



Synergistic effects of basalt and earthworms: enhanced nutrient availability and altered heavy metal dynamics

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10 **Abstract.** Enhanced weathering (EW), the application of crushed silicate rocks such as basalt to soils, has been proposed as a carbon dioxide removal (CDR) strategy. Besides CO₂ sequestration, EW can influence soil chemistry and crop nutrition, providing agronomic co-benefits, but it may also release heavy metals with potential risks for food safety. Soil organisms such as earthworms, which strongly influence nutrient cycling, and mineral dissolution, may further interact with EW processes, yet their role remains poorly understood. Here, we conducted a full-factorial experiment to test the combined effects of basalt and earthworms on soil chemistry, and growth, nutrients and heavy metal concentrations of *Zea mays*. Basalt significantly increased porewater pH, alkalinity, and nutrient concentration (Ca, Mg, Na, and Si). Earthworms further amplified most of these responses, suggesting increased weathering rates. Plant nutrient concentrations were in general positively affected by basalt and earthworms, while plant biomass remained unaffected. Furthermore, basalt decreased heavy metal concentrations in the aboveground plant parts, but V, Ni, and Al accumulated in their roots with basalt application. Basalt and earthworms thus show promise in improving agricultural soils, but trade-offs related to heavy metal accumulation must be addressed to optimize their use in sustainable agriculture.

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1. Introduction

Enhanced weathering (EW), the application of crushed silicate rocks to soils, is a promising carbon dioxide removal (CDR) strategy. Silicate weathering consumes atmospheric CO₂, forming bicarbonate ions that can be transported to the oceans for long-term storage (Hartmann et al., 2013). Besides carbon sequestration, EW may also affect agricultural soils and crops by increasing soil pH and improving nutrient availability (Beerling et al., 2018; Luchese et al., 2023; Nguyen et al., 2024). However, EW may also mobilize heavy metals, raising concerns for food safety and environmental contamination (Rijnders et al., 2024). Understanding such trade-offs is crucial for assessing EW in agriculture.

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30 The benefits of EW for crop growth are demonstrated in tropical regions (Swoboda et al., 2022), while evidence in temperate climates remains limited. A few EW experiments in temperate climates reported increased crop growth for basalt and dunite application alongside changes in



plant elemental composition, including increased Ca, Mg, and Si uptake (Rijnders et al., 2023, 2024; Skov et al., 2024). In all three studies, plant heavy metal uptake did not increase.

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Beyond plant responses, soil fauna — particularly earthworms — are key mediators of soil structure, nutrient cycling, and mineral weathering (Bertrand et al., 2015; Toor et al., 2024). However, their interactions with EW remain poorly understood (Vicca et al., 2022). EW effects on soil properties can affect earthworm populations (Curry, 2004). Conversely, earthworm bioturbation and gut processes can alter soil microenvironments and hydrology, potentially accelerating silicate dissolution (Vicca et al., 2022). Given the well-documented benefits of healthy earthworm populations for soils (Bertrand et al., 2015; Blouin et al., 2013), and of EW for crops (Beerling et al., 2018; Rijnders et al., 2023, 2024), understanding their interaction may help inform strategies to improve soil health and crop performance.

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Earthworm activity may affect silicate weathering through both physical and chemical processes (Vienne et al., 2024). Low pH conditions in the earthworm gut can enhance mineral dissolution and increase reactive surface area (Bayon et al., 2021), while burrowing improves aeration and water infiltration, altering mineral-water contact time (Cipolla et al., 2021; Lewis et al., 2021). Earthworms may transport weathering products away from reaction sites, maintaining concentration gradients that promote continued dissolution (Cipolla et al., 2021; Lewis et al., 2021). Additionally, stimulated microbial activity associated with earthworm activity and mortality can increase soil CO₂ concentrations, promoting silicate dissolution (Arunachalama & Entoori, 2022; Calogiuri et al., 2025a; Six et al., 2004; Van Groeningen et al., 2020).

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To investigate interactions between earthworms and EW, we conducted a 15-month mesocosm experiment examining the effects of basalt application and earthworms. While Boito et al (2025) examined soil CO₂ fluxes in this experiment, this study focuses on maize growth, nutrients and heavy metals. We hypothesized that: I) Basalt improves crop growth and nutrient availability; II) Basalt increases heavy metal availability; III) Earthworms reinforce these effects; and IV) These effects are smaller in the second growing season as weathering rates typically decline over time.

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2. Methodology

2.1 Experimental set-up

The experiment consisted of 32 mesocosms (0.6 m height, 0.25 m radius), which were located outdoors at the experimental site at the Drie-Eiken Campus of the University of Antwerp, Belgium (51°09' N, 04°24' E). The bottom 40 cm of each mesocosm was filled with sandy loam soil from a pasture in Zandhoven, Belgium (Table 1). The upper 20 cm was filled with the same soil, either unamended in the control treatment (16 replicates) or amended with 50 ton ha⁻¹ of basalt (Table S1) mixed into the topsoil layer (16 replicates). Each mesocosm was equipped with a 2 cm diameter hole at the bottom for leachate

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65 collection, and a root exclusion mesh covered the bottom of the mesocosm to prevent soil export through leaching. Glass collectors with a volume of 2.3 L were connected to the mesocosm via polyurethane tubing. Leachate bottles were emptied as necessary to avoid water buildup in the mesocosms. Each mesocosm was equipped with a Campbell Scientific CS616 sensor to monitor soil temperature and moisture, installed horizontally at a depth of 10 cm.

