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

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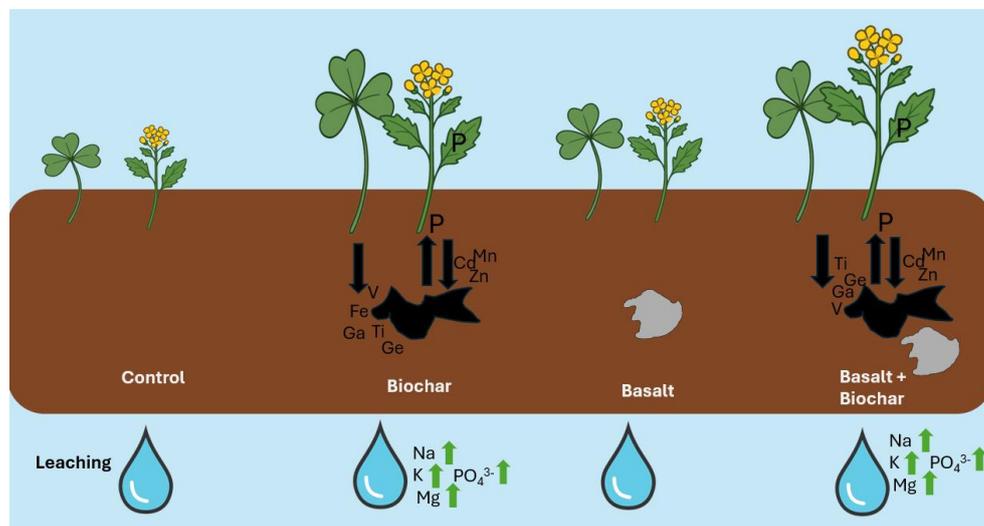
15   **Abstract.** Enhanced weathering (EW) and biochar amendment are proposed carbon dioxide removal (CDR) techniques with potential co-benefits for soil health and plant productivity. However, knowledge gaps remain regarding their impacts on soil carbon dynamics and heavy metal mobility. This study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

20   Basalt addition did not increase soil inorganic carbon, Tessier-extractable base cations, or dissolved inorganic carbon (DIC) in leachates, indicating no detectable inorganic C sequestration during this experiment. Weathering of the relatively coarse, albite-rich basalt may have been limited in the alkaline soil and/or the weathering products were retained in soil pools not accessible to the extraction scheme. Basalt increased Ni and Cr in the reducible soil fraction but did not elevate plant metal concentrations and even tended to reduce Ni and Zn in leachates. Biochar increased plant biomass, mustard phosphorus and

25   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 or reductions in plant heavy metals were observed after co-amendment in this alkaline soil. Overall, our findings suggest that in this alkaline urban soil, basalt weathering was limited and provided few immediate co-benefits, whereas biochar showed clearer advantages for plant growth and metal immobilization.

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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

35   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).

40   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

45   quality and C content (Buss et al., 2021; Farooqi et al., 2018; Taylor et al., 2021).

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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 CO_2 removal 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, potential contamination of the food chain by heavy metals may be a concern, as basalt dust contains 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.

Synergies between both EW and biochar have been postulated; Biochar has been 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. Biochar-induced hydrological changes may also enhance weathering. In sandy soils (like will be used in our study, see further) increased water-holding capacity could prolong water–mineral contact and thus promote weathering (Vorrath et al., 2025). This way, sorption of base cations by biochar may increase 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.

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 heavy metal contamination.

In an urban agricultural field experiment, we tested whether co-applying basalt and biochar in urban plots yields synergies for enhanced weathering, inorganic CO_2 removal, and reduced plant metal uptake. To investigate weathering and inorganic C

sequestration, we monitored base cations (in different soil pools and in leachates) and weathering products in soil 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*). We hypothesize that biochar would enhance basalt weathering, while simultaneously mitigating trace metal accumulation in plants through sorption into low-bioavailability biochar fractions.

