

Biochar did not affect inorganic C sequestration through steel slag weathering, but increased soil organic carbon loss in a leaching experiment

Jasper Roussard^{*1,3}, Sara Vicca¹, Ivan Janssens², Paul Quataert³, Arthur Vienne¹ & Bart Vandecasteele³

^{*}Corresponding author: jasper.roussard@uantwerpen.be

¹Biobased Sustainability Engineering (SUSTAIN), Department of Bioscience Engineering, University of Antwerp, Antwerp, Belgium

²Plants and Ecosystems (PLECO), Department of Biology, University of Antwerp, Antwerp, Belgium

³Flanders Research Institute of Agriculture, Fisheries and Food (ILVO), Plant Sciences Unit, Merelbeke-Melle, Belgium

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Abstract

Large-scale deployment of carbon dioxide removal (CDR) technologies will be needed to achieve the goals of the Paris Agreement. Enhanced silicate weathering (EW) and biochar are promising CDR strategies, yet little is known about their combined deployment. This study evaluated the effects of steel slag and two contrasting biochar types on weathering dynamics, inorganic C sequestration and soil organic carbon dynamics in a seven-week leaching experiment. Under intensive irrigation steel slag weathered rapidly, increasing soil pH and Ca release, which promoted inorganic C sequestration through both dissolved inorganic carbon export and pedogenic carbonate formation. Co-application with biochar did not significantly affect weathering rates or inorganic C sequestration. However, an interaction effect was observed for soil organic carbon dynamics; although biochar alone increased soil organic carbon stocks from 0.94 ± 0.003 mol to 1.86 ± 0.003 and 1.92 ± 0.003 mol (depending on biochar type), soil organic carbon stocks were 10.2% and 6.3% lower, respectively, when BOF slag and biochar were co-applied (1.67 ± 0.003 and 1.80 ± 0.003 mol) than under biochar application alone, suggesting a priming effect. These findings indicate that under co-deployment of EW and biochar soil organic carbon loss may offset inorganic C sequestration in the short term, highlighting the need for a mechanistic understanding of soil organic carbon cycling under combined application.

Introduction

Active carbon dioxide removal (CDR), complementing drastic greenhouse gas (GHG) emission reductions, is needed to limit climate change to well below 2 °C, as set out in the Paris Agreement (Gasser et al., 2015). Depending on the rate of decline of GHG emissions, 220-360 Gt of CO₂ will need to be removed from the atmosphere by 2100 (Calvin et al., 2023). Achieving this goal will require a portfolio of large-scale deployable CDR technologies. Enhanced silicate weathering (EW) and biochar are two promising options with potential for co-application onto soils (Amann & Hartmann, 2019).

The principle of EW involves accelerating the natural process of silicate rock (e.g. basalt) weathering by grinding this rock into powder and applying it onto soils or aquatic environments (Hartmann et al., 2013). In the soil, silicate minerals react with carbonic acid to form aqueous bicarbonate ions (HCO_3^-). These bicarbonates can either leach from the soil profile as dissolved inorganic carbon (DIC), eventually reaching the ocean or precipitating in the soil as pedogenic carbonate minerals. Both pathways possess the potential to sequester CO_2 for centuries and longer (Hartmann et al., 2013). Estimates of CDR potentials for EW range from 0.5 to 4 Gt CO_2 per year (Beerling et al., 2020; Fuss et al., 2018; IPCC, 2023).

While natural silicate rocks are abundant, energy consumption during quarrying, grinding, and transport may partially offset the CDR potential of EW (Lefebvre et al., 2019). For this reason, alkaline waste streams such as steel slags are being considered for EW purposes (Renforth, 2019). Slags, a byproduct of steel manufacturing, are available in large quantities as globally 0.2-0.4 Gt of slags are produced every year (Naidu et al., 2020; P. Xu & Reinhard, 2025). Valorizing steel slag for EW could help limit demands for natural silicate rock quarrying thereby offsetting CO_2 emissions and other environmental costs associated with it (Lefebvre et al., 2019). The theoretical CO_2 capture potential of steel slag is $\sim 0.6 \text{ t CO}_2 / \text{t slag}$ compared to $0.3 \text{ t CO}_2 / \text{t}$ for natural basalt (Renforth, 2019). Moreover, steel slags weather more rapidly and give stronger weathering signals than natural silicate rocks (Steinwider et al., 2025, 2026). One of the causes of uncertainty in EW experiments is the low resolvability of EW signals due to background noise originating from soil processes (Reershemius et al., 2023). The higher signal-to-noise ratio of steel slags may thus provide additional understanding on the process and implications of EW that naturally occurring minerals alone may not provide. Despite the large theoretical potential of steel slags, experimental work on the use of steel slag for EW remains limited.

A second promising CDR technology, biochar, is the carbon-rich solid product of organic matter pyrolysis that is resistant to microbial degradation (Chen et al., 2019; Lehmann et al., 2006). While the exact permanence of biochar C is still under investigation, recent research studied 64 commercial biochar samples and stated that 76% of the samples completely consisted of “inertinite”, one of the most stable forms of organic C on Earth with a half-life of 100 million years (Sanei et al., 2024). When applied onto soil, biochar increases soil organic carbon (SOC) stocks while potentially delivering important co-benefits for soil function, including improved nutrient and water retention, improved aeration and preventing soil acidification (Allohverdi et al., 2021; Schmidt et al., 2021). The global theoretical CDR potential of biochar ranges between 0.3 and 4.9 Gt CO_2 per year depending on the assumptions of feedstock availability (Bergero et al., 2024; Roe et al., 2019).

Co-deployment of EW and biochar is particularly interesting because both technologies share agricultural soils as one of their major fields of application and co-deployment could therefore elevate the total CDR capacity of those soils. Moreover, multiple potential synergies between the two have been hypothesized, leading to a considerable increase in their efficiency (Amann & Hartmann, 2019). For example, biochar can alter EW dynamics through changing the activity and composition of the microbial community (Palansooriya et al., 2019) and by changing soil hydrology (Omondi et al., 2016). In addition, the high sorption capacity of biochar can stimulate binding of weathering products, which may help in preventing their oversaturation in the porewater. Porewater oversaturation of weathering products may lead to secondary mineral formation, a key mechanism limiting inorganic C sequestration (Oelkers et al., 2019; Steinwider et al., 2026). Theoretically, biochar amended soils could store more base cations on their exchange complex and thereby reduce the risk of base cations to be locked in secondary minerals. While the soil exchange complex is a significant base cation sink that can delay

inorganic C sequestration up to decades (Kanzaki et al., 2025), this sink is considered to be less permanent than secondary minerals (Steinwider et al., 2026).

Although experimental work that focuses on disentangling the complex nature of EW-biochar interactions remains scarce, first studies indicate diverse interaction effects. A mesocosm experiment with basalt and woody biochar indicated additive effects for weathering rate indicators and inorganic carbon sequestration (Honvault et al., 2024). In addition, a three-year field study reported higher porewater DIC concentrations when metabasaltic rock was co-applied with compost and biochar, indicative of higher weathering activity compared to ground rock applied alone (although a biochar treatment without metabasaltic rock was lacking) (Anthony et al., 2025). Similarly, te Pas et al., (2026) also found positive effects of biochar on dunite weathering and inorganic C sequestration in a sandy soil. In contrast, they did not observe any of these effects in a clay soil (te Pas et al., 2026). Moreover, a field experiment with alkaline soil, indicated no effects of biochar on basalt weathering (Vienne et al., 2026b). Sohng et al., (2025) even reported negative effects of biochar on EW; when applied alone, metabasaltic rock weathering achieved inorganic C sequestration but when co-deployed with biochar the rock did not lead to inorganic carbon sequestration. The underlying mechanisms for these diverse effects remain to be explored.

In addition to their effects on inorganic C sequestration, soil amendments like biochar and silicate rock powder can affect SOC, potentially determining the net climate benefit of EW (Vicca et al., 2022). Recent work showed contrasting effects of EW on SOC decomposition and stabilization, indicating that EW-SOC interactions are not yet fully understood and require more attention (Buss et al., 2024; Sokol et al., 2024; J. Xu et al., 2024; Yan et al., 2023). On the other hand, knowledge on the priming effect of biochar is already more established as it typically depends on biochar feedstock, pyrolysis conditions and soil characteristics (Ding et al., 2018; Rasul et al., 2022). While biochar priming can be positive, negative or neutral (i.e. more, less or unchanged SOC decomposition, respectively), a meta-analysis indicated an overall negative priming effect (Wang et al., 2016). Given the effects of EW and biochar on SOC dynamics, exploring the CDR potential of their co-deployment necessitates including effects on SOC cycling.

Here, we studied the CDR potential of basic oxygen furnace (BOF) slag when applied onto soil alone and under co-deployment with two types of woody biochar in a column experiment. We investigated the effects on weathering dynamics and soil inorganic and organic carbon pools. We hypothesized that biochar facilitates inorganic carbon sequestration by BOF slag weathering. We also expected BOF slag to stimulate SOC mineralization in this short-term experiment by raising soil pH and nutrient availability, which typically reduces SOC adsorption and promotes microbial decomposition. Lastly, we expected biochar to, at least partially, offset the effect of BOF slag on SOC mineralization by sorbing nutrients and organic matter.

