



Increased soil CO₂ emissions after basalt amendment were partly offset by biochar addition in an urban field experiment.

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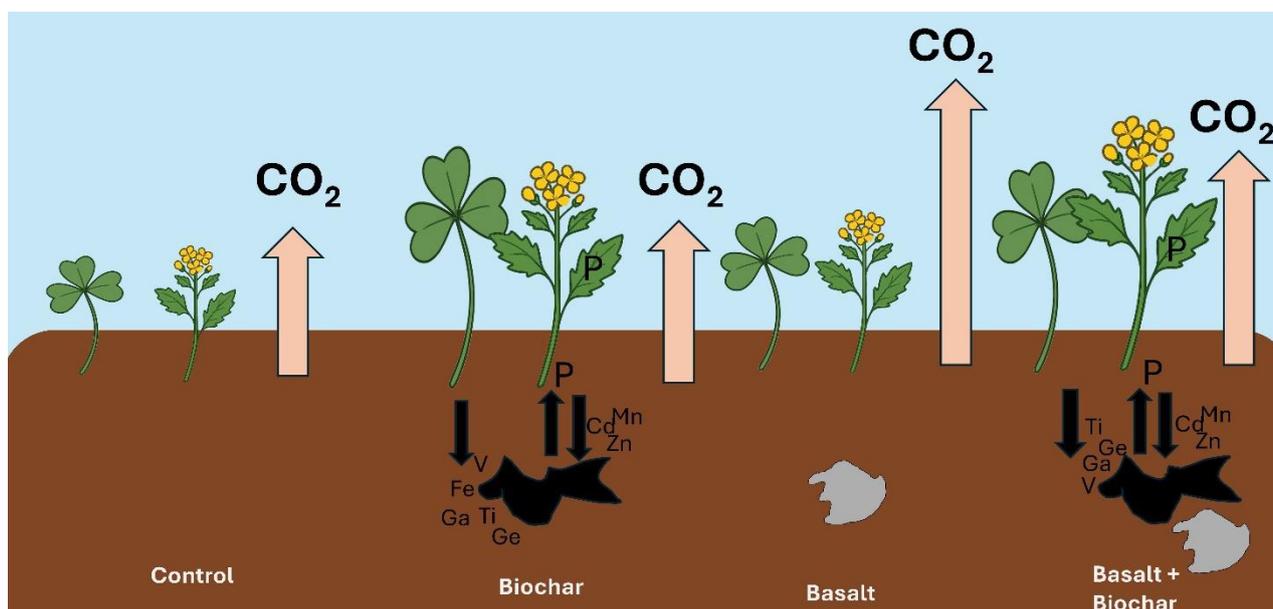
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10 Graphical abstract



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 CO₂ efflux (SCE), soil base cation dynamics, biomass yield and heavy metal uptake in clover (*Trifolium pratense*) and mustard (*Brassica juncea*) field plots. Despite potential CO₂ uptake through weathering, we found that basalt increased SCE in both crops, suggesting increases in soil organic matter (SOM) decomposition and/or rhizosphere respiration. Biochar enhanced plant biomass and reduced plant uptake of several trace metals in both mustard and clover plants, while basalt did not affect

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any of the 33 assessed elements in aboveground plant biomass. While basalt alone increased CO₂ efflux, co-application with
20 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 CO₂ 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 (CO₂)
25 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
30 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
35 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 CO₂ removal and potential co-benefits for soil health and nutrient dynamics (Beerling
40 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 CO₂ 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. 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
45 by EW (Klemme et al., 2022; Sokol et al., 2024; Steinwider 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).

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55 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).

60 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.

65 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, 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 provide as a risk mitigation technique for heavy metal contamination.

75 In this study, we therefore explore potential synergies of co-applying basalt and biochar in an urban agricultural setting. We assess soil CO₂ 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

80 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 heterogeneous 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.

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90 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. Biochar was added at an application rate of 33 t ha⁻¹. 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.

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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, 100 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 105 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 ($\text{pH}=8.22\pm 0.5$) with a SOC content of 6.38 ± 4.74 (**Table 2**).