Table 1: Soil characteristics of the original soil

Texture (Sand, silt, clay %)	Sandy loam (69.5, 28.1, 1.8)	70
pH	5.59 ± 0.14	
Organic C (%)	0.84 ± 0.05	
Cation exchange capacity (meq 100g ⁻¹)	3.92 ± 0.64	75

Two maize plants, inoculated with spores of arbuscular mycorrhizal fungi (AMF, species *Rhizophagus irregularis*; Symplanta, Oldenburg, Germany), were planted in each mesocosm on June 16, 2022, whereafter all pots were fertilized with nitrogen, phosphorus and potassium (NPK; 96 – 10 – 79 kg ha⁻¹) by adding ammonium nitrate (NH₄NO₃), triple super phosphate (TSP, 80 45% P₂O₅) and potassium sulphate (K₂SO₄). The fertilization rate was similar to that used in Ven et al. (2019), except for P, which was halved to avoid overfertilization in combination with the added silicates. All plants were harvested at the end of the growing season on September 12, 2022.

At the first harvest, destructive soil sampling was conducted on four mesocosms per treatment. The remaining four were left 85 as bare soil over winter and used to monitor the effects of basalt application on crop growth during a second growing season. Following soil freezing in December 2022, which halted cast production and presumably killed the earthworms, we reintroduced earthworms for the second growing season: 20 individuals per mesocosm were added in April 2023 and an additional 10 in June 2023. On June 6, 2023, each mesocosm was replanted with two maize seeds inoculated with the same AMF species. Plants were harvested on August 21, 2023. Daily precipitation and temperature data for both growing seasons 90 were obtained from visualcrossing (<https://www.visualcrossing.com/>) (Fig S1). Due to limited seed availability, a different dwarf maize variety with comparable traits was used in the second growing season (first season *golden midget*, second season *tom thumb*).

2.2 Biota measurements and chemical analysis

Plant height was measured weekly throughout both growing seasons. Leaf area index (LAI) was measured on July 19, 2022 95 using the method of Ven et al. (2019). In the second growing season, a LI-3000C portable leaf area meter (LI-COR, Lincoln, NE, USA) was available and used to measure leaf area on August 9, 2023. The measured leaf area was subsequently used to calculate the LAI. Earthworm activity was monitored throughout the experiment by tracking their cast production. Casts were collected from the mesocosm surface on a weekly basis, then air-dried and weighed to quantify earthworm activity.



Plants were harvested at the end of each growing season. First, the three youngest leaves from each plant were collected for
100 further analysis. The aboveground biomass was then harvested and separated into stems, leaves, tassels, and corn.

To estimate root biomass, soil cores were collected from each mesocosm. Three soil cores (100 cm³) were taken per mesocosm
at three depth intervals: 0-20 cm, 20-40 cm, 40-60 cm. One core was taken from the centre of the mesocosm, while the other
two were taken from beneath each maize plant. The soil samples were gently rinsed with tap water over a 2 mm sieve placed
105 above a receptacle. Roots retained on the sieve, as well as those floating in the receptacle, were collected.

The collected roots were oven-dried for 48h at 70 °C, after which average dry root biomass [g cm⁻³] was calculated. For each
soil layer, it was assumed that the core from the centre of the mesocosm represented 50% of the root distribution, while each
of the two cores beneath the plants contributed 25%. After drying for 48h at 70 °C, the dry weight of each plant part (stems,
110 leaves, tassels, corn) was determined per mesocosm. Leaves, stems, tassels, corn seeds, and roots were ground using a
centrifugal mill (model ZM 200, Retsch GmbH, Haan, Germany) equipped with a 0.25 mm mesh sieve.

For elemental analysis, 0.3 g of each plant sample was digested with a H₂SO₄, salicylic acid, H₂O₂, and selenium to determine
Ca, Fe, K, Mg, and P, Cd, Cr, Ni, Pb and V, following the protocol of Walinga et al. (1995). Si was extracted separately by
115 treating 0.03 g of plant material with 25 mL 0.5 M NaOH. All extractants were analysed through ICP-OES (iCAP 6300 duo,
Thermo Scientific). C and N content were determined via dry combustion, based on the Dumas method. Approximately 0.05
mg of each plant sample was analysed using an elemental analyser (model FLASH 2000, Thermo Fisher Scientific, USA).

2.3 Soil measurements and chemical analysis

Soil porewater samples were collected biweekly using rhizons (Rhizon Flex, Rhizosphere Research Products B.V.,
120 Wageningen, NL) installed at 5 cm depth in each mesocosm. Porewater pH was measured using a Metrohm 914
pH/Conductometer. For chemical analysis, samples were filtered through a 0.45 µm PET filter, and concentrations of Ca, Cd,
Cr, Fe, Mg, Ni, Pb, Si, and V were analysed via ICP-OES (iCAP 6300 duo, Thermo Scientific), while N in NH₄⁺, NO₃⁻ and
NO₂⁻, and P in PO₄³⁻ concentrations were measured using a continuous flow analyser (SAN++® Advanced Series, Skalar).
During the first growing season, porewater heavy metals (Al, Cr, Mn, Ni, and Zn) were also analysed once every two weeks
125 in the first growing season, while this was done twice during the second growing season.