Methods

Experimental design

A leaching experiment with 18 columns was set up to test the potential of BOF slag weathering with and without biochar for C sequestration. The equipment used for this experiment was similar to the percolation experiment of Vanden Nest et al., (2014); cylindric columns with a volume of 0.98 dm³ (diameter 125 mm, height 80 mm) were installed on top of a filtrate bottle that was connected with a tube to a vacuum pump (Fig. 1). At the bottom of each column there was a Macherey-Nagel GF/D filter (2.7 µm) and glass fiber filter (10-16 µm). On 26 March 2024 1.3 kg fresh soil, mixed with BOF slag and

biochar in a full factorial design, was added to each column. Two biochar types were used: one had a medium density fiberboard (MDF) feedstock while the second type was produced from European poplar woodchips (hereafter referred to as MDF biochar and poplar biochar, respectively). The two biochar types had a strongly contrasting pH (Table 2: Treatment product properties at the start of the experiment). Biochar stability was measured via the inertinite IBR₀2% benchmark (Sanei et al., 2025) revealing both biochar types to have an inert fraction of 99.7% while the remaining 0.3% is considered labile C.

The control soil, the topsoil of an arable field under organic agriculture, was classified as Eutric Retisol (Dondeyne et al., 2014; IUSS Working Group WRB, 2022). It had a sandy loam texture (66% sand, 20% silt and 14% clay) and contained 10.1 g organic carbon per kg dry soil. The pH (in KCl) was 5.1 at the start of the experiment and the potential cation exchange capacity (CEC) at pH 7 was 6.85 cmolc kg⁻¹ soil. Prior to filling the columns the treatment products were thoroughly mixed with the entire 1.3 kg fresh soil. Two treatment factors were established: factor 1, silicate application, had two levels (control, BOF slag) while factor 2, biochar, had three (control, MDF biochar, poplar biochar). Their full factorial design led to six different treatments to evaluate the individual and combined effects of BOF slag and biochar (Table 1). Each treatment was replicated three times. Biochar application rates were standardized based on their organic carbon content so that an equal amount of biochar-C was applied to all columns containing biochar. BOF slag contained trace amounts (0.34%) of organic carbon creating minor differences in organic carbon applied to each column (Table 1). BOF slag mineralogical and chemical composition, particle size distribution and specific surface area were via methodology described in (Ceyssens et al., 2026) and summarized in (Table S1).

After filling the columns, the top of the soil was covered with a Macherey-Nagel 640w paper filter to ensure equal distribution of the synthetic rainwater during irrigation. The synthetic rainwater had a pH of 5.6 and consisted of 0.02 mM SO₄²⁻, 0.04 mM Cl⁻, 0.02 mM Ca²⁺, 0.003 mM K⁺, 0.02 mM Na⁺ (anion: 0.08 meq L⁻¹; cation: 0.09 meq L⁻¹). This composition was based on the ‘artificial rain’ used by Lookman (1995) and the composition of rain nearby Chimay (Belgium), measured by (André et al., 2007). The leaching columns were held at unsaturated conditions by means of a vacuum pump, preventing anaerobic or more reduced conditions in the soil, and mimicking the negative pressure from the subsoil in a natural soil environment. This pump, connected to the filtrate bottles, kept the pressure in the whole system at 10 kPa below atmospheric pressure (= light textured soil at field capacity). The entire system was held at a constant temperature of 20.0 ± 0.5 °C. Total pore volume (TPV) of the soil columns was estimated assuming a bulk density (BD) of 1.3 kg/dm³ and a soil particle density of 2.65 kg/dm³ (Eq.1).

$$TPV (\%) = 100 \times \left(1 - \frac{\text{Bulk density}}{\text{soil particle density}} \right) \quad (Eq. 1)$$

Based on the TPV and cumulative leachate volumes, the number of times the soil pores were flushed was calculated.

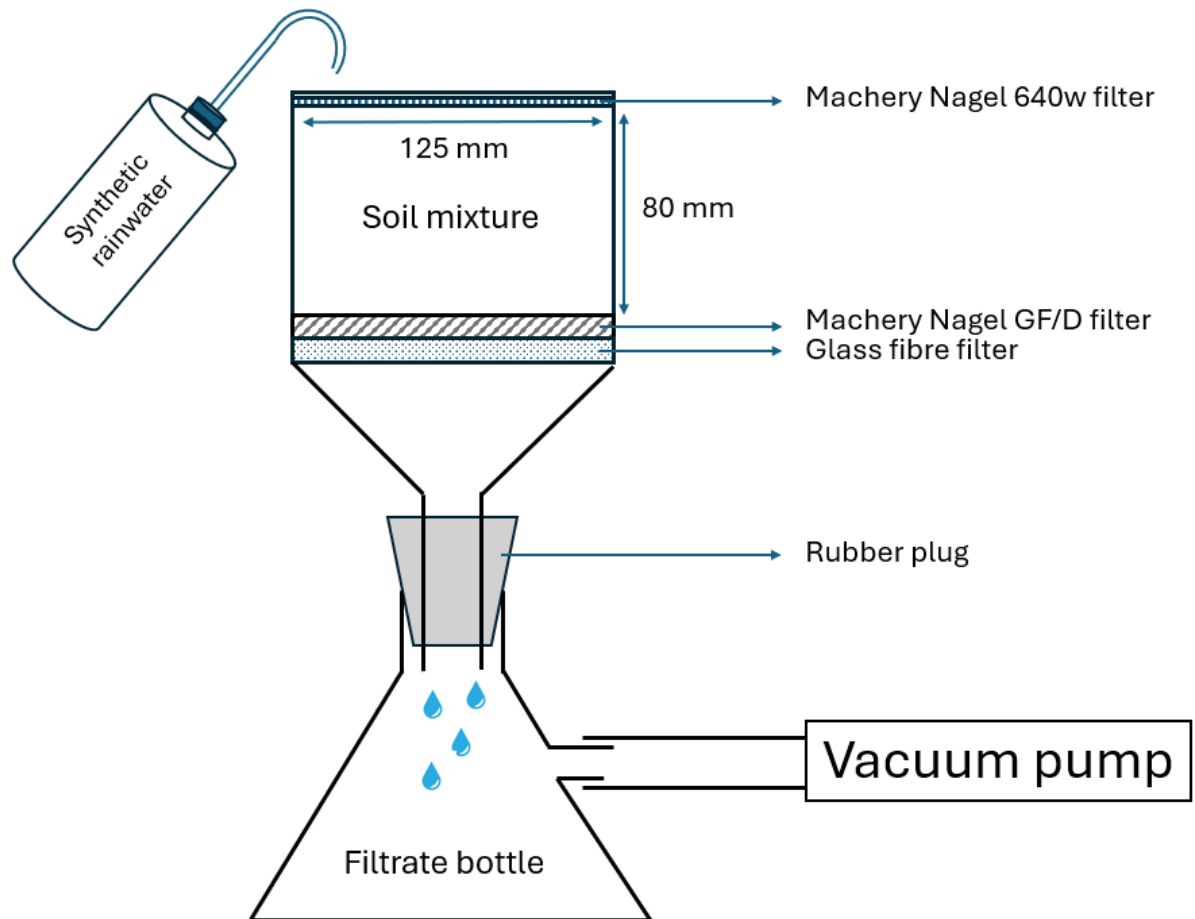


Fig. 1 Schematic overview of the experimental setup

Table 1: Overview of the treatments tested in the experiment

Silicate	Biochar	Treatment	Application rates (t ha ⁻¹)	OC (g per column)
Control	Control	Control soil	/	11.7
Control	MDF	MDF biochar	12.5	22.6
Control	Poplar	Poplar biochar	10.6	22.6
BOF slag	Control	BOF slag	16.8	11.8
BOF slag	MDF	BOF slag + MDF biochar	16.8 + 12.5	22.7
BOF slag	Poplar	BOF slag + poplar biochar	16.8 + 10.6	22.7

Table 2: Treatment product properties at the start of the experiment (expressed on dry matter basis)

Variable	BOF slag	MDF biochar	Poplar biochar
pH (H ₂ O)	12.37	3.32	10.58
Acid buffering capacity (mmol H ⁺ /L)	8783.1	0.50	475.80
Organic C (%)	0.34	71	84
Inorganic C (%)	0.95	<0.02	0.92
Total N (%)	0.02	4.20	0.33
C/N	15.4	16.90	251.20
Total P (%)	0.70	2.40	1.39
Total Ca (%)	33.20	0.59	3.11

Total Mg (%)	1.90	0.13	0.26
Total K (%)	< 0.03	0.22	0.99
Total Na (%)	0.10	0.18	0.03
CEC (cmolc/kg)	4.86	15.17	4.18

Irrigation scheme and leachate collection

Starting on 3 April 2024, the soil columns were manually irrigated five times per day with 0.018L of synthetic rainwater, every day from Monday-Friday. On Saturday and Sunday the columns did not receive any rainwater. This irrigation scheme is equivalent to approximately 1900 mm of rain per year which is +/- 2.1 times the annual rainfall in Belgium (Royal Meteorological Institute of Belgium [RMI], 2024) and is similar to a percolation experiment with a comparable experimental setup (Vanden Nest et al., 2014). As of 9 April, leachate samples were collected for chemical analysis every week for six weeks. On 30 April and 8 May (week 5 and 6 respectively), no leachate was recovered from column 3 (control soil treatment) due to clogging of the soil. During this period this column received no irrigation until the problem was resolved after week 6 by mixing the soil again. Therefore, data from soil column 3 for weeks 5 and 6 were excluded from all analyses.