2.3 Soil sampling and measurements

110 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
115 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-,
120 (hydr)oxide- and SOM-associated fractions. 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
125 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 and basalt characteristics of the experimental site in Belfast. Basalt particle size distribution can be found in Supplementary Table 4.



	Biochar characteristics		Basalt characteristics	
135	Feedstock	Digestate	Na ₂ O	2.11%w/w
	pH		MgO	4.82%w/w
	(1g:2.5mL H ₂ O)	10.47	Al ₂ O ₃	14.7%w/w
	Bulk Density	475 kg/m ³	SiO ₂	55.52%w/w
	Specific surface		P ₂ O ₅	0.17%w/w
	(BET)	463.68 m ² /g	SO ₃	0.17%w/w
140	Ash content	42.3%w/w	K ₂ O	2.81%w/w
	Total carbon	55.4%w/w	CaO	3.01%w/w
	Organic carbon	54.9%w/w	TiO ₂	0.74%w/w
	Total nitrogen	11.1 g/kg	Mn ₂ O ₃	0.11%w/w
	Na ₂ O	21.8 g/kg	Fe ₂ O ₃	6.69%w/w
	MgO	28.2 g/kg	BaO	0.05%w/w
	SiO ₂	158 g/kg	Loss on Ignition	8.5%w/w
145	P ₂ O ₅	40.6 g/kg	Albite	62.1%w/w
	SO ₃	14.4 g/kg	Pyroxene	31.4%w/w
	K ₂ O	41.6 g/kg	Olivine	6.2%w/w
	CaO	69.9 g/kg	Montmorillonite	1.2%w/w
	Fe ₂ O ₃	11.7 g/kg		
150				

2.4 Soil CO₂ flux and temperature and moisture measurements

Soil CO₂ efflux (SCE) was measured in the center of each plot using the WMA-4 portable CO₂ 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 CO₂ 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. Permanent TOMST
 160 temperature and soil water content (SWC) sensors were installed at each plot, and SWC and temperature at a depth of -6cm,
 +2cm, and +15cm from the soil surface were recorded at the time of SCE measurement.

Table 2: Background soil characteristics.

Texture type		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

2.5 Plant measurements

165 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
 170 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.

2.6 Data analysis

For measurements that were repeated in time (SCE, LOI and elemental soil data from sequential extractions), 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. 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

Basalt significantly increased soil exchangeable Ca, reducible Mg and oxidizable Na (**Figure 3**). This increase, however, decreased in time. We did not observe significant increases of extracted base cations in time after amendment in any of the four soil pools (**Figure 3**). Hence, basalt did not increase carbonate cations or SIC in time. Biochar increased exchangeable bases (Na, K and Mg) and also increased Ca, K and Na in the carbonate soil fraction. We found no significant basalt x biochar interaction effects.

For soil trace metals, we found that basalt significantly increased reducible Ni and Cr and oxidizable Ni, while biochar decreased exchangeable Ni. 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**).