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 (BBio) and biochar only (Bio) 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 in other studies (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

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were installed at each plot, and SWC and temperature at a depth of -6cm, +2cm, and +15cm were monitored. Clover plots were seeded with *Trifolium pratense* at 4.5 g/m², while Mustard plots were seeded with *Brassica juncea* at 2.0 g/m². 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. To produce

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115 this digestate, 20m^3 of dairy cattle slurry and 4t of perennial ryegrass silage were fed daily to a continuously stirred tank reactor anaerobic digestion facility consisting of a 650 m³ main digestion tank, heated to 39°C, with a hydraulic retention time of 28 days for biogas production. Biochar was produced from mechanically separated (Screw Press) anaerobic digestate solid fraction. 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

120 of the digestate Biochar was undertaken by a commercial accredited laboratory (Eurofins Umwelt Gmbh, Germany) (**Table 1**). The dry biochar had a H/Corg ratio of 0.11 and an O/C molar ratio of 0.011. The utilized slurry / silage mix resulted in a biochar relatively low in C but high in minerals; Both the digestate and resulting biochar were therefore already nutrient-loaded and would supply nutrients to the soil rather than removing them, reducing the need for additional biochar nutrient charging.

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 The studied soil was an alkaline soil (pH=8.22±0.5) with a SOC content of 3.70±0.22 (**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

130 (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.

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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

140 minerals such as CaCO₃, 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$_2$OH.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$_2$O$_2$ solutions. Tessier's

145 sequential extractions were also used in recent EW studies (Boito et al., 2025; Niron et al., 2024; Steinwidder et al., 2025; Vienne et al., 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$_2$O: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,

150 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.

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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/m³	Al_2O_3	14.7%w/w
Specific surface (BET)	463.68 m²/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 clover. In this protocol, we leach 1 kopecky ring of soil (5 cm height, 5 cm 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

190   field site over 81 days (estimate based on open source weather data).

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

195   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

200   mg L^{-1} to µg element g^{-1} soil.

Table 2: Background soil characteristics.

Texture (clay: silt: sand %)*	Loamy sand (0.07: 20.82: 79.13)				
Property	**Unit**	*Max*	*Min*	*Median*	*Mean + - standard deviation*
pH		9.00	7	8.4	8.22±0.5
SOM**	%				6.38±0.38
SOC**	%				3.70±0.22
Exchangeable bases ***	mEq/100g				7.72±0.47
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

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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.**SOM was measured at day 0 in the control soils of clover plots and a SOC/SOM ratio of 0.58 was assumed (Van Bemmelen, 1890). *** measured at day 0 in the control soils of clover plots.

2.6 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. Plant elemental concentrations were determined in the first crop harvest, six months after sowing. The growing period for elemental biomass analysis was thus November 2023-May 2024 for mustard and summer harvest May 2023-November 2023 for clover. Plants were 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 Data analysis

For measurements that were not repeated in time (i.e., plant elemental concentrations, heavy metal sequential extractions and 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 (biomass, LOI, base cation 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. Although weathering dynamics may initially show an exponential behavior, a linear model is more appropriate for our dataset with low temporal resolution. The mixed linear model was fitted 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. If the interaction effects (biochar x basalt, basalt x time or biochar x time) were not statistically significant, a new model without the non-significant interaction effect was applied. All analyses were executed in R studio (R-4.0.5) and a significance threshold of 0.05 was used.

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230 **3 Results**

3.1 Soil base cations and trace metals

Basalt significantly increased soil exchangeable Ca (+12%) and reducible Mg (+91%) (**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
235 found) (**Figure 3**). Hence, basalt did also not increase carbonate cations and SIC in time.

Biochar significantly increased base cations in the exchangeable pool (+320% , +674% , +31% 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%, 184%, 103% and 110% for K, Na, Ca and Mg
240 respectively, **Table S3**). Again for Na, this increase significantly decreased with time (**Table S3**). 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. Exchangeable Al was the only parameter for which a basalt x
245 biochar interaction effect was observed (**Table S3**); Exchangeable Al increased after co-application of basalt and biochar (+232%, **Table S3**). Basalt amendment significantly decreased 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 treatment, however significantly decreased in time (**Fig. S8, Table S3**), potentially indicating formation of more
250 crystalline secondary minerals, unextractable with the Tessier scheme.

For soil trace metals, we found that basalt significantly increased reducible Ni and Cr (+62% and +45% respectively, **Table S2, Figure 4**) and oxidizable Ni (+18%, **Table S2, Figure 4**), while biochar decreased exchangeable Ni (-41%, **Table S2, Figure 4**). We found no statistically significant basalt x biochar interaction effects for Ni or Cr. No significant effects of basalt,
255 biochar or their interaction were found for Cu, Zn and Pb in any of the soil fractions (**Table S2**).