Leachates were filtered over 0.45 μm and analyzed for DIC and dissolved organic carbon (DOC) concentrations with a Skalar (FORMACS^{HT}). Leachate pH was measured with Metrohm 785 DMP Titrino and electric conductivity (EC) was measured with Metrohm 856. Dissolved anions (Cl^- , SO_4^{2-} , NO_3^- and PO_4^{3-}) were analyzed with Dionex ICS-3000. Ammonium nitrogen ($\text{NH}_4^+\text{-N}$) was measured with a Skalar San ++ Continuous Flow Analyzer (Skalar Analytical B.V., Breda, The Netherlands). Element concentrations Al, Ca, Fe, K, Mg, Mn, Na, P and Si were measured via ICP-OES 5110 VDV. On 16 May 2024 irrigation stopped and on 10 June 2024 150 g of soil was sampled from each column for chemical analysis. Soil samples were analyzed for inorganic and organic carbon content via ISO 10694 and for total nitrogen with ISO 13878, and for pH via ISO 10390. CEC was determined at pH 7 using 1M ammonium acetate.

Soil CO₂ efflux measurements

Starting on 2 April 2024, soil CO₂ efflux (SCE) was measured every Monday morning before the first irrigation event of the week. To enable SCE measurements, the Macherey-Nagel 640w paper filter was removed from the soil surface and a PVC ring (42 mm in height, 96 mm in diameter) was gently pushed into the upper 2 mm of soil in the center of each column. A custom-built respiration chamber with a volume of 0.60L connected to an infrared gas analyzer (EGM-5, PP Systems, Hitchin, UK) was used to measure SCE. During each measurement, the respiration chamber was placed on top of the PVC ring, and the increase in CO₂ concentration was measured over 111 seconds. The SCE was then calculated from the change in CO₂ concentration over time. After finishing the SCE measurement the PVC ring was gently removed from the soil and the paper filter was put back on top of the soil. The SCE measurements started one week before we could collect the first leachate sample and SCE was measured on seven occasions.

Data analysis

All data analyses were conducted in R (RStudio 2023.12.1 + 402). Principal component analysis (PCA) was performed to visualize multivariate patterns for the leachate properties using FactoMineR (Husson et al. 2024) and factoextra (Kassambra & Mundt, 2020) packages. The PCA was conducted on treatment-level mean values calculated for each sampling week. The variables included pH, Ca, Mg, K, Na, SO₄, Cl, NO₃, EC, PO₄, DIC, DOC, P, Si and Mn. Leachate NH₄, Fe and Al were excluded from this

analysis because too many values remained below the detection limit. Data were centered and scaled before PCA.

Inorganic C sequestration was estimated as the sum of the change in total leached DIC (ΔDIC_{total}) and the change in precipitated SIC (ΔSIC) in the BOF slag treatments relative to their respective controls and corrected for the inherent inorganic C present in the applied BOF slag ($IC_{BOF\ slag}$) and biochar ($IC_{biochar}$) feedstocks (Eq. 2). Thus, inorganic C sequestration was calculated as:

$$Inorganic\ C\ sequestration\ (mol\ C) = \Delta DIC_{total} + \Delta SIC - IC_{BOF\ slag} - IC_{biochar} \text{ (Eq. 2)}$$

Total CDR was subsequently estimated by combining this net inorganic C sequestration with the changes in SOC (ΔSOC) and total DOC (ΔDOC_{total}) between the BOF slag treatments and their respective controls (Eq. 3):

$$CDR \left(\frac{t\ CO_2}{t\ slag} \right) \approx [inorganic\ C\ sequestration + \Delta SOC + \Delta DOC_{total}] * M_{CO_2} / m_{BOF\ slag} \text{ (Eq. 3)}$$

where M_{CO_2} is the molar mass of CO_2 and $m_{BOF\ slag}$ is the mass of BOF slag applied (20.6 g of dry matter in this experiment). The resulting CDR therefore represents the CO_2 removal attributable to the BOF slag treatments, expressed as tons of CO_2 per ton of BOF slag applied.

Statistical analyses were done using lme4 (Bates et al. 2015), lmerTest (Kuznetsova et al 2017) and emmeans (Lenth 2024). Linear models were used to assess effects of silicate (control, BOF slag) and biochar (control, MDF biochar and poplar biochar) application on soil properties. For the measurements repeated over time (leachate chemistry and SCE), linear mixed models were used with column as a random effect. Silicate, biochar and time were included as fixed effects. Interaction effects between silicate, biochar and time were tested and by stepwise regression statistically significant interactions were retained in the final model based on the AIC-criterion. The significance level was set at $p \leq 0.05$. Residual normality (Q-Q plots) and homoscedasticity (residuals vs. fitted values) were visually inspected with ggResidpanel (Goode & Rey, 2019) and ggfortify (Tang et al. 2016). Data were square-root transformed in case model assumptions were not met. Model outputs were summarized in Table S4, Table S5 and Table S6 in the supplementary information.

Results

Leaching dynamics

Throughout the experiment each soil column received a total volume of 2.88 L synthetic rainwater. We did not observe any treatment effect on weekly collected leachate volumes (Fig. 2; Table S4). Cumulative leachate volumes were lowest in the unamended control soil (Table S2). The TPV of the soil was estimated to be 50.9% indicating the soil was flushed between 3.5 and 3.8 times depending on the treatment (Table S2).

BOF slag increased leachate pH up to 8.18 ± 0.11 (Fig. 2). The increase in pH stabilized after approximately four weeks (significant BOF slag x time interaction effect; Table S4). The two biochar types affected leachate pH differently; MDF biochar reduced leachate pH while poplar biochar increased pH, reflecting the effect of the acid-buffering capacity and pH of the pure biochar (Table 2). As the experiment progressed, the effects of both biochar types diverged, as reflected in a significant biochar x time interaction effect (Table S4). Furthermore, we observed a BOF slag x biochar x time interaction effect (Table S4); the singular biochar effects were offset by BOF slag, leading to a synergistic

interaction effect between BOF slag and MDF biochar and an antagonistic interaction effect between BOF slag and poplar biochar (Fig. 2).

BOF slag increased Ca leaching throughout the entire seven-week period (Table S4; Fig. 2). It also affected the temporal dynamics of Ca leaching (Table S4); in columns without BOF slag, Ca leaching strongly declined after the second week and stabilized from week four onwards, while for BOF slag columns this decline was more gradual over the first five weeks before it became relatively constant in weeks six and seven (Fig. 2). Moreover, Ca leaching was lower in biochar columns, mostly in the second week, while it did not exhibit any effect later in the experiment, resulting in a significant biochar x time interaction effect (Table S4). We also observed a significant interaction effect between BOF slag and biochar (Table S4); overall, less Ca leached when BOF slag was co-applied with poplar biochar (6.64 ± 0.38 mmol) compared to BOF slag applied alone (7.62 ± 0.20 mmol) or with MDF biochar (8.15 ± 0.07 mmol). This effect became more pronounced as the experiment progressed (significant BOF slag x biochar x time interaction effect; Table S4).

BOF slag significantly elevated DIC leaching with a steady rise in the first four weeks (Fig. 2). Later in the experiment DIC leaching stabilized (significant BOF x time interaction effect; Table S4). We also found a significant biochar x time interaction effect (Table S4) since poplar biochar increased DIC leaching gradually throughout the experiment. Furthermore, we observed a significant BOF x biochar interaction effect (Table S4). Overall, 6.60 ± 0.35 mmol DIC leached from BOF slag columns, compared to 6.21 ± 0.73 and 7.51 ± 0.04 mmol respectively when BOF slag was applied with poplar biochar or MDF biochar. These differences in DIC leaching became more prominent after week four (significant three-way interaction effect between BOF slag, biochar and time; Table S4).

BOF slag promoted DOC leaching, especially in the first half of the experiment (Fig. 2; significant BOF x time interaction effect; Table S4). We also observed a biochar x time interaction effect (Table S4); DOC leaching was lower in poplar biochar columns (4.80 ± 0.23 mmol) compared to MDF biochar (7.50 ± 0.03 mmol) and control soil (8.05 ± 0.18 mmol) and remained relatively stable throughout the experiment compared to MDF biochar and control soil columns (Fig. 2). In the first four weeks, poplar biochar strongly reduced the BOF slag-induced effect on DOC leaching. Later, this negative effect became less pronounced (significant three-way interaction effect between BOF slag, biochar and time; Table S4).