Cation exchange capacity (CEC) of the soil was determined following the protocol of Brown (1943), for which approximately
2.5 g of air-dried soil was extracted with 1M NH₄Acetate (pH 7) for 1h at room temperature under continuous agitation.
Extracts were analysed using ICP-OES (iCAP 6300 duo, Thermo Scientific). Soil organic C was measured via Loss-On-
130 Ignition (LOI), following Heiri et al. (2001). After LOI, 30 mg of the same sample was used to quantify soil inorganic C by



dry using the Dumas method with an elemental analyser (model FLASH 2000, Thermo Fisher Scientific, USA). Soil texture analysis were conducted according to Gee and Bauder (1986).

2.4 Statistical analysis

135 All statistical analysis were conducted in R (Rstudio, 2021.09.0.0) with a significance level set at $p \leq 0.05$. Data normality of residuals was assessed using the Shapiro–Wilk test, and homoscedasticity was evaluated by plotting the residuals against the fitted values. When the assumptions of normality or homoscedasticity were violated, data were transformed using logarithmic, square root, or inverse transformations Omega² values were calculated using the *effectsize* package (Ben-Shachar et al., 2020).

140 Linear regression analyses were performed to explore the fixed effect of basalt application, earthworms, and the basalt x worms interaction effect on the variables of interest, i.e. plant biomass, nutrient, and heavy metal content of the different plant parts. If the normality or homoscedasticity of the residuals of the linear model was not met after data transformation, a non-parametric Kruskal-Wallis test was used.

145 Temporal changes in plant height, porewater pH and alkalinity, soil porewater nutrient and heavy metal concentrations, and earthworm cast production were analysed using linear mixed models using the *nlme* package (Pinheiro et al., 2013). Basalt application, earthworm presence, time (days after planting of the corn), and the three-way interactions basalt x earthworms x growing season, and basalt x growing season x time were included as fixed effects, while mesocosm was treated as a random effect. For worm cast weights, only the basalt x growing season x time interaction was included. The appropriate model was then selected with backwards stepwise selection by removing the least significant interaction sequentially. When
150 heteroscedasticity was detected, the `weights = varIdent` function was incorporated to account for variance differences across timepoints, using time as the grouping factor.

To identify soil parameters associated with differences in plant biomass, an initial linear model was constructed including all measured soil variables (porewater pH, porewater nutrient concentrations, and porewater heavy metal concentrations). The
155 best-fitting model was selected based on the Aikake information criterion (AIC), followed by a multiple linear regression analysis to determine which soil parameters significantly influenced plant biomass.

Principal component analysis (PCA) was conducted to reduce the dimensionality of the dataset and identify the major sources of variation in soil variables (porewater pH, porewater nutrients, and porewater heavy metals). Variables were standardized
160 using Z-scores prior to analysis. Linear regression analysis was then performed with the two largest principal components (PC) as response variables, with basalt application, earthworm presence, growing season, and their interactions as predictors. To



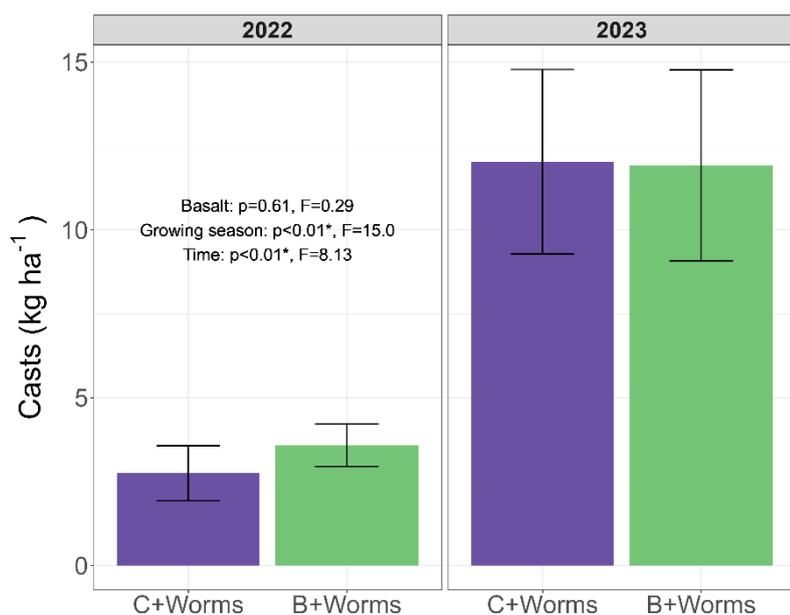
investigate whether biomass was affected by these components, a separate linear regression analysis was performed with biomass as a function of PC1 and PC2.

3. Results

165 3.1 Worm casts

Basalt application did not significantly affect the dry weight of earthworm casts that were collected during the experiment (Fig 1). With a few exceptions, no earthworm casts were found in the treatments without earthworms. In line with the absence of a basalt effect on earthworm casts, we also found no basalt effect on the number and dry weight of earthworms collected at the time of harvest (Table S2a, b).

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Figure 1: The sum of worm cast dry weight (kg ha⁻¹) during two consecutive growing seasons of maize (2022 and 2023) for the two worm treatments (C+worms = control with earthworms, B+worms: basalt with earthworms). p- and F-values from a linear regression analysis are shown with dry weight as fixed effect, and basalt and growing season as covariables. Their interaction was not statistically significant and was excluded from the model. Statistically significant relationships are indicated by an asterisk (*).