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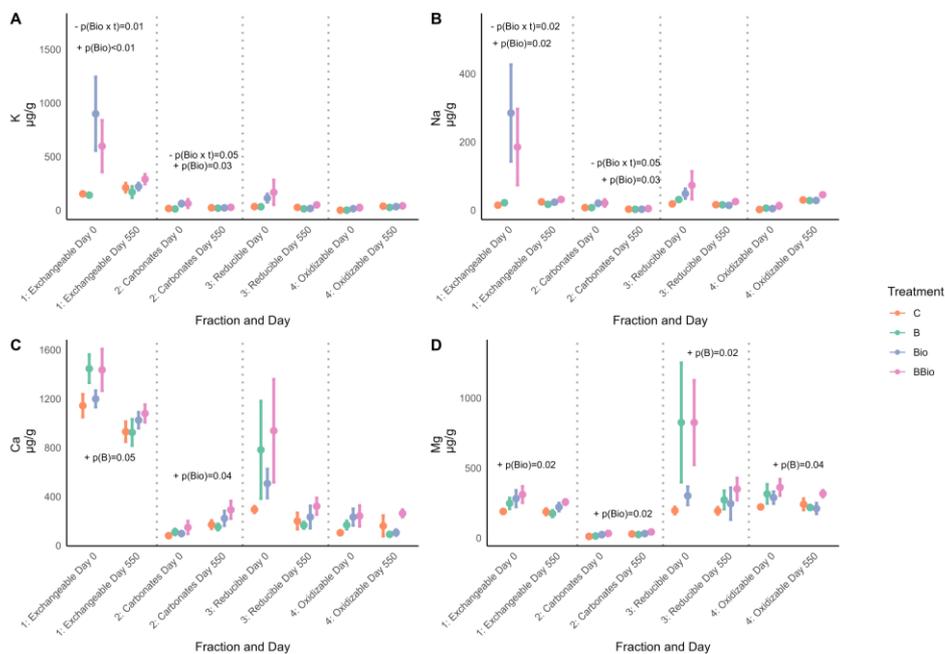
265 **Figure 3:** (A) K, (B) Na, (C) Ca and (D) Mg in µg element/g soil for different soil fractions in clover plots for different sampling times (initial = directly after amendment and last = after 550 days). Dots and error bars represent averages and standard errors. P values for basalt, biochar and time effects (p(B), p(Bio), p(t) respectively) are annotated on the plots. Significant positive and negative effects are indicated with a + and – respectively. A vertical dotted line is plotted in between different soil fractions.

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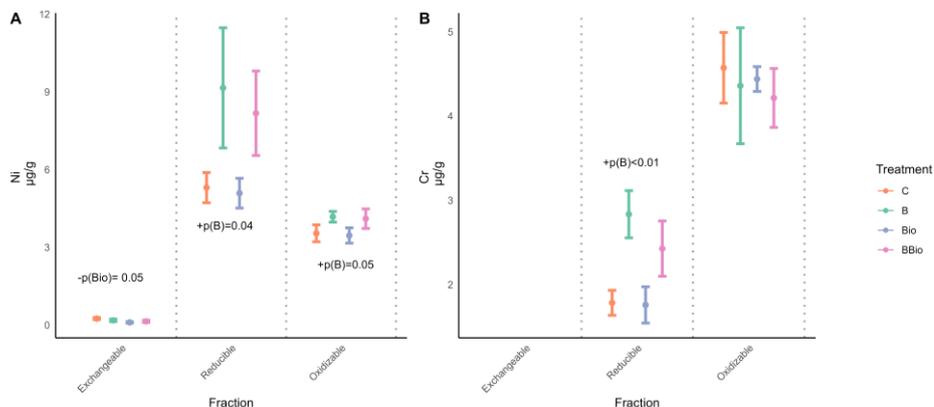
Figure 4: Ni and Cr in the 4 different considered soil fractions. These soil elements were extracted after initial soil sampling in clover plots. P(B) and p(Bio) are p values for basalt and biochar, respectively. Carbonate-Ni, carbonate-Cr and exchangeable Cr were below detection limits and are not shown in this plot. Significant positive and negative effects are indicated with a + and – respectively. A vertical dotted line is plotted in between different soil fractions.