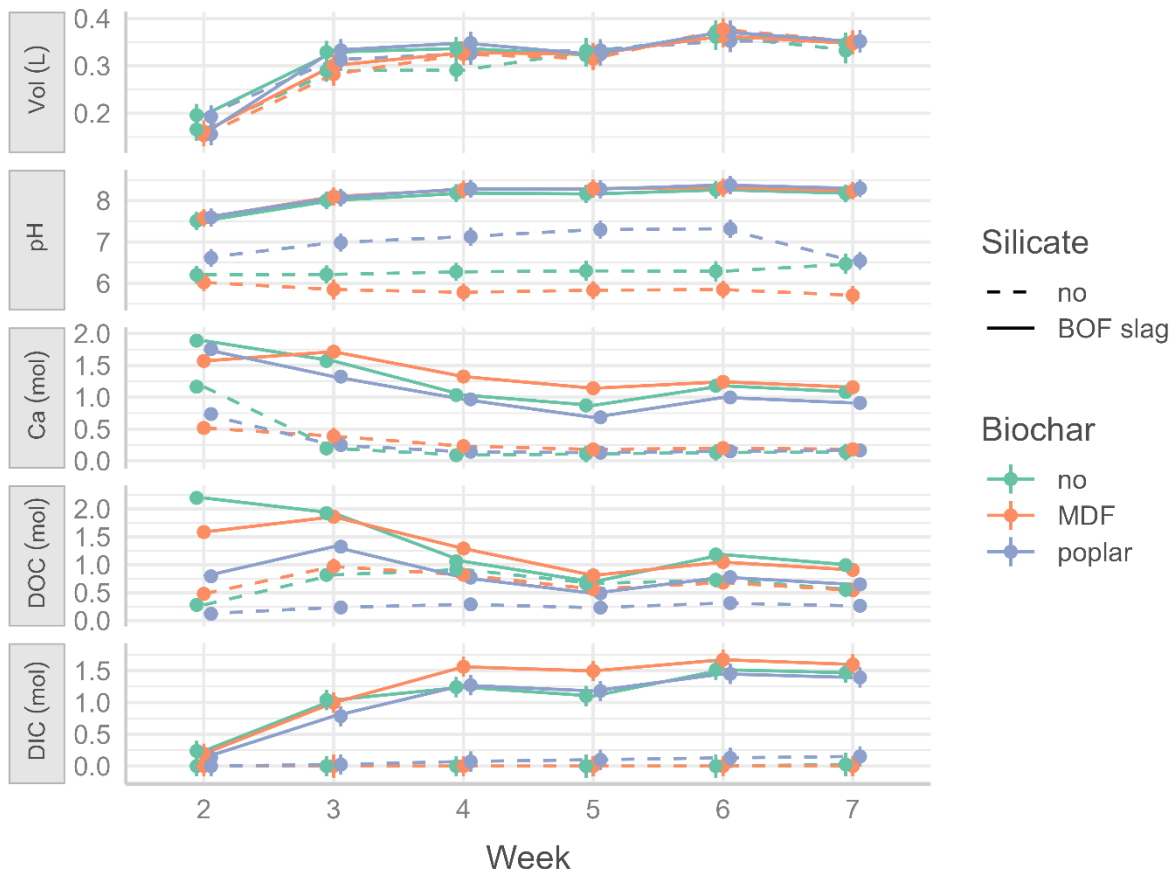


Fig. 2 Estimated marginal means of leachate volume, pH, Ca, DOC and DIC throughout the experiment. First leachate samples could be collected in week 2 of the experiment. Error bars depict 95% confidence intervals.

A PCA on the leachate chemistry indicates a strong correlation between pH and DIC (Fig. 3). Ca leaching was more strongly correlated to DOC leaching than to DIC leaching. Moreover, base cations other than Ca were not strongly correlated to DIC or DOC leaching. Electric conductivity was most strongly correlated to SO_4 , Cl, NO_3 and Na.

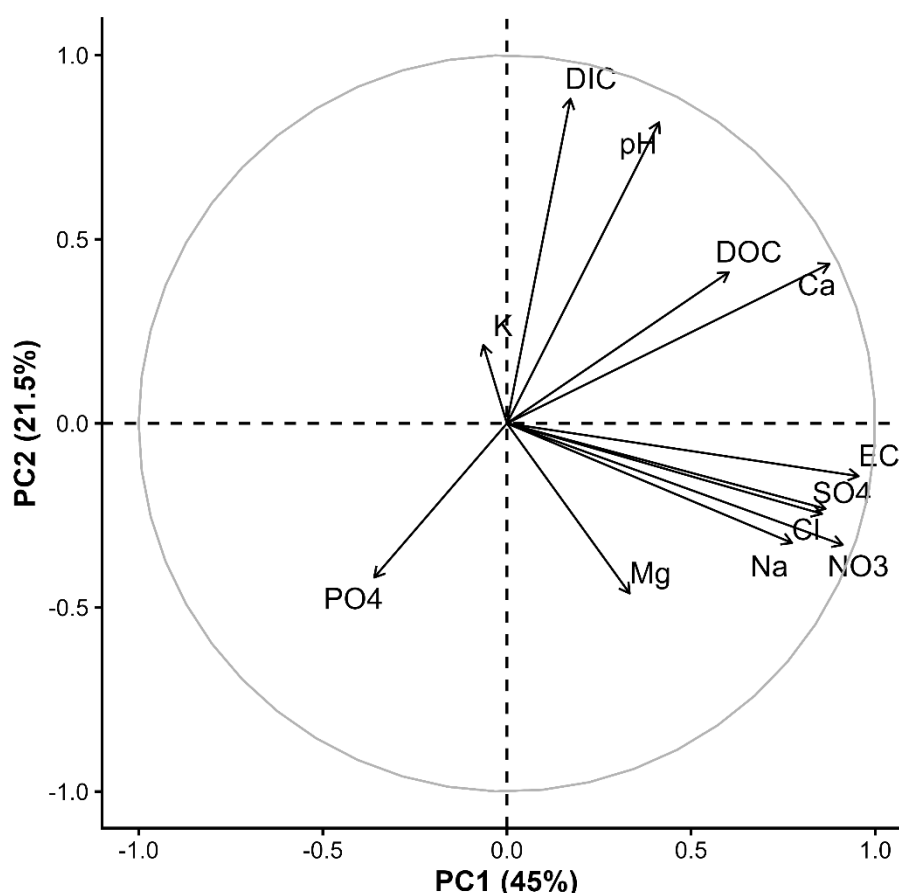


Fig. 3 Principle component analysis for the leachate chemistry

Soil properties

At the end of the experiment, soil pH for the BOF slag treatment had increased to up to 8.22 ± 0.03 compared to a pH of 4.95 ± 0.03 in the unamended control soil (Fig. 4). Poplar biochar also elevated soil pH up to 6.20 ± 0.03 , while MDF biochar did not affect soil pH. We observed an antagonistic BOF slag x biochar interaction effect (Table S5); the individual effect of poplar biochar disappeared under co-deployment with BOF slag as soil pH was similar whether BOF slag was applied alone or with biochar (Fig. 4). The strong pH increase upon BOF slag application is reflected in a clear increase in SIC of up to 0.039 ± 0.001 mol for the entire column. Biochar application did not affect SIC by itself (Fig. 4) but interacted with BOF slag (Table S5); poplar biochar increased SIC up to 0.050 ± 0.001 mol in BOF slag columns while MDF biochar did not change SIC compared to BOF slag applied alone.

Contrary to its effect on SIC, SOC was not influenced by BOF slag after the seven-week leaching period (Fig. 4). Biochar strongly elevated SOC stocks up to 1.86 ± 0.02 and 1.92 ± 0.02 mol for poplar and MDF biochar respectively. When co-deployed with BOF slag, SOC content was lower in biochar columns (Table S5), i.e. 1.67 ± 0.02 and 1.80 ± 0.02 mol for BOF slag with poplar and MDF biochar respectively. CEC did not significantly increase with BOF slag, poplar or MDF biochar application (Fig. 4), but we did detect a small but significant BOF x poplar biochar interaction effect (Table S5).