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3.2 Soil properties

Porewater pH and alkalinity significantly increased with basalt, but decreased with earthworms. A significant basalt x time interaction effect was found on porewater alkalinity, with a larger increase with basalt towards the end of the growing season (Fig 2). For pH, only a borderline significant basalt x earthworms interaction effect was found. The increase in pH with basalt tended to be higher with earthworms, compared to without earthworms, and this effect was comparable in both growing seasons (Fig 2, method S1).

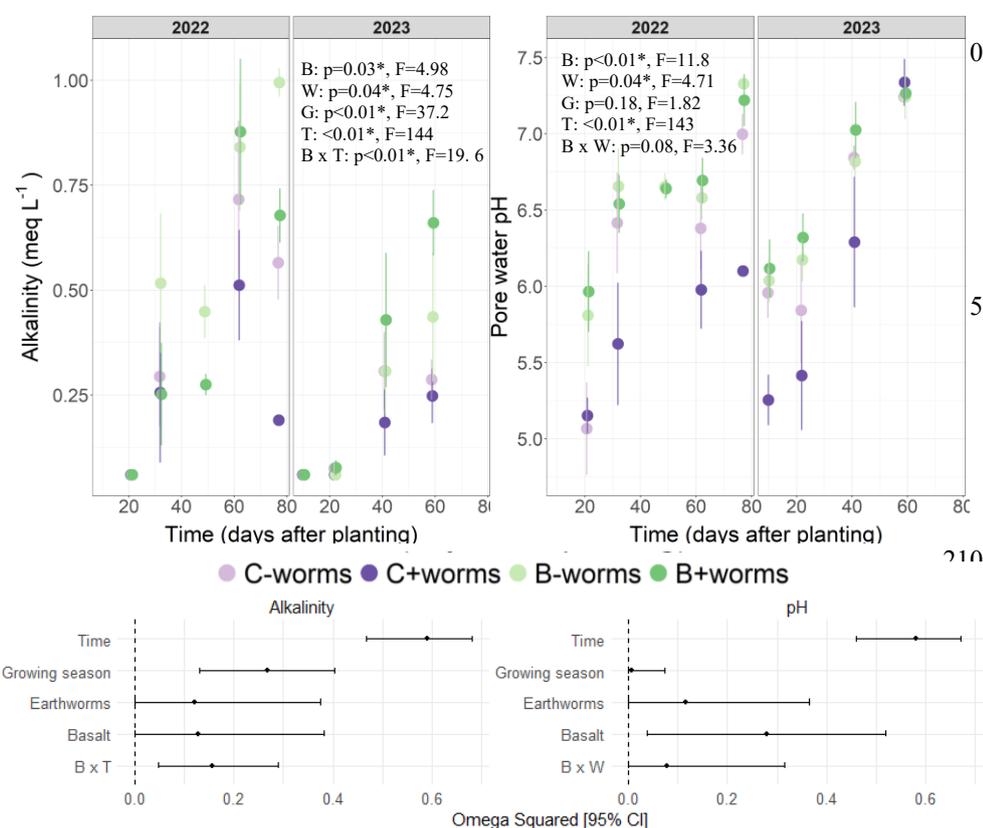
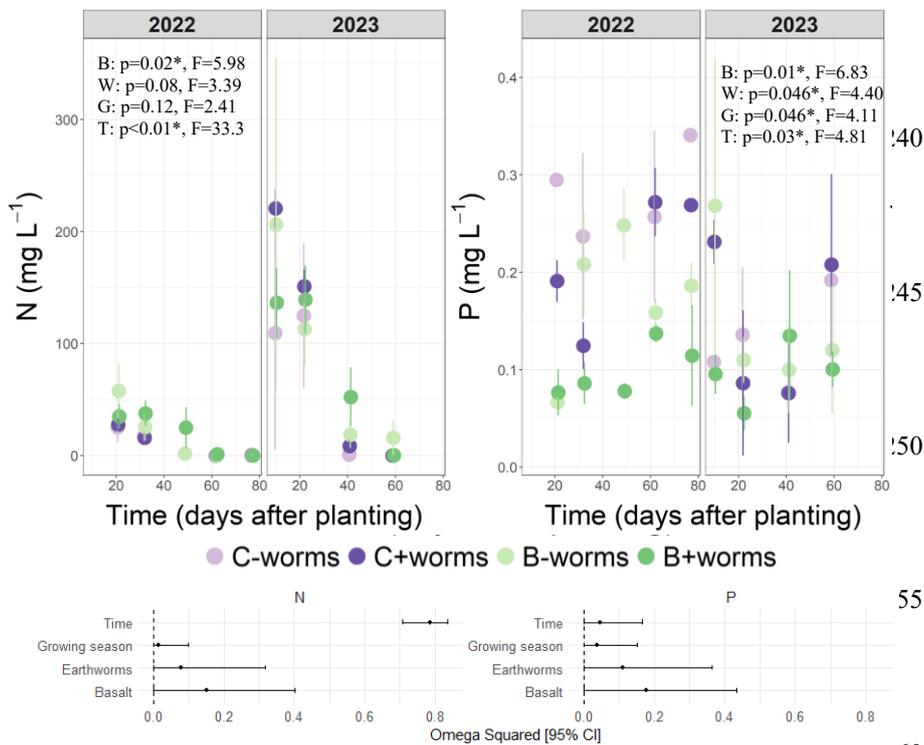


Figure 2: Porewater alkalinity and pH during two consecutive growing seasons of maize (2022 and 2023) for the four treatments (C-worms = control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B + worms: basalt with earthworms). The numbers of replicates in 2022 was eight, in 2023 four. p- and F-values and effect sizes (Ω^2 with 95% confidence interval (CI)) from a linear regression analysis are shown with pH or alkalinity as fixed effect, and basalt (B), earthworms (W), growing season (G), time (T) and their interaction as covariables. Non-statistically significant interactions were excluded from the model. Statistically significant relationships are indicated by an asterisk (*).