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 5H**) and Zn (p=0.08,-35%, **Figure 5I**). 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 5A,B,C,K**). These increases were also reflected in a significant rise in 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**).
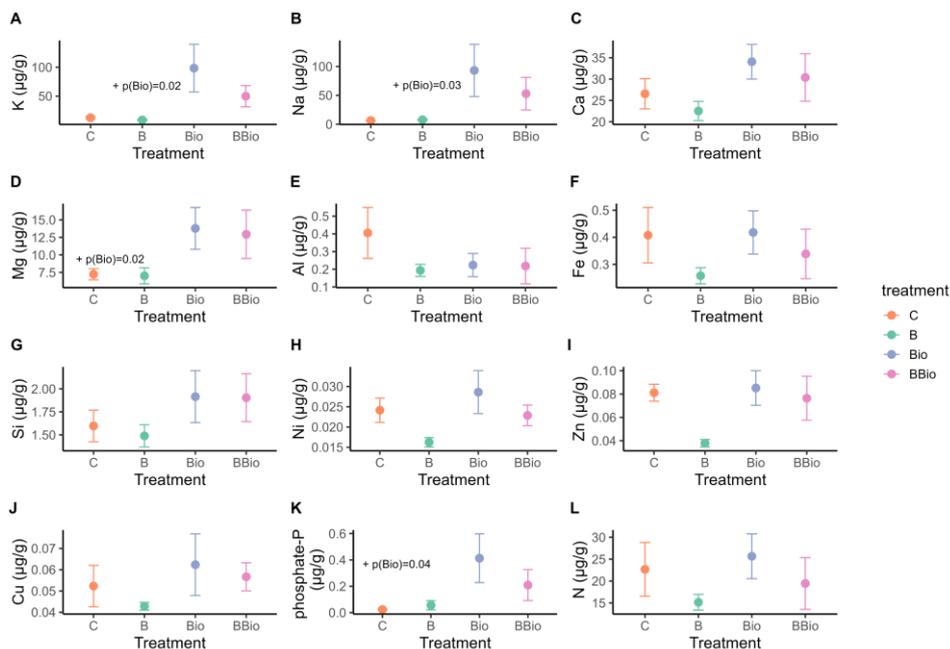
Figure 5: Results from the soil leaching test for samples taken instantly after basalt and biochar amendments. Dots and error bars represent averages and standard errors of the mean. P(B) and p(Bio) are p values for basalt and biochar, respectively. Significant positive and negative effects are indicated with a + and – respectively.

3.3 Plant biomass

Basalt amendment did not significantly influence clover or mustard 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**). While clover yield significantly decreased in time, mustard yield increased marginally, yet significantly in time.

3.4 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** and **Supplementary Figures 1-6**), neither for clover, nor for mustard plants. In clover plants, Ti, V, Fe, Ga and Ge significantly decreased after biochar amendment (with -

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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.