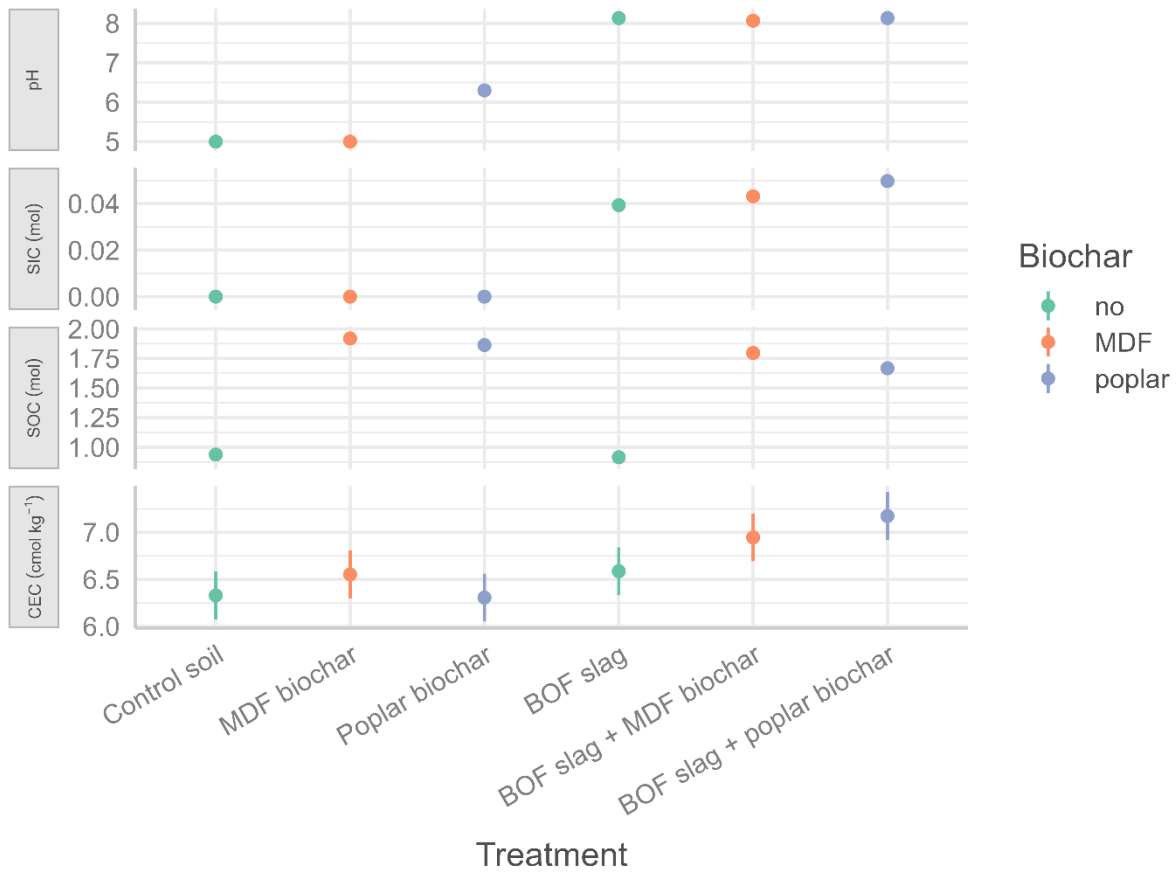


Fig. 4 Estimated marginal means of soil pH, SIC, SOC and CEC at the end of the experiment. Error bars depict 95% confidence intervals (invisible for pH, SIC and SOC).

Soil CO₂ efflux and CO₂ removal

Negative CO₂ emissions were measured in BOF slag columns in the first two weeks while later in the experiment SCE did not differ from the control treatment anymore (Fig. 5). Biochar application did not affect SCE. However, we observed a significant BOF x biochar x time interaction effect (Table S6). Biochar application did not strongly affect inorganic C sequestration of BOF slag but a loss of SOC in BOF-biochar columns relative to biochar alone led to a negative CDR estimate (Table 3). This effect was most clear for poplar biochar.

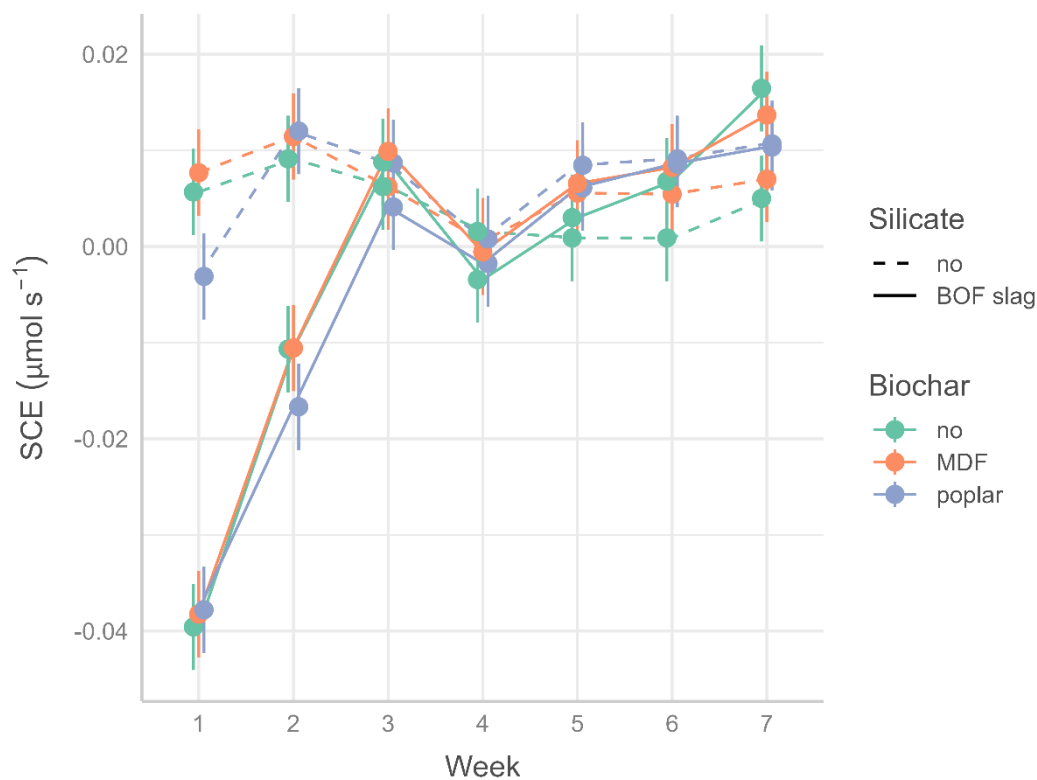


Fig. 5 Estimated marginal means of soil CO₂ efflux measured weekly throughout the experiment. Error bars depict 95% confidence intervals.

Table 3: Inorganic C sequestration $\pm$ se calculated as indicated by Eq. 2. Δ TOC $\pm$ se represents the difference in total organic carbon (Δ SOC + Δ DOC) between BOF slag treatments and their respective control. Estimated CDR $\pm$ se was calculated as indicated in Eq. 3, taking into account both inorganic and organic C.

	BOF slag	BOF slag + MDF biochar	BOF slag + poplar biochar
Inorganic C sequestration (mol C)	0.05 $\pm$ 0.00	0.05 $\pm$ 0.00	0.06 $\pm$ 0.00
Δ TOC (mol C)	-0.02 $\pm$ 0.05	-0.08 $\pm$ 0.09	-0.14 $\pm$ 0.06
Estimated CDR (t CO ₂ t ⁻¹ slag)	0.06 $\pm$ 0.10	-0.06 $\pm$ 0.19	-0.17 $\pm$ 0.13

Discussion

Weathering dynamics

In a leaching experiment, we evaluated the effect of BOF slag on cation release and inorganic and organic C fluxes. Ca is the dominant base cation in BOF slag minerals (Table S1), and the strong effect of BOF slag on Ca leaching and pH is therefore a clear indication of active weathering. The gradual decline of Ca leaching suggests that weathering rates slowed down and/or secondary minerals consumed weathering reaction products. Nevertheless, leachate Ca and pH remained higher in BOF slag amended columns compared to columns without slag, indicating weathering remained active throughout the whole experiment. Over the entire period, 0.008 mol of the applied 0.29 mol (~ 0.03%) of Ca leached from the soil-BOF slag mixture over seven weeks, leaving the majority of Ca to be retained in the soil, potentially available for future export. The clear SIC increase suggests that a fraction of BOF slag-derived Ca ended up in pedogenic carbonates. Assuming all carbonates formed with Ca and not

with any other metal (i.e. one mol of Ca per mol of SIC), this corresponds to 0.14% of the initially applied Ca. Other soil pools, such as the exchange complex and secondary minerals (e.g. clays and oxides) may also have consumed a significant fraction of Ca as these are known sinks that can reduce base cation leaching during EW (Niron et al., 2024; Steinwider et al., 2026; Vienne et al., 2024; Vienne et al., 2026a). Moreover, a fraction of the Ca may have precipitated with P given the alkaline pH range in the present experiment (Manimel Wadu et al., 2013). The lower total P leaching from BOF slag columns compared to the control soil supports this hypothesis (Table S3).

Besides the single BOF slag application, its interaction effects with two biochar types were tested. One postulated mechanism through which biochar application could affect Ca leaching is by changing soil hydrology. We did not find an effect of biochar on weekly collected leachate volumes. Thus, under the intensive irrigation scheme in the present experiment, none of the two biochar types likely altered EW dynamics by changing the water percolation regime.

By adding reactive surface area to the soil, biochar application could increase soil CEC, thereby affecting EW rates and/or base cation leaching. Here, the MDF biochar type did not alter Ca leaching and did not increase CEC, suggesting it did not affect BOF slag weathering rates. This finding is in line with earlier work that found no effects of biochar on basalt weathering (Honvault et al., 2024; Vienne et al., 2026b). In contrast to MDF biochar, poplar biochar did reduce Ca leaching from BOF slag columns. This could indicate that this biochar type slowed BOF slag weathering and/or that it increased cation retention in the soil. Co-application of BOF slag and poplar biochar resulted in a small increase of the soil CEC compared to BOF slag applied alone. The additional sorption sites possibly promoted Ca retention on the exchange complex leading to reduced leaching, thus reducing realization of CDR. The soil exchange complex can induce significant lag times for CDR lasting for less than one year to many decades (Kanzaki et al., 2025). By elevating soil CEC, biochar might extend lag times, thereby postponing inorganic C sequestration. Nevertheless, if a higher CEC prevents weathering products from oversaturating the porewater, it could lower the risk of cations to be locked away even more permanently in secondary minerals (Steinwider et al., 2026). Moreover, exchangeable Ca is often positively correlated with SOC at alkaline soil pH (Rowley et al., 2018) and a key parameter for SOC accrual through EW (T. Xu et al., 2025).

The contrasting effects of MDF and poplar biochar on Ca leaching may therefore reflect differences in their effects on cation retention, although other biogeochemical interactions may also have contributed. For example, biochar application can regulate soil P availability by serving as a P source and by affecting soil P cycling (Zhang et al., 2025). Here, particularly the MDF biochar type contained relatively high P levels (Table 2) and its effect on P leaching depended on presence of BOF slag (Fig. S2). Thus, the P released from the MDF biochar feedstock may have co-precipitated with BOF slag-derived Ca thereby serving as another Ca sink in the soil. These results indicate that interactions between EW, biochar and P cycling may require further attention in the future, especially when Ca-rich silicate rocks are deployed.