Porewater N concentration increased with basalt, and decreased with time, but did not differ with earthworms or between growing seasons (Fig 3). Both basalt and earthworms significantly decreased porewater P concentrations, and significantly lower P concentrations were found in 2023 compared to 2022. No interaction effect of basalt and earthworms was found for N or P porewater concentrations. As expected, Ca, Mg, and Na concentrations significantly differed among the treatments, with a statistically significant basalt x earthworm interaction effect. Earthworms reinforced the increase of these concentrations by basalt (Fig 4, Fig S2, method S1). While Ca increased with basalt and earthworms, and Mg increased with basalt, the Ca/Mg ratio significantly decreased with basalt application, with a larger difference in 2023 (Fig 5).

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Figure 3: Porewater N and P concentrations during two consecutive growing seasons of maize (2022 and 2023) for the four treatments (C-worms = control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms: basalt with earthworms). The numbers of replicates in 2022 was eight, in 2023 four. p- and F-values and effect sizes (Ω^2 with 95% confidence interval (CI)) from a linear regression analysis are shown with concentration of N, or P as fixed effect, and basalt (B), earthworms (W), growing season (G), time (T) and their interaction as covariables. Interactions that were not statistically significant were excluded from the model. Statistically significant relationships are indicated by an asterisk (*).