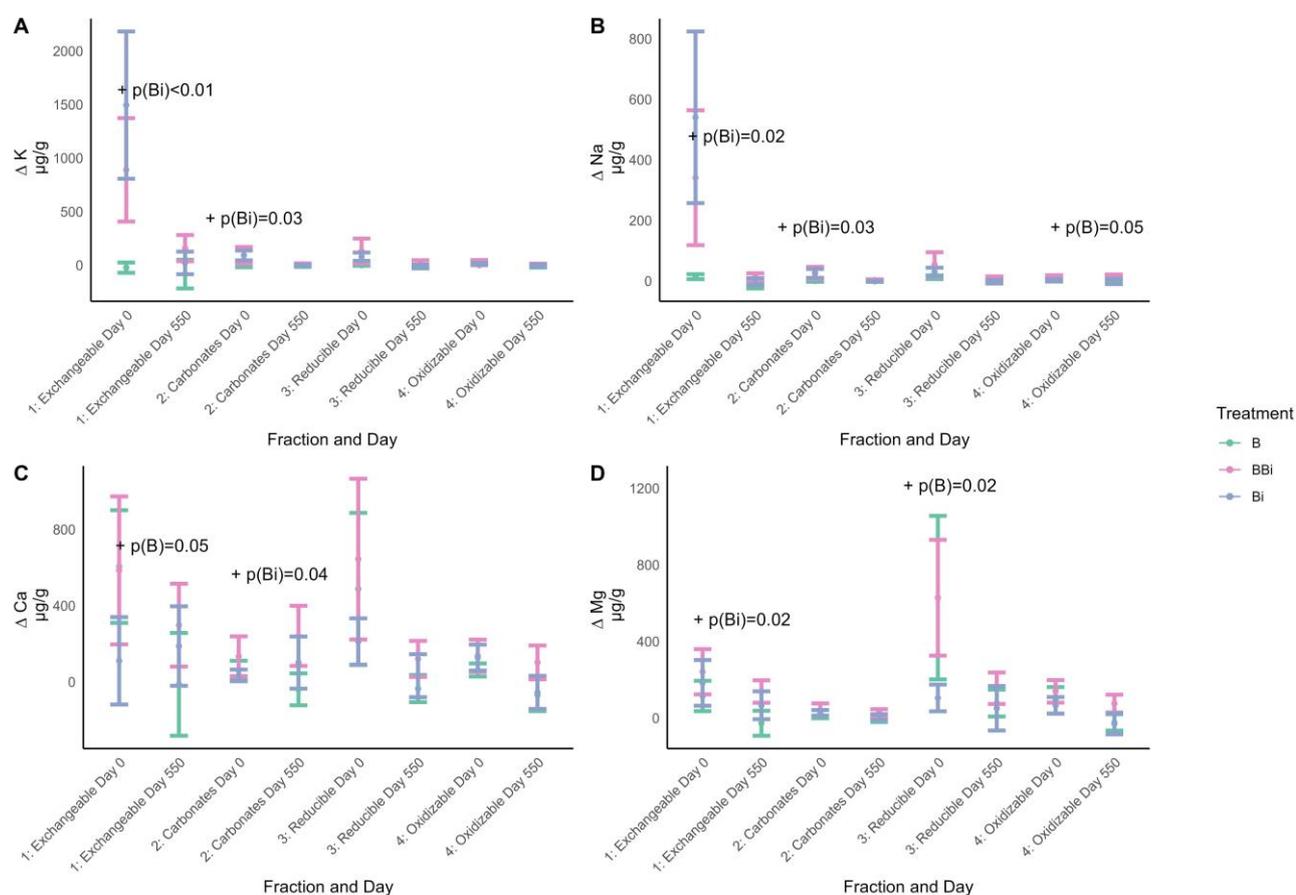


Figure 3: Changes in (A) K, (B) Na, (C) Ca and (D) Mg in μg element/g soil for different soil fractions in clover plots, 205 relative to control soil for different sampling times (initial = directly after amendment and last = after 550 days). Dots and error bars represent averages and standard errors. P values for basalt and biochar effects ($p(B)$ and $p(Bi)$) are annotated on the plots.

