified here, we did not find indications for substantial changes in SIC; The cation analyses suggest limited realization of inorganic CO_2 removal, and also in other studies, observed inorganic CO_2 removal was at least one order of magnitude smaller than the organic CO_2 fluxes (Steinwidder et al., 2025; Vienne et al., 2024). The increased SCE after basalt amendment can thus result from an increase in rhizosphere respiration and/or SOM decomposition. Although only aboveground biomass was measured, the tendency towards greater mustard aboveground biomass also suggest higher belowground carbon allocation and associated rhizosphere respiration.

Recent studies suggest that EW can affect soil organic carbon (SOC) stocks in both directions (Buss et al., 2024; Dietzen et al., 2018; Sokol et al. 2024; Yan et al., 2023). While secondary minerals formed after basalt weathering may stabilize SOC (Niron et al., 2024), SOM decomposition can also be stimulated by EW (Klemme et al., 2022). While pH is a known driver, (typically promoting decomposition when pH increases from 4 to 8 (Leifeld et al., 2008)) our control soils were already alkaline (**Table 2**), suggesting pH was not the driver of this effect here. Instead, increased SCE may be linked to weathering congruency, causing a "priming effect" as proposed by Fang et al. (2023). In essence, when weathering is congruent, minerals dissolve entirely into their constituent ions, while incongruent weathering produces both dissolved ions and secondary minerals. The "priming effect" in this context suggests that when weathering is more congruent, decomposition of SOM is higher, leading to quicker turnover of carbon and nutrients (= priming) in soils. Faunal activity can also affect SOM decomposition and recent experiments have shown that basalt may increase earthworm abundance and thereby stimulate SCE (Dupla et al., 2024; Vienne et al., 2024). In our experiment, we did not determine earthworm abundance and further research is needed to verify their potential contribution to EW impacts on soil organic carbon dynamics.

Increased SCE and SOM decomposition after basalt amendment however do not necessarily mean that basalt reduces SOC (Steinwidder et al., 2025). Higher plant productivity can simultaneously boost belowground carbon inputs, increase rhizosphere respiration, SOM decomposition and thus SCE and lead to increased SOC stocks if increased plant belowground C inputs compensate the increased SOM decomposition.

While biochar alone did not significantly affect SCE, we observed a significant interaction between biochar and basalt. Consistent with our hypothesis, the co-application of basalt and biochar resulted in lower SCE compared to basalt alone. However, we initially anticipated that biochar would reduce SCE by enhancing the inorganic CDR of basalt. This mechanism appears to have had only a minor effect, as extractable base cation levels (which can be charge balanced by HCO_3^-(Vienne et al., 2025)) remained unchanged. Therefore, inorganic carbon processes likely played a limited role in the observed SCE reduction. In addition, SCE generally primarily results from rhizosphere respiration and SOM decomposition (Weil & Brady, 2016). We have not measured rhizosphere respiration here, but increases in aboveground mustard biomass indicate that belowground C inputs and rhizosphere respiration may also have increased. Despite the indication for greater rhizosphere respiration in the co-application treatment, SCE decreased relative to the basalt-only treatment, suggesting that biochar suppressed SOM decomposition.

Mechanistically, biochar may suppress SOM decomposition by adsorbing free base cations and DOC, reducing weathering congruency and causing negative priming (Fang et al., 2023; Lu et al., 2014). This observation aligns with results from Anthony et al. (2025), who observed a SOC loss 3 years after amending with only basalt, while SOC increased in time when both basalt and compost were added as an amendment, and SOC even increased more when this basalt-compost mixture was supplemented with biochar. The only other study that investigated SCE with basalt-biochar co-application, Honvault et al. (2024), found however no synergistic effects of basalt and biochar on SCE. In conclusion, further research is needed to clarify when and how biochar may decrease SCE and SOM decomposition in EW systems. Given the recent studies that found increases in SOM decomposition after basalt amendment (Dietzen et al., 2018; Steinwidder et al., 2025; Vienne et al., 2024), biochar may be a valuable additive in EW that has the potential to mitigate the risk of SOC losses and improve the climate mitigation potential of terrestrial EW.

5 Conclusions

In this urban field experiment, basalt amendment did not increase soil inorganic carbon, nor did it raise base cations in carbonate fractions or base cations in a leachate test, indicating no detectable inorganic C sequestration over 550 days. The most plausible explanation for this unexpected finding is retention of released cations in secondary minerals or strongly bound pools not captured by the Tessier extractions. Interestingly, basalt amendment shifted Ni and Cr towards less bioavailable (reducible/oxidizable) soil fractions, and did not increase metal concentrations in plant biomass.