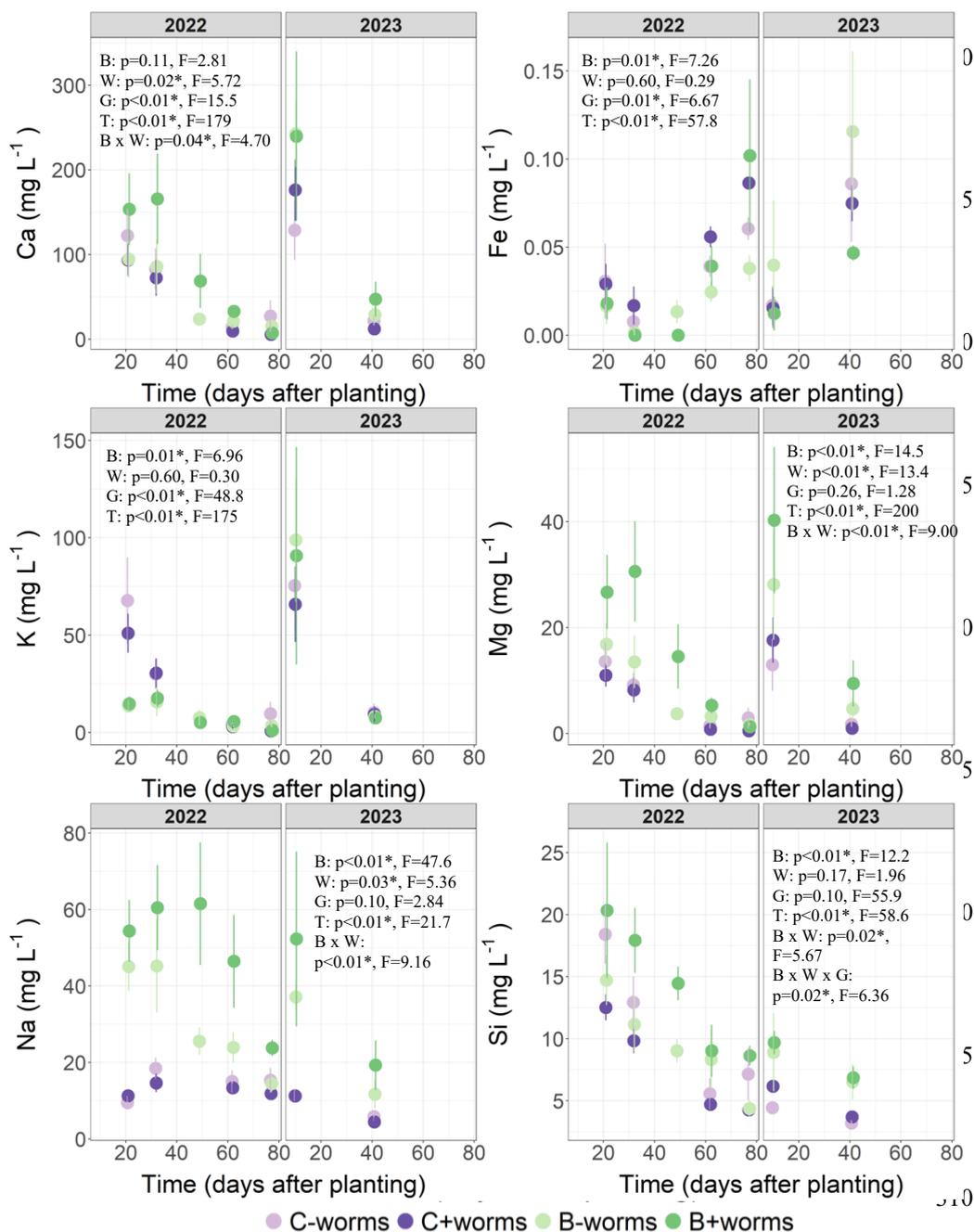


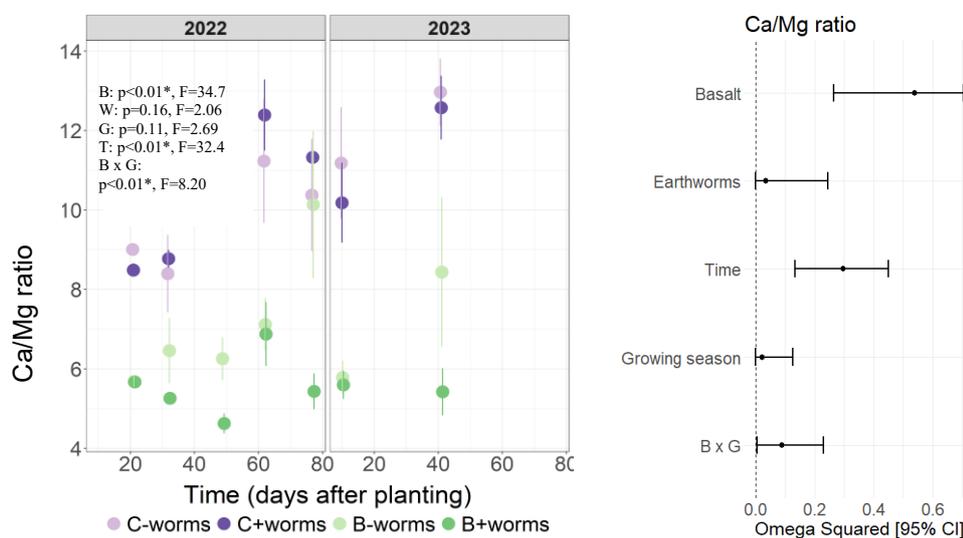
Figure 4: Porewater nutrient concentrations (Ca, Fe, K, Mg, Na, and Si) during two consecutive growing seasons of maize (2022 and 2023) for the four treatments (C-worms = control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms: basalt with earthworms). The number of replicates in 2022 was eight, in 2023 four. The p- and F-values from a linear regression analysis are shown with concentration of Ca, Fe, K, Mg, Na, or Si as fixed effect, and basalt (B), earthworms (W), growing season (G), time (T) and their interaction as covariables. Interactions that were not statistically significant were excluded from the model. Statistically significant relationships are indicated by an asterisk (*). Effect sizes (Ω^2) can be found in Fig S2.

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320 For Si, a significant three-way interaction effect was found of basalt x earthworms x growing season. The basalt-mediated increase of porewater Si concentrations was reinforced by earthworms in 2022, but not in 2023. Conversely, basalt decreased Fe and K concentrations in the porewater (Fig 4, Fig S2, method S1). This was not affected by earthworms and did not differ between the growing seasons.

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345 **Figure 5:** Ca/Mg ratio in the porewater during two consecutive growing seasons of maize (2022 and 2023) for the four treatments (C-worms = control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms). The numbers of replicates in 2022 is eight, in 2023 four. p- and F-values from a linear regression analysis are shown with Ca/Mg ratio as fixed effect, and basalt (B), earthworms (W), growing season (G), time (T) and their interaction as covariables. Interactions that were not statistically significant were excluded from the model. Statistically significant relationships are indicated by an asterisk (*). A forest plot of the effect sizes of basalt, earthworms, time, growing season and the statistically significant interaction are shown as Ω^2 with 95% confidence interval [CI].

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Porewater Cr concentrations were all below the limit of quantification (LOQ) (19.5 ppb), precluding statistical analysis. For Ni, 70% of the samples were below LOQ (19.4 ppb), and residuals of the model did not meet the assumption of normality.

355 Hence, no statistical analysis could be performed. Nonetheless, although not statistically supported, Ni concentrations in the porewater tended to be higher with basalt compared to the control, especially in the first growing season (Fig 6, method S1). Mn concentrations tended to be lower in the basalt treatments, but the homoscedasticity assumption was not met, precluding statistical analysis (Fig 6, method S1).

360 Porewater Al and Zn concentrations were all above LOQ, and both decreased significantly with basalt, while these were not significantly affected by earthworms (Fig 6, Fig S2). Only a tendency of higher Al concentrations with earthworms was found.

For Zn, this basalt effect was not affected by earthworms, while a significant growing season x basalt interaction effect was found for Al (Fig 6, Fig S2, method S1).