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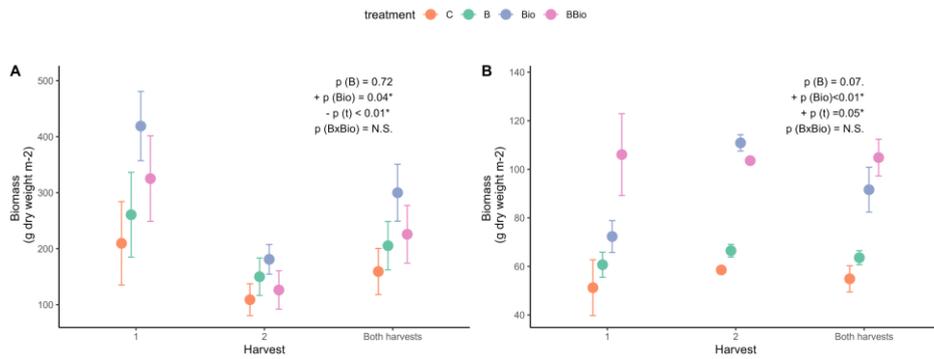
Figure 6: Aboveground dry biomass in function of time after amendment for (A) clover and (B) mustard plots. "N.S." = Not significant, this is indicated when the interaction effect was tested for but was not statistically significant. p(B), p(Bio), p(t) and p(BxBio) represent p values of basalt, biochar, time and basalt x biochar effects. Dots and error bars represent mean
310 biomass +- the standard error of the mean. Significant positive and negative effects are indicated with a + and – respectively.
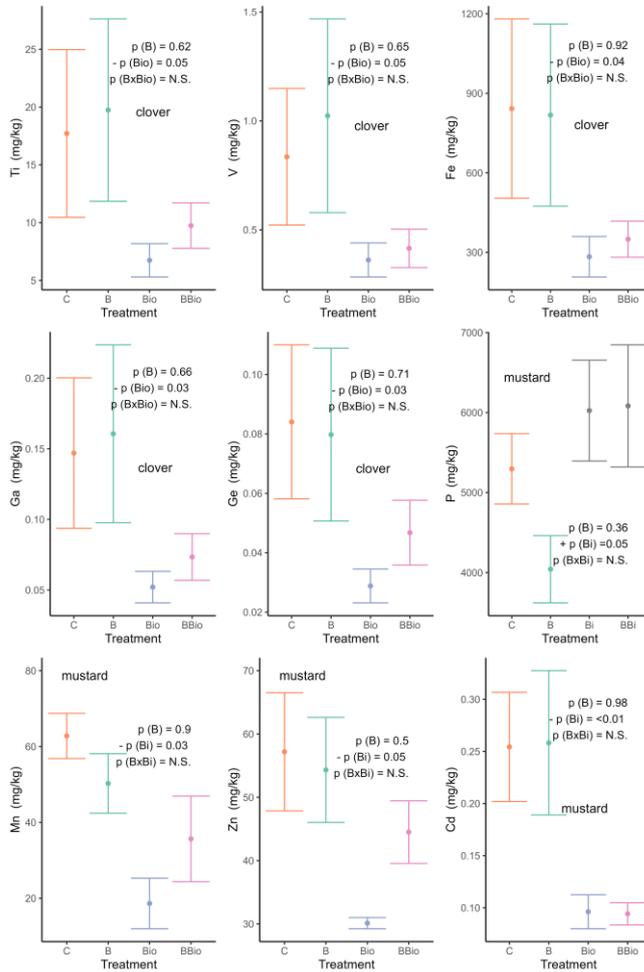
Figure 7: Elements in clover or mustard plants for different treatments. Error bars represent averages +- standard errors. Only elements with significant changes are shown here. For all plant (trace) elements, we refer to **Supplementary Figure 1-6**. Significant positive and negative effects are indicated with a + and – respectively. P(B), p(Bio) and p(BxBio) are p values for basalt and biochar, and their interaction, respectively. N.S. = Not significant.

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 did not increase in time. We also 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. The lack of an increase in base cations in the carbonate fraction indicates that soil carbonates or SIC did not increase. The absence of accumulation of base cations topsoil

325 over time can indicate that positively charged base cations, along with negatively charged bicarbonate, leached into deeper soil layers. Nonetheless, the leaching test with topsoil samples showed no increase in leaching of base cations or DIC.

Hence, the absence of an accumulation of base cations in any of the four extracted soil pools as well as in the leachates implies either no detectable basalt weathering within 550 days or –redistribution of released base cations such as Ca into secondary

330 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 $\sim 10^{-12}$ mol/m²/s at pH 8). Nonetheless, there was also 6% olivine present in the rock feedstock, for which we expect a theoretical weathering rate

335 of $\sim 10^{-10}$ 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 (Pogge von Strandmann et al., 2025). 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

340 resistant to extraction (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).

345 Importantly, basalt application did not increase concentrations of trace metals in the most bio-available soil pool, i.e., the exchangeable pool, and even decreased Zn and Ni leaching in our leaching test. On the other hand 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 SOM, while Cr increases were confined to the reducible pool. The tendency for lower Ni

350 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).

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
355 scavengers (Sun et al., 2022). Acidity and organic acids can however promote leaching of these Fe-Cr-oxides. In natural basaltic soils in Northern Ireland (soils overlying the Antrim basalts, similar to the basalt used in this study), the availability of Cr in the soil was however extremely low due to the high stability of Cr bound to Fe-oxides (Cox et al., 2013, 2017). 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
360 Cr and its ability to react with organic ligands increases its mobility (Barałkiewicz & Siepak, 1999). The higher accumulation of Ni in the oxidizable fraction following basalt addition thus likely reflects this affinity for organic complexes, while Cr remained predominantly in the reducible fraction indicative of its immobilization in Fe-Cr-oxides. These distributions indicate that the added metals were largely sequestered in more stable pools, reducing their immediate bioavailability to plants.