In contrast with basalt, biochar increased clover and mustard biomass and reduced plant uptake of several trace metals, which is consistent with expected agronomic and remediation co-benefits. Co-application of basalt and biochar did not show significant interaction effects, on weathering indicators, biomass, or plant metal uptake. The alkaline soil (pH ~8.2), coarse basalt particle size and high albite content and basaltic background, with abundant Fe-oxide sorption sites, may have constrained basalt effects and detectability of the weathering of the (relatively coarse) rock dust in our experiment. Responses may differ in more acidic soils, with finer basalt with a more reactive mineralogy, or with fewer Fe-oxide sinks. Experiments across soil pH, mineralogy and particle sizes are needed to further evaluate EW-driven inorganic C gains and any context-dependent synergies with biochar.

6 code and data availability

Code and data used in this manuscript are publicly available on the zenodo platform of Arthur Vienne: (https://zenodo.org/records/15001309).

7 Supplement link

The link to the supplement will be provided here.

8 Author contribution

JN and AV set up and conceptualized the experiment together. AV measured soil samples, conducted the data analysis and drafted the manuscript. JN measured SCE, plant biomass and plant trace metals. JR drafted the discussion on SCE and provided expertise on biochar. JN, JR, SFC, SV, RD all contributed to writing the manuscript. GL sourced the biochar and provided details on its production and composition.

9 Competing interests

At least one of the (co-)authors (Sara Vicca) is a member of the editorial board of Biogeosciences.

10 Acknowledgements

We thank Anne Cools, Steven Joosen and Anke De Boeck for their assistance with ICP-OES for sequential extraction samples; Queen's University Belfast Technical Support Staff for their aid in setting up the research plots and constructing gas collection chambers; Geoff Davis for undertaking XRD analysis; Dr Bakul Budhiraja for assistance with climate data collection; Dr Manus Carey for assistance with acid digestion and ICP-MS analysis of plant samples; and Northstone Materials for assistance with basalt procurement. An AI tool (Microsoft Copilot) was utilized to enhance the clarity, grammar, and phrasing of language in this manuscript.

11 Financial support

We also acknowledge support of the UPSURGE project, which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101003818. This research was also supported by the Research Foundation— Flanders (FWO) [1S06325N], the C-Farms project (S004023N) and an EPSRC PhD studentship. JN was funded by the EPSRC.

12 References

Almassy, D., & Maia, S. (2018). Urban Nature Atlas. Naturvation Project . https://una.city/

Al-Mur, B. A. (2020). Geochemical fractionation of heavy metals in sediments of the Red Sea, Saudi Arabia. *Oceanologia*, *62*(1), 31–44. https://doi.org/10.1016/j.oceano.2019.07.001

Amann, T., & Hartmann, J. (2019). Ideas and perspectives: Synergies from co-deployment of negative emission technologies. *Biogeosciences*, *16*(15), 2949–2960. https://doi.org/10.5194/bg-16-2949-2019

Anthony, T. L., Jones, A. R., & Silver, W. L. (2025). Supplementing Enhanced Weathering With Organic Amendments Accelerates the Net Climate Benefit of Soil Amendments in Rangeland Soils. *AGU Advances*, *6*(2). https://doi.org/10.1029/2024AV001480

Barałkiewicz, D., & Siepak, J. (1999). Chromium, Nickel and Cobalt in Environmental Samples and Existing Legal Norms. *Polish Journal of Environmental Studies*, *8*(4), 201–208.

Beerling, D. J., Epihov, D. Z., Kantola, I. B., Masters, M. D., Reershemius, T., Planavsky, N. J., & Reinhard, C. T. (2024). *Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits*. 1–10. https://doi.org/10.1073/pnas.