3.2 Plant biomass

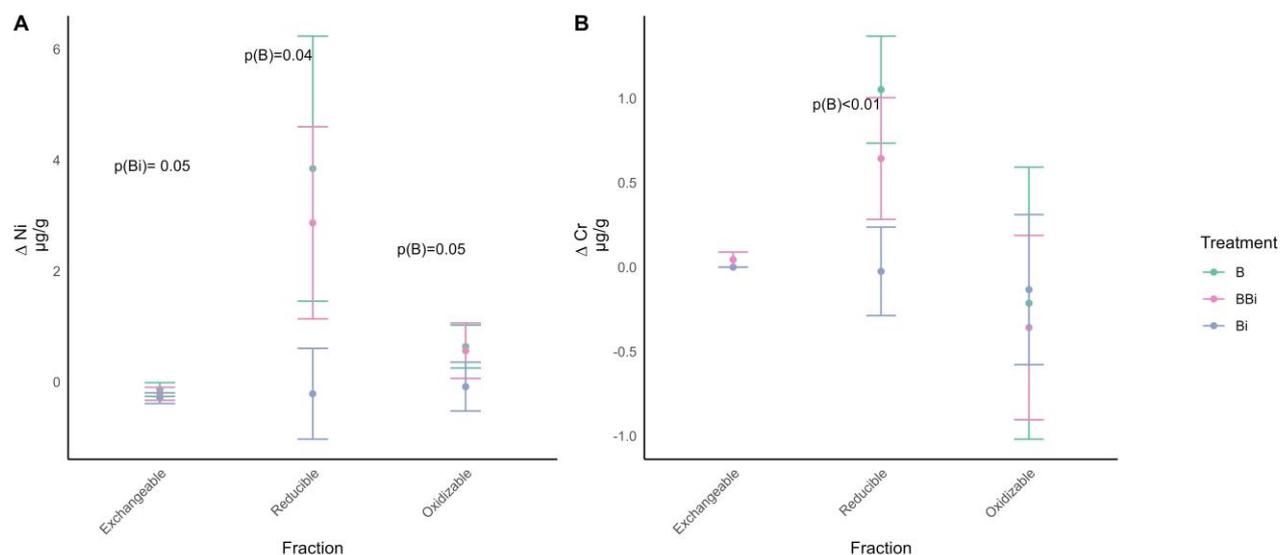
Basalt amendment did not significantly influence clover or mustard yield, although a tendency towards higher biomass 210 ($p=0.07$) was observed for mustard. Biochar did significantly increase biomass of both crops. No significant basalt x biochar interaction effects on biomass were observed (**Figure 5**). While clover yield significantly decreased in time, mustard yield increased slightly, yet significantly in time.

3.3 Plant Trace metals

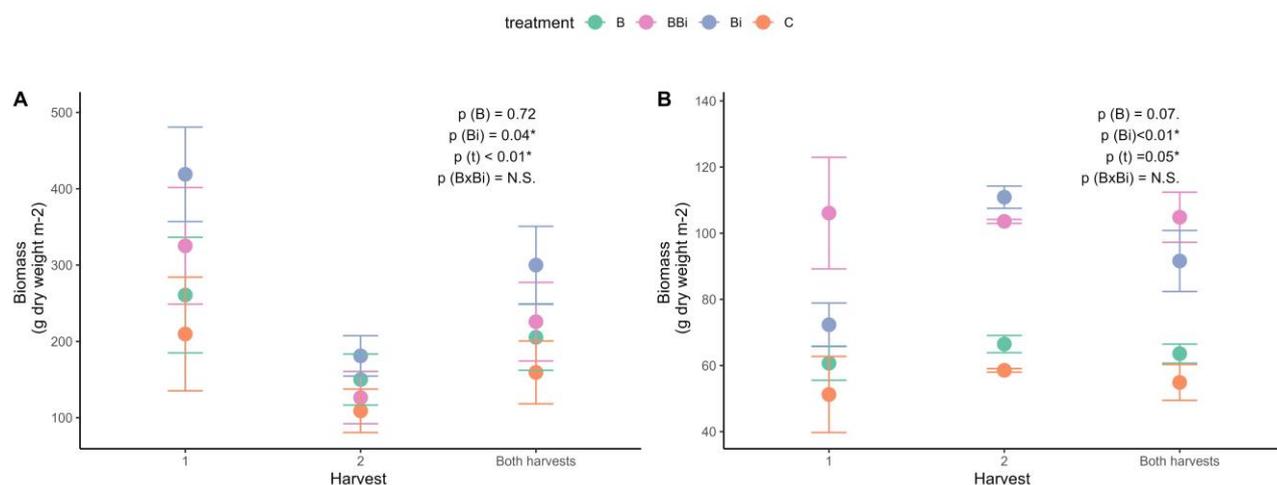
While basalt significantly increased reducible Ni and Cr in soils (**Figure 4**), we did not observe increases for these elements 215 and any of the other 33 assessed elements in aboveground biomass (**Figure 6** and **Supplementary Figures 1-6**) for both clover