365 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, contains carbonate minerals and promotes the formation of SIC (Amann & Hartmann, 2019; Dong et al., 2019; Vorrath et al., 2025). 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
370 biochar in our sequential extractions was Ni, which significantly decreased in the exchangeable soil fraction.

We hypothesized that biochar would increase basalt weathering through retention of base cations in the exchangeable pool or through increased $_{water}$–mineral contact (yet we did not observe a significant biochar effect on soil moisture, Fig. S10). In contrast with our hypothesis there were no synergistic basalt x biochar interaction effects for any of the base cations, neither
375 in the soil fractions, nor in the 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 in agreement with Honvault et al. (2024), this suggests that the effects of basalt and biochar on soil base cations are additive rather than synergistic (Honvault et al., 2024).
380 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 a more reactive pyroxene mineralogy, with only 18% of relatively slower dissolving albite. Nonetheless, the synergy on weathering was also absent in the study by Honvault et al., (2024). Besides the latter study, we are not aware of other studies with full factorial basalt x biochar designs that investigated

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the fate of weathering products in the soil, so more research is needed to confirm this finding. In addition, more research should be done to assess how co-pyrolysis of basalt and biochar (Vorrath et al., 2025) influences inorganic CO_2 removal and weathering products in the soil.

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 did 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-amended soil leachates significantly increased. For clover, there was an inverse correlation between aboveground biomass Li, Co, V, Ge and Fe and aboveground biomass. We expect that lower amounts of toxic trace metals were taken up by clover in the biochar treatments. 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. Mustard yield was higher in the combined basalt + biochar treatment than in the single-amendment treatments in the first harvest, but this difference was not observed in the second harvest. Because overall yield levels did not differ between harvests, a general seasonal effect appears unlikely. The mechanism underlying this transient response in the combined treatment remains unclear.

The positive effect of biochar on clover 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 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). 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

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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}) to a soil with a pH (in H$_2$O) of ~6 (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 biochar decreased trace metals, in particular Mn, Zn and Cd. This is in line with Zang et al. (2023) who found decreased Cd in mustard post biochar amendment. Similarly, Gonzaga et al. (2019), observed decreases in plant Cu with mustard after biochar amendment. Biochar can reduce plant metal uptake through increasing pH. Biochar is typically alkaline (our biochar had a pH of 10.47) and can thus immobilize metals 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. (2024) 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.

4.4 Limitations

This study sampled only the 0–5 cm soil layer and measured cations at two time points (day 0 and day 550), with leaching tests performed solely at day 550. Such a restricted temporal and vertical sampling scheme may have limited detection of treatment effects, as dissolved elements could have percolated below the sampled layer over the course of the experiment. Future studies incorporating deeper soil horizons and more frequent measurements would provide a more robust assessment of treatment-induced changes in soil cation dynamics.

Last, the absence of observation of significant changes in SOC (**Fig. S11**) may result from the relatively short experimental duration of this study. Monitoring soil CO$_2$ efflux (SCE) can help overcome the difficulty of detecting short-term changes in

SOC caused by spatial heterogeneity(Vienne et al., 2024). However, to draw mechanistic conclusions about SOC dynamics in planted soils, SCE measurements must be partitioned into SOM–derived respiration and rhizosphere respiration, which requires a specific experimental set-up.(Boito et al., 2025).

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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 in leachates during a lab test, indicating no detectable inorganic C sequestration over 550 days. The

460 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 did increase clover and mustard biomass and reduced plant uptake of several trace metals,

465 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 may have constrained basalt effects and detectability of the weathering in our experiment. Responses may differ in more acidic soils, with finer basalt and a more reactive mineralogy. Experiments across a range of soil pH, mineralogy and rock particle size are needed to further evaluate EW-driven inorganic C gains and any

470 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).

475 ## 7 Supplement link

The link to the supplement will be provided here.

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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 measuredplant biomass and plant trace metals. JR assisted in drafting the discussion 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

11 Financial support

12 References

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