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J. F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9

Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., Bird, M., Kantzas, E., Taylor, L. L., Sarkar, B., Kelland, M., DeLucia, E., Kantola, I., Müller, C., Rau, G., & Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security /631/449 /706/1143 /704/47 /704/106 perspective. *Nature Plants*, *4*(3), 138–147. https://doi.org/10.1038/s41477-018-0108-y

Beesley, L., & Hardman, M. (2024). Social prescribing of urban agriculture : The importance of minimizing risks from soil contamination. *Cities*, *149*(December 2022), 104971. https://doi.org/10.1016/j.cities.2024.104971

Boito, L., Steinwidder, L., Rijnders, J., Berwouts, J., Janse, S., Niron, H., Roussard, J., Vienne, A., & Vicca, S. (2025). Enhanced Rock Weathering Altered Soil Organic Carbon Fluxes in a Plant Trial. *Global Change Biology*, *31*(8), 1–19. https://doi.org/10.1111/gcb.70373

Buss, W., Yeates, K., Rohling, E. J., & Borevitz, J. (2021). Enhancing natural cycles in agro-ecosystems to boost plant carbon capture and soil storage. *Oxford Open Climate Change*, *1*(1), 1–13. https://doi.org/10.1093/oxfclm/kgab006

CDR.FYI. (2025). *CDR.fyi*. https://www.cdr.fyi/

Chen, L., Li, W., & Xiao, Y. (2021). Biochar and nitrogen fertilizer increase Glomus synergism and abundance and promote Trifolium pratense growth while inhibiting pollutant accumulation. *Ecological Indicators*, *133*, 108377. https://doi.org/10.1016/j.ecolind.2021.108377

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016). *Nature-based Solutions to address global societal challenges*.

Cox, S. F., Chelliah, M. C. M., McKinley, J. M., Palmer, S., Ofterdinger, U., Young, M. E., Cave, M. R., & Wragg, J. (2013). The importance of solid-phase distribution on the oral bioaccessibility of Ni and Cr in soils overlying Palaeogene basalt lavas, Northern Ireland. *Environmental Geochemistry and Health*, *35*(5), 553–567. https://doi.org/10.1007/s10653-013-9539-6

Cox, S. F., Rollinson, G., & McKinley, J. M. (2017). Mineralogical characterisation to improve understanding of oral bioaccessibility of Cr and Ni in basaltic soils in Northern Ireland. *Journal of Geochemical Exploration*, *183*, 166–177. https://doi.org/10.1016/j.gexplo.2017.02.006

Dong, X., Singh, B. P., Li, G., Lin, Q., & Zhao, X. (2019). Biochar increased field soil inorganic carbon content five years after application. *Soil and Tillage Research*, *186*(January 2018), 36–41. https://doi.org/10.1016/j.still.2018.09.013

Dupla, X., Claustre, R., Bonvin, E., Graf, I., Le Bayon, R. C., & Grand, S. (2024). Let the dust settle: Impact of enhanced rock weathering on soil biological, physical, and geochemical fertility. *Science of the Total Environment*, *954*(September). https://doi.org/10.1016/j.scitotenv.2024.176297

Dupla, X., Möller, B., & Baveye, P. C. (2023). *Potential accumulation of toxic trace elements in soils during enhanced rock weathering*. *December 2022*, 1–14. https://doi.org/10.1111/ejss.13343

Farooqi, Z. U. R., Sabir, M., Zeeshan, N., Naveed, K., & Hussain, M. M. (2018). Enhancing Carbon Sequestration Using Organic Amendments and Agricultural Practices. *Carbon Capture, Utilization and Sequestration*, *September*. https://doi.org/10.5772/intechopen.79336

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. V., Wilcox, J., Del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6). https://doi.org/10.1088/1748-9326/aabf9f

Haque, F., Santos, R. M., & Chiang, Y. W. (2020a). CO2 sequestration by wollastonite-amended agricultural soils – An Ontario field study. *International Journal of Greenhouse Gas Control*, *97*(July 2019), 103017. https://doi.org/10.1016/j.ijggc.2020.103017

Haque, F., Santos, R. M., & Chiang, Y. W. (2020b). Optimizing Inorganic Carbon Sequestration and Crop Yield With Wollastonite Soil Amendment in a Microplot Study. *Frontiers in Plant Science*, *11*(July), 1–12. https://doi.org/10.3389/fpls.2020.01012

Haque, F., Santos, R. M., & Chiang, Y. W. (2021). *Urban Farming with Enhanced Rock Weathering As a Prospective Climate Stabilization Wedge*. 10–13. https://doi.org/10.1021/acs.est.1c04111