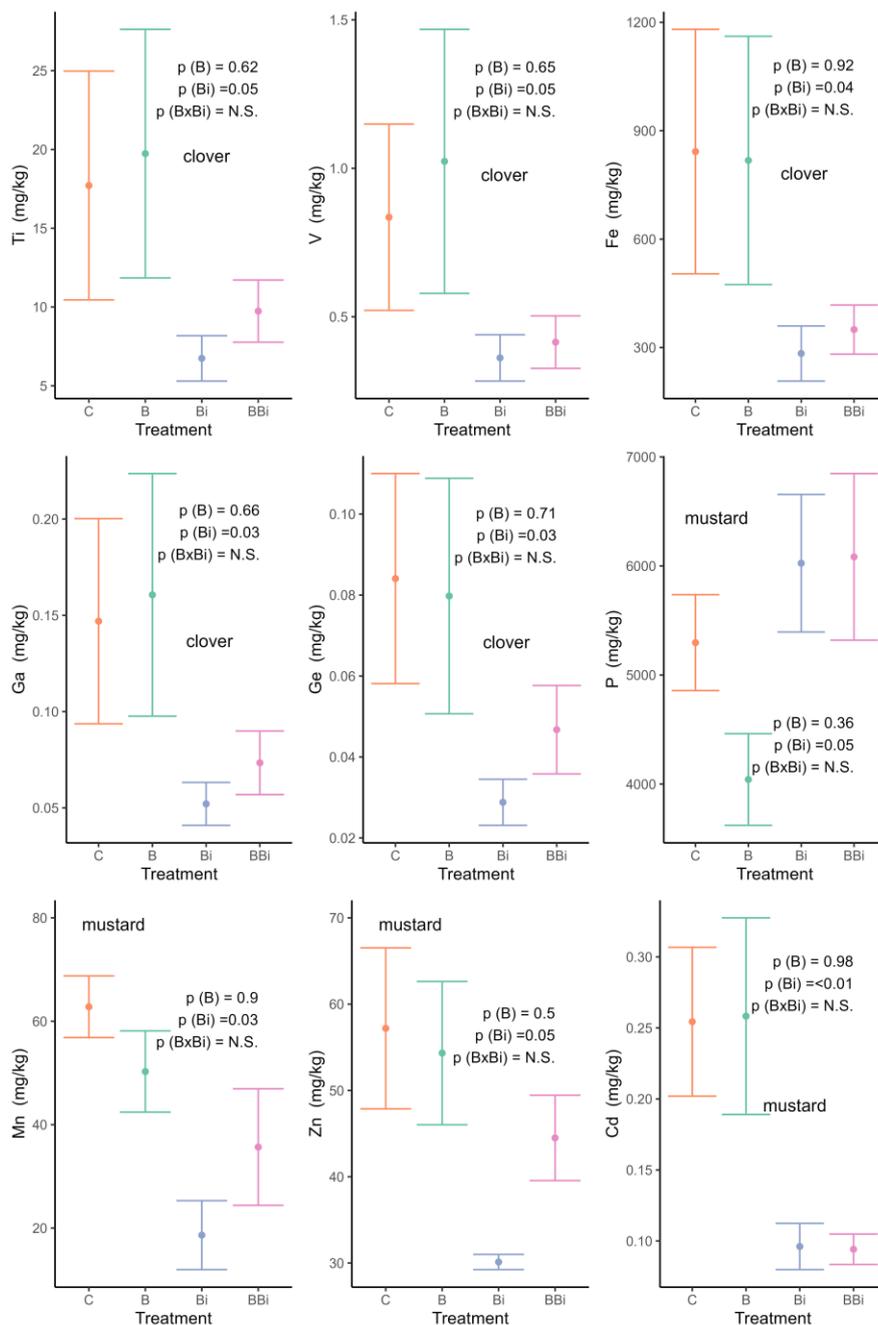
and mustard plants. In clover plants, Ti, V, Fe and Ge significantly decreased after biochar amendment. In mustard plants, biochar decreased concentrations of Mn, Zn and Cd. In contrast, biochar increased P in mustard plants.