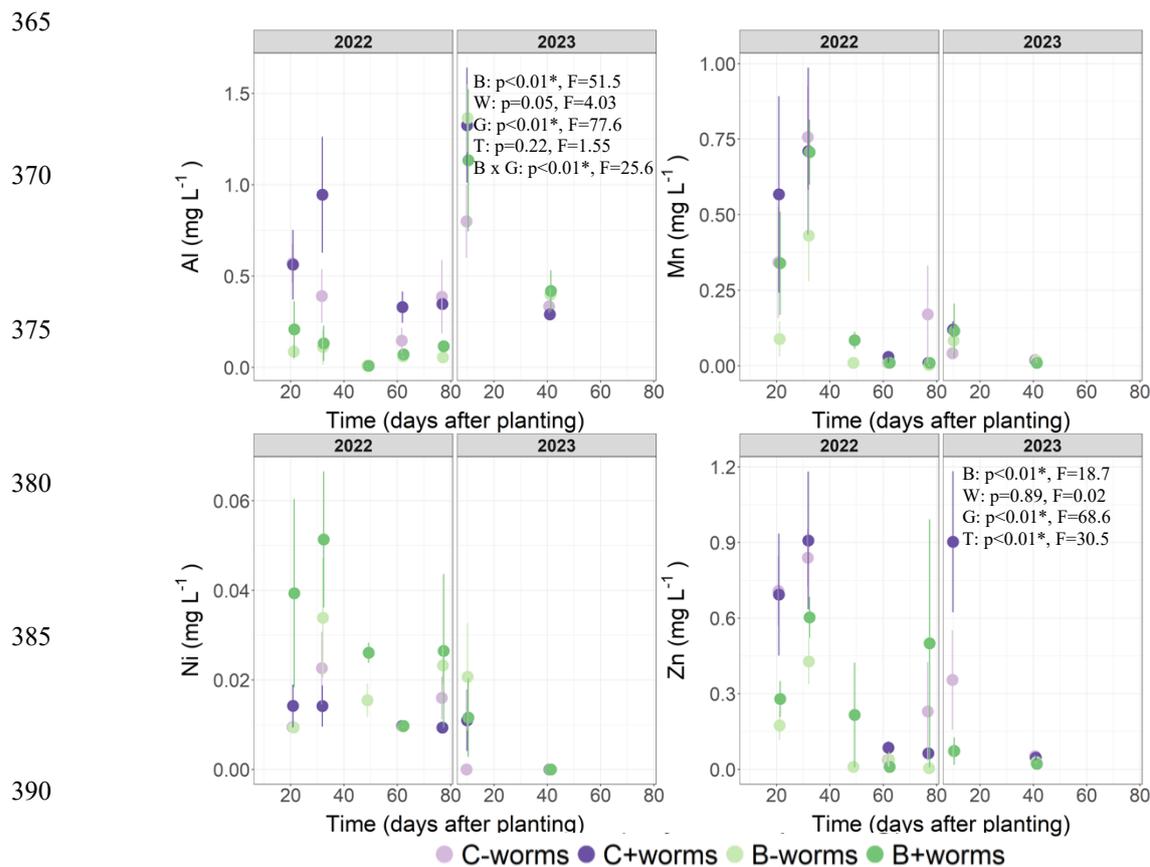
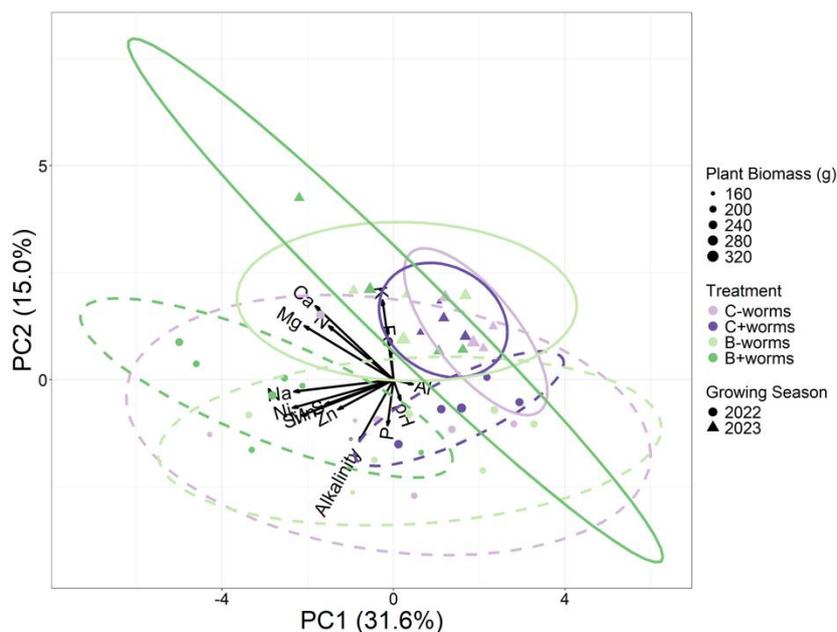


Figure 6: Porewater heavy metal concentrations (Al, Mn, Ni, and Zn) during two consecutive growing seasons of maize (2022 and 2023) for the four treatments (C-worms = control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms). Concentrations of Cr were all below the detection limit and are therefore not shown. The numbers of replicates in 2022 was eight, in 2023 four. p- and F-values from a linear regression analysis are shown with concentration of Al, Mn, Ni, or Zn as fixed effect, and basalt (B), earthworms (W), growing season (G), time (T) and their interaction as covariables. Interactions that were not statistically significant were excluded from the model. Statistically significant relationships are indicated by an asterisk (*). Effect sizes (Ω^2) for AL and Zn can be found in Fig S2.