Honvault, N., Tiouchichine, M. L., Sauze, J., Piel, C., Landais, D., Devidal, S., Gritti, E., Bosch, D., & Milcu, A. (2024). Additive effects of basalt enhanced weathering and biochar co-application on carbon sequestration, soil nutrient status and plant performance in a mesocosm experiment. *Applied Geochemistry*, *169*(May). https://doi.org/10.1016/j.apgeochem.2024.106054

Iff, N., Renforth, P., & Pogge von Strandmann, P. A. E. (2024). The dissolution of olivine added to soil at 32°C: the fate of weathering products and its implications for enhanced weathering at different temperatures. *Frontiers in Climate*, *6*(April), 1–18. https://doi.org/10.3389/fclim.2024.1252210

IPCC. (2021). Summary for Policymakers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Kantola, I. B., Blanc-, E., Michael, B., Elliot, D. M., Marklein, A., Moore, C. E., Haden, A. Von, Bernacchi, C. J., Wolf, A., Epihov, D. Z., Beerling, D. J., & Delucia, E. H. (2023). *Improved net carbon budgets in the US Midwest through direct measured impacts of enhanced weathering*. *May*, 1–17. https://doi.org/10.1111/gcb.16903

Larkin, C. S., Andrews, M. G., Pearce, C. R., Yeong, K. L., Beerling, D. J., Bellamy, J., Benedick, S., Freckleton, R. P., Goring-harford, H., Sadekar, S., & James, R. H. (2022). *Quantification of CO removal in a large-scale enhanced weathering field trial on an oil palm plantation in Sabah , Malaysia*.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., & Paz-Ferreiro, J. (2013). Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. *Plant and Soil*, *373*(1–2), 583–594. https://doi.org/10.1007/s11104-013-1806-x

Mei, Y., Zhuang, S., & Wang, J. (2025). Adsorption of heavy metals by biochar in aqueous solution: A review. *Science of the Total Environment*, *968*(February), 178898. https://doi.org/10.1016/j.scitotenv.2025.178898

Meng, L., Wu, Y., Mu, M., Wang, Z., Chen, Z., Wang, L., Ma, Z., Cui, G., & Yin, X. (2023). Effects of different concentrations of biochar amendments and Pb toxicity on rhizosphere soil characteristics and bacterial community of red clover (Trifolium pretense L.). *Frontiers in Plant Science*, *14*(March), 1–13. https://doi.org/10.3389/fpls.2023.1112002

Niron, H., Vienne, A., Frings, P., Poetra, R., & Vicca, S. (2024). Exploring the synergy of enhanced weathering and Bacillus subtilis: A promising strategy for sustainable agriculture. *Global Change Biology*, *30*(9), 1–18. https://doi.org/10.1111/gcb.17511

Palandri, J. L., & Kharaka, Y. K. (2004). A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling. *USGS Open File Report*, *2004–1068*(December 2013), 71. http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA440035

Pescatore, A., Grassi, C., Rizzo, A. M., Orlandini, S., & Napoli, M. (2022). Effects of biochar on berseem clover (Trifolium alexandrinum, L.) growth and heavy metal (Cd, Cr, Cu, Ni, Pb, and Zn) accumulation. *Chemosphere*, *287*(P1), 131986. https://doi.org/10.1016/j.chemosphere.2021.131986

Power, I. M., Hatten, V. N. J., Guo, M., Rausis, K., & Klyn-hesselink, H. (2025). *Are enhanced rock weathering rates overestimated ? A few geochemical and mineralogical pitfalls*. *January*, 1–9. https://doi.org/10.3389/fclim.2024.1510747

Rijnders, J., Vienne, A., & Vicca, S. (2024). *Effects of basalt , concrete fines , and steel slag on maize growth and heavy metal accumulation in an enhanced weathering experiment*. *October*, 1–34.

Rogelj, J., Shindell, D., Jiang, K., & Fifita, S. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. *Global Warming of 1.5°C. An IPCC Special Report [...]*, 2.

Sanei, H., Rudra, A., Zia, M., Kousted, S., Sindlev, B., Zheng, X., Nielsen, B., & Ingermann, H. (2024). *International Journal of Coal Geology Assessing biochar ' s permanence : An inertinite benchmark*. *281*(November 2023). https://doi.org/10.1016/j.coal.2023.104409

Silva Gonzaga, M. I., Oliveira da Silva, P. S., Carlos de Jesus Santos, J., & Ganassali de Oliveira Junior, L. F. (2019). Biochar increases plant water use efficiency and biomass production while reducing Cu concentration in Brassica juncea L. in a Cu-contaminated soil. *Ecotoxicology and Environmental Safety*, *183*(April), 109557. https://doi.org/10.1016/j.ecoenv.2019.109557

Steinwidder, L., Boito, L., Frings, P., Niron, H., Rijnders, J., De Schutter, A., Vienne, A., & Vicca, S. (2025). Beyond inorganic carbon : Soil organic carbon as key pathway for carbon sequestration in Enhanced Weathering. *Global Change Biology (in Press.)*.