220 **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 were all below detection limits and are not shown in this plot.



225 **Figure 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.



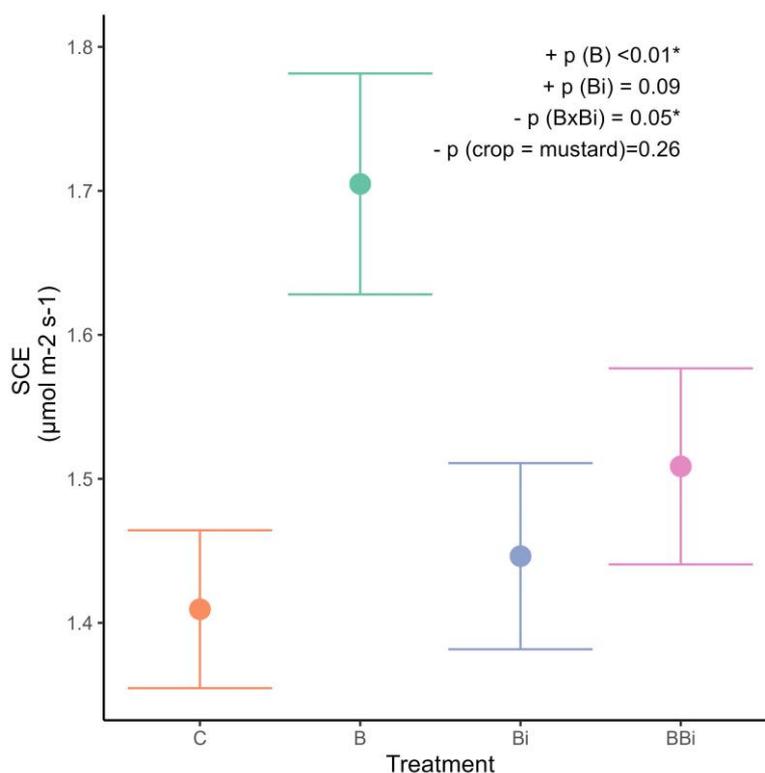
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Figure 6: Elements in clover or mustard plants for different treatments. Error bars represent averages \pm standard errors. Only elements with significant changes are shown here. For all plant (trace) elements, we refer to **Supplementary Figure 1-6**.



3.4 Soil CO₂ emissions

235 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).



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Figure 7: SCE in function of treatment. $p(B)$, $p(Bi)$ and $p(B \times Bi)$ and $p(\text{crop})$ 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

245 crops are presented in Supplementary Figure 12.



4 Discussion

4.1 Effects on inorganic CDR and soil chemistry

250 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. The decreases over time may indicate that positively charged base cations, along with
negatively charged bicarbonate, leached into deeper soil layers. Base cations may also have precipitated as solid carbonates or
conclude no increases in carbonates. Secondary oxides and clays may have formed but gone undetected if they were retained
255 in a residual soil fraction resistant to extraction by the Tessier sequential scheme (Steinwider et al., 2025). Recent studies
have indeed indicated the potentially significant production of secondary minerals and associated degassing of bicarbonate (Iff
et al., 2024; Niron et al., 2024; Steinwider et al., 2025; Vienne et al., 2025).

Importantly, basalt application did not increase concentrations in the most bio-available soil pool, being the exchangeable pool.
260 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. This distribution indicates that the added metals were largely sequestered in more stable
pools, reducing their immediate bioavailability to plants.

265 Biochar alone 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 inorganic carbon (SIC) (Amann & Hartmann, 2019; Dong et al., 2019).
We presume that biochar caused trace elements to shift towards fraction that are chemically stable, immobile and biologically
270 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 and soil fractions.
275 Similarly, the heavy metals did not show a significant basalt x biochar interaction effect for any of the soil pools. This suggests
that the effects of basalt and biochar on soil base cations are additive and not synergistic (Amann & Hartmann, 2019; Honvault
et al., 2024). We are not aware of other studies that investigate the fate of weathering products in the soil after co-application
of basalt and biochar, so more research is needed to confirm this finding.