Carbon dioxide removal

The inorganic C sequestration of BOF slag application was evaluated by monitoring DIC leaching and SIC precipitation. BOF slag clearly increased DIC leaching. Over the entire duration of the experiment 6.57 ± 0.35 mmol of DIC was exported from BOF slag columns (corrected for control soil) which consisted mostly of HCO_3^- at a leachate pH around 8. This amount of DIC is equivalent to 0.014 ± 0.001 ton CO_2 per ton slag. In addition to DIC leaching, the strong rise in soil pH to above 8 induced significant SIC precipitation (Fig. 4). Approximately six times more inorganic C ended up in pedogenic carbonate minerals than in leachate DIC. After correcting for the inherent carbonate-C of the BOF slag feedstock

(Table 2) this results in an inorganic C sequestration of 0.05 ± 0.00 mol (Table 3: Inorganic C sequestration $\pm$ se calculated as indicated by Eq. 2. $\Delta\text{TOC} \pm$ se represents the difference in total organic carbon ($\Delta\text{SOC} + \Delta\text{DOC}$) between BOF slag treatments and their respective control. Estimated CDR $\pm$ se was calculated as indicated in Eq.), corresponding to 0.050 ± 0.003 ton CO_2 per ton slag. This is an order of magnitude higher than the 0.004 ± 0.003 ton CO_2 per ton slag in a 15-month mesocosm experiment at an application rate of 5 t ha^{-1} (Steinwigger et al., 2026). In a UK field trial, steel slag applied at 50 t ha^{-1} was estimated to yield 0.02 ± 0.004 inorganic C sequestration potential $\text{ha}^{-1} \text{ yr}^{-1}$ (Buckingham & Henderson, 2024). However, as acknowledged also in that study, such high dosages of steel slag might be undesirable due to accumulation of heavy metals. Moreover, direct comparisons of the present experiment with these studies are complicated by the variability in experimental conditions.

Biochar can influence inorganic C sequestration through EW by affecting weathering rates and/or the fate of the released base cations. In this experiment, Ca leaching was lower when BOF slag was co-applied with poplar biochar while it remained unchanged under co-deployment with MDF biochar. Despite these contrasting effects on Ca leaching, none of the biochar types affected inorganic C sequestration through soil DIC export. Yet, under co-deployment with poplar biochar more SIC precipitated in BOF slag columns compared to the singular BOF slag application. Nonetheless, after correcting for the inherent inorganic C of the biochar feedstock (Table 2), SIC formation under co-deployment was not higher compared to BOF slag applied alone. Thus, biochar did not change inorganic C sequestration here (Table 3), supporting earlier work (Sohng et al., 2025; Vienne et al., 2026b).

EW does not only carry potential for inorganic C sequestration but also affects SOC cycling which has important implications for its net CDR potential (Buss et al., 2024; Lei et al., 2025; Steinwigger et al., 2025). Here, BOF slag weathering stimulated DOC export from the soil columns (Fig. 2). This contrasts with a similar percolation experiment in which basanite reduced DOC leaching (Vorrath et al., 2025). As DOC leaching was closely correlated to Ca leaching (Fig. 3), DOC likely competed with DIC to charge balance BOF slag-derived Ca, hampering inorganic C sequestration. The fact that only 43% of the charge generated by Ca (15.2 ± 0.4 mmol) that leached from BOF columns was balanced by DIC (6.6 ± 0.4 mmol) supports this hypothesis.

Besides affecting the efficiency of inorganic C sequestration, DOC plays a crucial role in SOC cycling as it can be both a substrate and a product of SOC decomposition. The strong increase in DOC leaching with BOF slag could have been a result of desorption of mineral-associated DOC as pH is known to be an important modulator of organo-mineral associations (Kleber et al., 2015; Rowley et al., 2018). In addition, the pH increase may have stimulated SOC mineralization, which can affect both DOC production and consumption simultaneously. Despite the higher availability of DOC, we could not detect a change in bulk SOC (Table 3) and found no increase in SCE compared to the control soil contradicting our second hypothesis. Earlier work showed context-dependency on whether SOC decomposition was stimulated through EW or not (Boito et al., 2025; Buss et al., 2024; Lei et al., 2025). Potentially, BOF slag promoted both SOC stabilization and decomposition mechanisms simultaneously, balancing each other out. Alternatively, heavy metal release from the slag negatively influenced microbial activity, offsetting the beneficial effect of pH increase. Nevertheless, the lack of detectable changes in bulk SOC does not necessarily imply that SOC dynamics remained unaffected, as changes in SOC pools or composition may still have occurred (Neff et al., 2002; Yang et al., 2026). Moreover, our interpretation of SCE as a measure for SOC decomposition is being complicated by the high soil pH that led to a detectable CO_2 influx through EW. While in acidic and circumneutral soils heterotrophic and autotrophic respiration typically dominate CO_2 fluxes, in alkaline soils inorganic C cycling can

significantly influence SCE and even lead to negative CO₂ emissions (i.e. influxes) in unplanted areas (Ma et al., 2013).

Several studies already reported the capacity of certain biochar types to sorb DOC from the soil solution (Feng et al., 2024; Smebye et al., 2016; Vorrath et al., 2025). Here, the MDF biochar type did not exhibit any effect on soil DOC export. Yet, poplar biochar strongly reduced the EW effect on DOC leaching, likely by providing additional sorption sites. This effect could explain why we did not observe a poplar biochar effect on DIC export despite lower Ca leaching. If biochar sorbed more DOC, it would be less available to compete with DIC in charge balancing Ca. Thus, poplar biochar might have increased the inorganic C sequestration efficiency of BOF slag weathering despite reducing Ca leaching. Moreover, poplar biochar partially counteracted the BOF slag-induced increase in DOC leaching, potentially protecting it from decomposition.

Despite the counteracting biochar effect on DOC leaching, total SOC at the end of the experiment in co-applied BOF-biochar columns was lower compared to columns that only received a biochar amendment, indicating a positive priming effect induced by the BOF slag and resulting in a net negative CDR estimate (Table 3). This was most pronounced in the poplar biochar treatment. The very small amount of labile C in both MDF and poplar biochar (0.3%), indicated by the inertinite benchmarking, suggests that mainly native SOC was lost. The lack of an individual biochar effect on SCE further suggests that this positive priming effect only occurred under co-deployment of BOF slag and the two biochar types. Similarly, Sohng et al., (2025) found a decrease in MAOC under EW-biochar co-application relative to biochar amended soil and te Pas et al., (2026) measured higher soil CO₂ emissions in co-applied columns compared to dunitite applied alone. Here, we did not measure such an increase in SCE under co-application, potentially related to the alkaline soil pH in BOF slag columns causing the CO₂ uptake through EW to be detectable in the SCE measurements.

Limitations and implications

In the present leaching experiment, intensive irrigation and relatively high application rates of BOF slag and biochar were deliberately used to maximize short-term interaction effects between EW and biochar. These conditions likely increased the signal-to-noise ratio by accelerating mineral dissolution and the irrigation regime potentially partially counteracted secondary mineral precipitation. However, the intensive irrigation also promoted leaching losses of nutrients, particularly NO₃⁻ during the early stages of the experiment (Fig. S2). This potentially altered soil chemical and microbial processes that may have affected both weathering and SOC dynamics. Moreover, the seven-week duration of the experiment limits our observations to short-term responses, and whether the observed effects on SOC persist over longer timescales remains unknown.

Similarly, the relatively high BOF slag application rate was chosen to maximize the likelihood of detecting treatment effects within the limited experimental duration. While appropriate for this controlled study, such application rates may be less suitable under field conditions, where rapid increases in soil pH (up to approximately 8 in this experiment) could adversely affect nutrient availability and crop performance. Consequently, field application rates should be tailored to soil properties and crop requirements and should avoid heavy metal contamination.

Finally, BOF slag and biochar were homogeneously mixed throughout the entire soil column, preventing interactions with an underlying unamended soil layer. Earlier work demonstrated substantial weathering in silicate-amended topsoil but found no corresponding increase in DIC concentrations in leachates collected beneath an unamended subsoil layer (Steinwigger et al., 2026; Vienne et al.,

2026a). Consequently, the absence of unamended subsoil in the present experiment may have led to an overestimation of inorganic C sequestration compared to field conditions where a subsoil is present.

Conclusion

In a lab experiment, BOF slag weathered rapidly, substantially increasing soil pH and Ca release as well as inorganic C sequestration through DIC export and pedogenic carbonate formation. Co-application with two contrasting biochar types had limited effects on BOF slag weathering and did not affect inorganic C sequestration. However, SOC stocks were lower under BOF slag-biochar co-application than under biochar application alone, indicating a positive priming effect. These findings show that co-deployment of BOF slag and biochar does not necessarily enhance inorganic C sequestration and may affect SOC dynamics in the short term. Whether these SOC effects persist over longer timescales remains to be determined.