Sun, S. S., Ao, M., Geng, K. R., Chen, J. Q., Deng, T. H. B., Li, J. J., Guan, Z. T., Mo, B. L., Liu, T., Yang, W. J., Tang, Y. T., & Qiu, R. L. (2022). Enrichment and speciation of chromium during basalt weathering: Insights from variably weathered profiles in the Leizhou Peninsula, South China. *Science of the Total Environment*, *822*, 153304. https://doi.org/10.1016/j.scitotenv.2022.153304

Taylor, L., Driscoll, C., Groffman, P., Rau, G., Blum, J., & Beerling, D. (2021). Increased carbon capture by a silicate-treated forested watershed affected by acid deposition. *Biogeosciences Discussions*, 1–29. https://doi.org/10.5194/bg-2020-288

Tessier, A., Campbell, P. G. C., & Bisson, M. (1979). Sequential Extraction Procedure for the Speciation of Particulate Trace Metals. *Analytical Chemistry*, *51*(7), 844–851. https://doi.org/10.1021/ac50043a017

Van Bemmelen, J. (1890). Über Die Bestimmung Des Wassers, Des Humus, Des Schwefels, Der in Den Colloïdalen Silikaten Gebundenen Kieselsäure, Des Mangans U. S. W. Im Ackerboden. *Die Landwirthschaftlichen Versuchs-Stationen*, *37*, 279–290.

van Raffe, F., Comans, R. N. J., & Groenenberg, J. E. (2025). Chromium(III) Binding to Purified Fulvic and Humic Acids and Their Solid-Solution Partitioning and Speciation in Soil. *ACS Earth and Space Chemistry*, *Iii*. https://doi.org/10.1021/acsearthspacechem.5c00075

Vienne, A. (2025). Weathering without inorganic CDR revealed through cation tracing. *EGU Soils*, *7*(November), 2588–2593.

Viotti, P., Marzeddu, S., Antonucci, A., Décima, M. A., Lovascio, P., Tatti, F., & Boni, M. R. (2024). Biochar as Alternative Material for Heavy Metal Adsorption from Groundwaters: Lab-Scale (Column) Experiment Review. *Materials*, *17*(4), 1–53. https://doi.org/10.3390/ma17040809

Wang, Q., Wang, B., Ma, Y., Zhang, X., Lyu, W., & Chen, M. (2022). Stabilization of heavy metals in biochar derived from plants in antimony mining area and its environmental implications. *Environmental Pollution*, *300*(January), 118902. https://doi.org/10.1016/j.envpol.2022.118902

Xu, Y., Axe, L., Boonfueng, T., Tyson, T. A., Trivedi, P., & Pandya, K. (2007). Ni(II) complexation to amorphous hydrous ferric oxide: An X-ray absorption spectroscopy study. *Journal of Colloid and Interface Science*, *314*(1), 10–17. https://doi.org/10.1016/j.jcis.2007.05.037

Yusuf, M., Fariduddin, Q., Hayat, S., & Ahmad, A. (2011). Nickel: An overview of uptake, essentiality and toxicity in plants. *Bulletin of Environmental Contamination and Toxicology*, *86*(1), 1–17. https://doi.org/10.1007/s00128-010-0171-1

Zang, Y., Wang, M., Shohag, M. J. I., Lu, L., He, T., Liao, C., Zhang, Z., Chen, J., You, X., Zhao, Y., Wei, Y., & Tian, S. (2023). Biochar performance for preventing cadmium and arsenic accumulation, and the health risks associated with mustard (Brassica juncea) grown in co-contaminated soils. *Ecotoxicology and Environmental Safety*, *263*(July), 115216. https://doi.org/10.1016/j.ecoenv.2023.115216

Zhou, R., Zhang, M., & Shao, S. (2022). Optimization of target biochar for the adsorption of target heavy metal ion. *Scientific Reports*, *12*(1), 1–17. https://doi.org/10.1038/s41598-022-17901-w