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285 **4.2 Plant Biomass**

Basalt did not significantly affect biomass and plant trace metal concentrations in our experiment. Biochar, on the other hand, significantly increased biomass of both clover and mustard plants. 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 P₂O₅ 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.

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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).

305 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; Biochar decreased Mn, Zn and Cd in *Brassica juncea*, in line with Zang et al. (2023) who found decreased Cd in *Brassica juncea* post biochar amendment. Similarly, Gonzaga et al. (2019), observed decreases in plant Cu with *Brassica juncea* after biochar amendment.

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Mechanistically, biochar can reduce plant metal uptake through increasing pH; Typically, biochar is alkaline (our biochar had a pH of 10.47) and therefore increases 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



315 phenolic groups) can adsorb heavy metals (Viotti et al., 2024; Zhou et al., 2022). As heavy metals decreased in plants without
increasing in the four extracted soil fractions, we presume that heavy metals sorbed by biochar here can be retrieved in the
residual fraction, unextractable with the Tessier extraction methodology.

Biochar reduced plant trace metal uptake, but no synergistic effect with basalt was observed. We expect that the pH increase
320 and sorption capacity of biochar were more important than the pH increase due of basalt addition, meaning that basalt does
not provide additional reductions in plant heavy metal uptake.

4.4 Changes in SCE

325 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 CO₂ fluxes related to inorganic C processes.
In general, CO₂ 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 CO₂ removal, and also in other studies, observed inorganic
330 CO₂ removal was at least one order of magnitude smaller than the organic CO₂ fluxes (Steinwider 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.

335 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,
340 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
345 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 (Steinwider et al., 2025). Higher plant productivity can simultaneously boost belowground carbon inputs, increase
350 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.
355 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
360 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
365 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
370 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; Steinwider 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

375 This study provides new insights into the interactions between basalt amendment, biochar application, and soil carbon dynamics in field conditions that may be applied in the implementation of CDR in urban NBS. We observed no significant changes in soil inorganic carbon, while Tessier-extractable base cations declined over time. This suggests that basalt may have promoted the formation of crystalline secondary minerals, which are resistant to extraction. Such mineral formation could scavenge base cations, limiting inorganic carbon removal while potentially contributing to SOC stabilization in the long-term.



380 Contrary to the hypothesis that EW would reduce soil CO₂ emissions, basalt amendment increased soil CO₂ efflux over the
one-year experimental period, indicating increases in SOM decomposition and/or rhizosphere respiration. We emphasize that
increased SOM decomposition does not necessarily result in SOC losses after basalt addition, if increased belowground C
inputs compensate for the increased microbial activity. These findings highlight the importance of monitoring both organic
and inorganic carbon pools when assessing the CDR potential of enhanced weathering strategies in long-term field assessments
385 in urban or agricultural spaces. Additionally, although basalt increased trace metals in the reducible fraction, it did not elevate
metal concentrations in plant biomass, indicating limited bioavailability.

Biochar has been shown proven to have value as a fertilizer. In our experiment, biochar alone increased aboveground biomass,
demonstrating a fertilization effect in this urban soil. In agreement with recent literature, biochar effectively reduced trace
390 metal uptake in plants, demonstrating its co-benefits for soil remediation. Besides being a stable stock of C which can have
degradation half times in the order of million years, biochar alone did not significantly impact soil CO₂ efflux here.

Co-application of basalt and biochar did not lead to significant synergistic improvements in biomass production or reductions
in plant trace metals. While CO₂ efflux increased with basalt alone, co-application with biochar dampened this response,
395 possibly mitigating a 'basalt priming effect' on SOM decomposition. In conclusion, biochar could thus reduce environmental
risks related to plant heavy metal uptake, while it may also mitigate the risk for potential SOC losses after enhanced weathering
deployment.

6 code and data availability

Code and data used in this manuscript are publicly available on the zenodo platform of Arthur Vienne:
400 (<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
405 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.

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