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Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

717 Author Contributions

718 **Jasper Roussard:** conceptualization, methodology, formal analysis, data curation, writing – original
719 draft, visualization. **Sara Vicca:** conceptualization, writing – review and editing, supervision, funding
720 acquisition. **Ivan Janssens:** writing – review and editing, supervision, funding acquisition. **Paul**
721 **Quataert:** formal analysis, data curation, writing – review and editing, visualization. **Arthur Vienne:**
722 conceptualization, writing – review and editing. **Bart Vandecasteele:** conceptualization, methodology,
723 writing – review and editing, supervision, funding acquisition.

724 Data availability

725 The data that support the findings of this study are available in Zenodo at [10.5281/zenodo.22706651](https://zenodo.org/record/22706651)

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727 Supplementary information

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729 **Table S1:** BOF slag properties at the start of the experiment.

BOF slag XRD (%)		730
Srebrodolskite (Ca ₂ FeO ₅)	9.64	731
Calcite (CaCO ₃)	9.40	732
Beta-C ₂ S (Ca ₂ SiO ₄)	8.79	
Bredigite (Ca ₁₄ Mg ₂ (SiO ₄) ₈)	7.91	733
Wuestite (FeO)	5.08	
Portlandite (Ca(OH) ₂)	4.18	734
Periclase (MgO)	2.70	735
Quartz (SiO ₂)	1.96	
Magnetite (Fe ₃ O ₄)	1.91	736
Iron (Fe)	0.87	737
Hematite (Fe ₂ O ₃)	0.15	
Lime (CaO)	0.06	738
Amorphous/Undetected	48,23	
BOF slag XRF (%)		739
CaO	57.80	740
Fe ₂ O ₃	20.60	
SiO ₂	11.90	741
MnO	2.59	742
Al ₂ O ₃	2.13	
MgO	1.79	743
P ₂ O ₅	1.19	
TiO ₂	0.62	744
V ₂ O ₅	0.52	745
SO ₃	0.34	
Cl	0.32	746
Cr ₂ O ₃	0.14	747
Particle size distribution		
109 µm (D50)		748
Specific surface area		
7,31 m ² /g		749

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Table S2: Water volume balance of the experiment (mean $\pm$ se). Evaporation was estimated by subtracting total leached volume and volume of water retained in the soil from total irrigation.

Treatment	Initial soil mixture dry matter (g)	Final dry matter content (%)	Irrigated (mL)	Total leached volume (mL)	Soil pores flushed	Water retained in soil (mL)	Evaporated (mL)
Control soil	1160.9	78.3 $\pm$ 0.3	2880	1769 $\pm$ 63	3.5 $\pm$ 0.1	252.5 $\pm$ 9.3	858.5 $\pm$ 63.7
MDF biochar	1176.2	78.5 $\pm$ 0.3	2880	1805 $\pm$ 22	3.6 $\pm$ 0.0	252.9 $\pm$ 3.5	822.1 $\pm$ 22.3
Poplar biochar	1173.9	78.9 $\pm$ 0.2	2880	1870 $\pm$ 23	3.7 $\pm$ 0.1	247.7 $\pm$ 2.3	762.3 $\pm$ 23.1
BOF slag	1181.5	81.2 $\pm$ 0.2	2880	1904 $\pm$ 36	3.8 $\pm$ 0.1	222.1 $\pm$ 2.4	753.9 $\pm$ 36.1
BOF slag + MDF biochar	1196.8	80.1 $\pm$ 0.1	2880	1826 $\pm$ 17	3.7 $\pm$ 0.0	238.2 $\pm$ 1.2	815.8 $\pm$ 17.0
BOF slag + poplar biochar	1194.5	80.6 $\pm$ 0.35	2880	1886 $\pm$ 25	3.8 $\pm$ 0.1	231.7 $\pm$ 4.2	762.3 $\pm$ 25.4

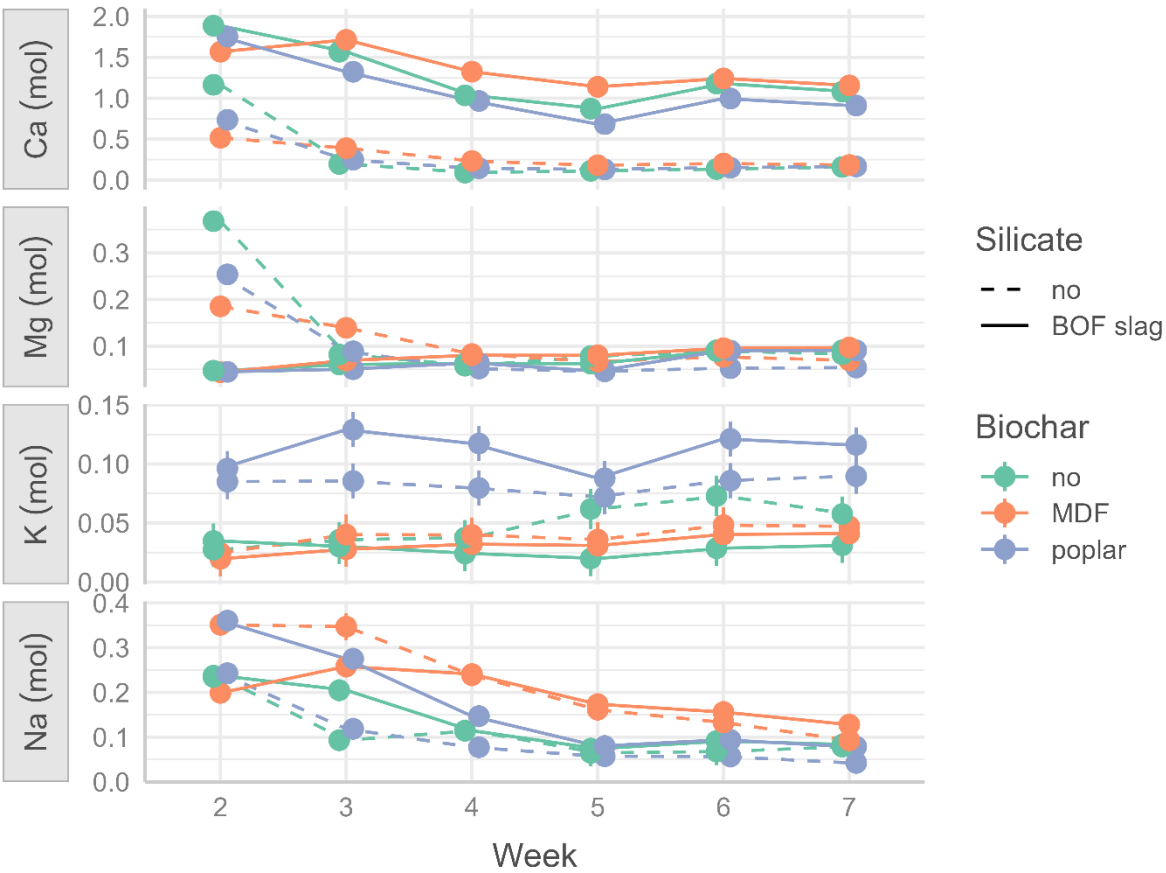
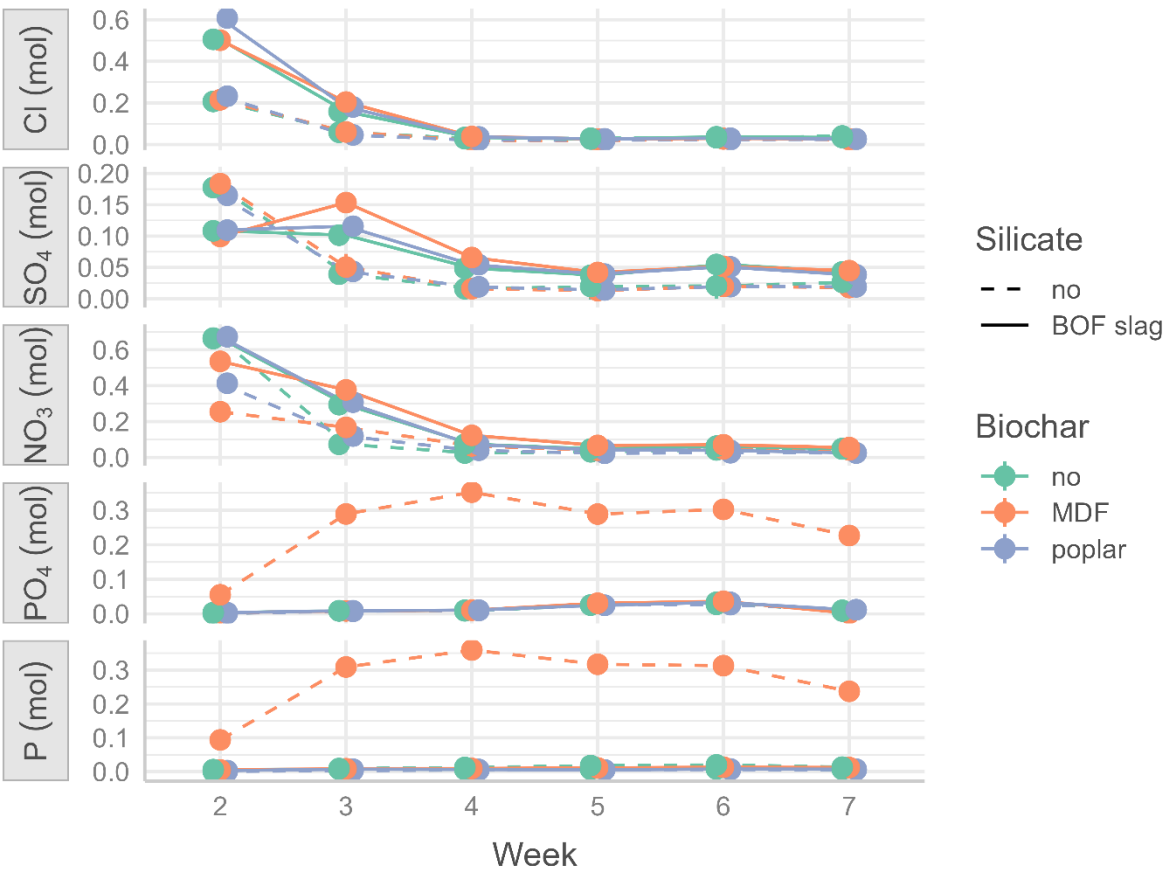


Fig. S6 Estimated marginal means of base cation leaching throughout the experiment. First leachate samples could be collected in week 2 of the experiment. Error bars depict 95% confidence intervals.

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Fig. S7 Estimated marginal means of anion and total P leaching throughout the experiment. First leachate samples could be collected in week 2 of the experiment. Error bars depict 95% confidence intervals.

	Control soil	MDF biochar	Poplar biochar	BOF slag	BOF slag + MDF biochar	BOF slag + poplar biochar
DIC	0.02 ± 0.02	0.00 ± 0.00	0.48 ± 0.13	6.60 ± 0.35	7.51 ± 0.04	6.21 ± 0.73
DOC	3.47 ± 0.27	3.99 ± 0.11	1.45 ± 0.07	8.05 ± 0.18	7.50 ± 0.03	4.80 ± 0.23
Ca	1.77 ± 0.05	1.72 ± 0.04	1.58 ± 0.06	7.62 ± 0.20	8.15 ± 0.07	6.64 ± 0.38
Mg	0.70 ± 0.03	0.62 ± 0.01	0.55 ± 0.02	0.42 ± 0.01	0.47 ± 0.00	0.39 ± 0.04
K	0.25 ± 0.06	0.24 ± 0.01	0.50 ± 0.03	0.17 ± 0.01	0.19 ± 0.02	0.67 ± 0.06
Na	0.60 ± 0.02	1.33 ± 0.00	0.60 ± 0.02	0.81 ± 0.03	1.16 ± 0.01	1.04 ± 0.04
PO ₄	0.06 ± 0.02	1.48 ± 0.08	0.08 ± 0.00	0.09 ± 0.00	0.09 ± 0.00	0.09 ± 0.00
P	0.06 ± 0.01	1.59 ± 0.09	0.03 ± 0.00	0.04 ± 0.00	0.06 ± 0.00	0.04 ± 0.00
NO ₃	0.85 ± 0.05	0.63 ± 0.05	0.65 ± 0.04	1.19 ± 0.08	1.23 ± 0.03	1.16 ± 0.04
NH ₄	0.03 ± 0.01	0.04 ± 0.00	0.04 ± 0.01	0.04 ± 0.00	0.05 ± 0.01	0.06 ± 0.02
SO ₄	0.29 ± 0.00	0.31 ± 0.01	0.28 ± 0.01	0.39 ± 0.01	0.46 ± 0.04	0.41 ± 0.02
Cl	0.38 ± 0.02	0.37 ± 0.01	0.37 ± 0.01	0.80 ± 0.00	0.83 ± 0.01	0.91 ± 0.01
Fe	0.42 ± 0.11	0.05 ± 0.00	0.06 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Al	1.37 ± 0.36	0.14 ± 0.01	0.18 ± 0.03	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Mn	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Si	4.41 ± 0.66	1.59 ± 0.05	1.60 ± 0.10	1.72 ± 0.10	1.97 ± 0.06	1.39 ± 0.25

Response variable	ANOVA (fixed effects)	p-value	Tukey post hoc (EMM)
Volume	Silicate	n.s.	
	Biochar	n.s.	
	Time	< 0.001	
pH	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	< 0.001	MDF v control: p = 0.02 Poplar v control: p < 0.001 MDF v poplar: p < 0.001
	Time	< 0.001	
	Silicate x biochar	< 0.001	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	
sqrt(Ca)	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	< 0.001	MDF v control: n.s. Poplar v control: n.s. MDF v poplar: n.s.
	Time	< 0.001	
	Silicate x biochar	0.03	Bof v Bof + MDF: n.s. Bof v Bof + poplar: p = 0.04 Bof + MDF v Bof + poplar: p < 0.01
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	
sqrt(DOC)	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	< 0.001	MDF v control: n.s. Poplar v control: p < 0.001 MDF v poplar: p < 0.001
	Time	< 0.001	
	Silicate x biochar	0.04	Bof v Bof + MDF: n.s. Bof v Bof + poplar: p < 0.001 Bof + MDF v Bof + poplar: p < 0.001
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	
sqrt(DIC)	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	0.05	MDF v control: n.s. Poplar v control: p < 0.01 MDF v poplar: p < 0.01
	Time	< 0.001	
	Silicate x biochar	< 0.001	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	

	Silicate x biochar x time	< 0.01	
NO ₃	Silicate	< 0.001	Bof v control: p < 0.01
	Biochar	0.07	MDF v control: p = 0.05 Poplar v control: p = 0.09 MDF v poplar: n.s.
	Time	< 0.001	
	Silicate x biochar	0.05	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	
sqrt(PO ₄)	Silicate	< 0.001	Bof v control: n.s.
	Biochar	< 0.001	MDF v control: p < 0.001 Poplar v control: n.s. MDF v poplar: p < 0.001
	Time	< 0.001	
	Silicate x biochar	< 0.001	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	
SO ₄	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	n.s.	
	Time	< 0.001	
	Silicate x time	< 0.001	
sqrt(Cl)	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	n.s.	MDF v control: n.s. Poplar v control: n.s. MDF v poplar: n.s.
	Time	< 0.001	
	Silicate x biochar	< 0.01	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
Mg	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	< 0.001	MDF v control: p = 0.02 Poplar v control: p < 0.001 MDF v poplar: n.s.
	Time	< 0.001	
	Silicate x biochar	< 0.01	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	
K	Silicate	n.s.	

	Biochar	< 0.001	MDF v control: n.s. Poplar v control: p < 0.01 MDF v poplar: p < 0.001
	Time	< 0.001	
	Silicate x biochar	< 0.01	Bof v Bof + MDF: n.s. Bof v Bof + poplar: p < 0.001 Bof + MDF v Bof + poplar: p < 0.001
	Silicate x time	0.07	
	Biochar x time	0.01	
	Silicate x biochar x time	< 0.01	
Na	Silicate	< 0.001	Bof v control: p < 0.01
	Biochar	< 0.001	MDF v control: p < 0.001 Poplar v control: n.s. MDF v poplar: p < 0.001
	Time	< 0.001	
	Silicate x biochar	< 0.001	Bof v Bof + MDF: p < 0.001 Bof v Bof + poplar: p < 0.01 Bof + MDF v Bof + poplar: < 0.1
	Silicate x time	< 0.001	
	Biochar x time	< 0.001	
	Silicate x biochar x time	< 0.001	

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791 **Table S5** Linear model and post hoc test outputs for the soil characteristics

Response variable	ANOVA (fixed effects)	p-value	Tukey post hoc (EMM)
Soil pH	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	< 0.001	MDF v control: n.s. Poplar v control: p < 0.001 MDF v poplar: p < 0.001
	Silicate x biochar	< 0.001	Bof v Bof + MDF: n.s. Bof v Bof + poplar: n.s. Bof + MDF v Bof + poplar: n.s.
SIC	Silicate	< 0.001	Bof v control: p < 0.001
	Biochar	< 0.01	MDF v control: n.s. Poplar v control: n.s. MDF v poplar: n.s.
	Silicate x biochar	< 0.01	Bof v Bof + MDF: n.s. Bof v Bof + poplar: p < 0.01 Bof + MDF v Bof + poplar: p = 0.05
SOC	Silicate	< 0.001	Bof v control: n.s.
	Biochar	< 0.001	MDF v control: p < 0.001 Poplar v control: p < 0.001 MDF v poplar: n.s.
	Silicate x biochar	< 0.01	MDF v Bof + MDF: p < 0.05 poplar v Bof + poplar: p < 0.001 Bof + MDF v Bof + poplar: p < 0.01
CEC	Silicate	< 0.001	Bof v control: n.s.
	Biochar	0.05	MDF v control: n.s. Poplar v control: n.s. MDF v poplar: n.s.
	Silicate x biochar	0.05	Bof v Bof + MDF: n.s. Bof v Bof + poplar: p = 0.04 Bof + MDF v Bof + poplar: n.s.

799 **Table S6** Linear mixed model and post hoc test outputs for the soil CO₂ efflux

Response variable	ANOVA (fixed effects)	p-value	Tukey post hoc (EMM)
SCE	Silicate	< 0.001	Bof v control: p <0.001
	Biochar	n.s.	
	Time	< 0.001	
	Silicate x biochar	n.s.	
	Silicate x time	< 0.001	
	Biochar x time	n.s.	
	Silicate x biochar x time	0.03	

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