A PCA of the soil variables showed that 31.6% of the variance of the data was explained by PC1, which was negatively correlated with Ca, Mg, Si, Ni, Mn, and Na. PC2 explained 15% of the variance within the data, which was positively correlated with Ca, K, N, and Mg, and negatively with P and alkalinity (Fig 7). A significant basalt x earthworm x growing season interaction effect was found on PC1 (Table 2). Values of PC1 decreased significantly with basalt in both growing seasons, but in 2022, only with earthworms (Fig S3, Table 2). Values of both PC1 and PC2 were significantly higher in 2023 than 2022 (Fig 7, Table 2).



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435 **Figure 7:** PC1 and PC2 of the principal component analysis with porewater nutrient concentrations (Ca, Fe, K, Mg, N, Na, PO₄³⁻, Si), heavy
 440 metal concentrations (Al, Mn, Ni, Zn), porewater pH, and alkalinity. Data shown for the four treatments (C-worms = control without
 earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) for the two
 growing seasons. Sizes represent the total biomass of the plants. The ellipses separate the four treatments for 2022 (dashed line), and for
 2023 (solid line). Statistical analysis can be found in Table 2.

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Table 2: p- and F-values of values from a linear regression analysis with PC1 or PC2 as fixed effect, and basalt (B), earthworms (W), growing
 season (G) and their interaction as covariables. For PC1, a significant three way interaction was found, and data were analysed for both
 growing seasons separately to simplify the outcome (Fig S3). Interactions that were not statistically significant were excluded from the
 445 model. Statistically significant relationships are in bold and indicated by an asterisk (*).

	PC1		PC2		PC1 2022		PC1 2023	
	p-value	F	p-value	F	p-value	F	p-value	F
B	<0.01*	11.5	0.94	<0.01	0.02*	6.42	0.02*	6.96
W	0.16	2.07	0.05*	4.18	0.24	1.43	0.31	1.09
G	0.03*	5.41	<0.01*	73.3	na	na	na	na
B*W	<0.01*	9.61	ns	ns	<0.01*	12.7	ns	ns
B*G	0.65	0.21	ns	ns				
W*G	0.89	0.02	ns	ns				
B*W*G	0.01*	6.84	ns	ns				



3.3 Plant growth and nutrients

460 Even though plant height showed a significant basalt x earthworm interaction effect, which differed between the growing seasons, the high variability of the effect size suggests that the effect may not be consistently reliable across different samples. Despite differences in plant height, aboveground biomass of the different plant parts, total aboveground and belowground biomass, and LAI were unaffected by basalt addition or earthworm presence, except for the leaf biomass in 2022 (Fig S4, Fig S5, Fig S6, Table 3). Here, a basalt x earthworm interaction effect was found (Table 3); basalt significantly decreased leaf biomass, but only with earthworms (Fig S4). However, Ω^2 was small and showed high variability.

Table 3: p- and F-values from a linear regression analysis with biomass of the different plant parts, and total biomass, as fixed effect, and basalt (=B), earthworms (=W) and their interaction (B x W) as covariables for both growing seasons. Interactions that were not significant were excluded from the model and are shown as 'ns'. For 2023, no significant interactions were detected and are thus not shown here. 470 Statistically significant relationships are in bold and indicated by an asterisk (*) (Figure S4, Fig S5). The effect sizes (Ω^2) with 95% confidence interval [CI] are shown for the statistically significant findings.

	<i>Stem</i>		<i>Leaves</i>			<i>Corn</i>		<i>Tassel</i>		<i>Total biomass</i>	
2022	p-value	F	p-value	F	Ω^2 [95%CI] (leaves)	p-value	F	p-value	F	p-value	F
<i>B</i>	0.69	0.17	<0.01*	13.4	0.28 [0.04, 0.51]	0.97	<0.01	0.41	0.69	0.11	2.71
<i>W</i>	0.35	0.56	0.67	0.18	0.00 [0.00, 0.00]	0.31	1.08	0.07	3.46	0.10	2.84
<i>B x W</i>	ns	ns	0.03*	5.01	0.11 [0.00, 0.35]	ns	ns	ns	ns	ns	ns
	Stem		Leaves		Corn			Tassel		Total biomass	
2023					Ω^2 [95%CI] (corn)						
<i>B</i>	0.54	0.40	0.54	0.40	0.00 [0.00, 0.00]	0.40	0.77	0.40	0.75	0.38	0.82
<i>W</i>	0.31	1.10	0.57	0.35	0.19 [0.00, 0.52]	0.048*	4.75	0.58	0.33	0.13	2.65

The model selected by the AIC method to investigate which soil parameters influenced total aboveground biomass included Ca, Fe, K, Na, P, and Zn concentrations in the soil porewater. The regression model was statistically significant ($F=3.90$, $p<0.01$) and explained approximately 40.1% of the variance in biomass ($R^2=0.40$). Of these variables, total aboveground biomass was significantly positively correlated with soil porewater Ca ($p=0.04$) and Fe ($p<0.01$), and significantly negatively correlated with Zn concentrations ($p=0.02$). A borderline significant negative effect was found for Na ($p=0.05$), while P and K did not significantly affect biomass ($p=0.20$, and 0.19 , respectively). Plant biomass was not associated with PC1, while it was significantly positively associated with PC2 (Fig 7, Fig S7), which is positively correlated with porewater Ca, K, N, and Mg concentrations, and negatively with porewater P concentrations, and alkalinity.

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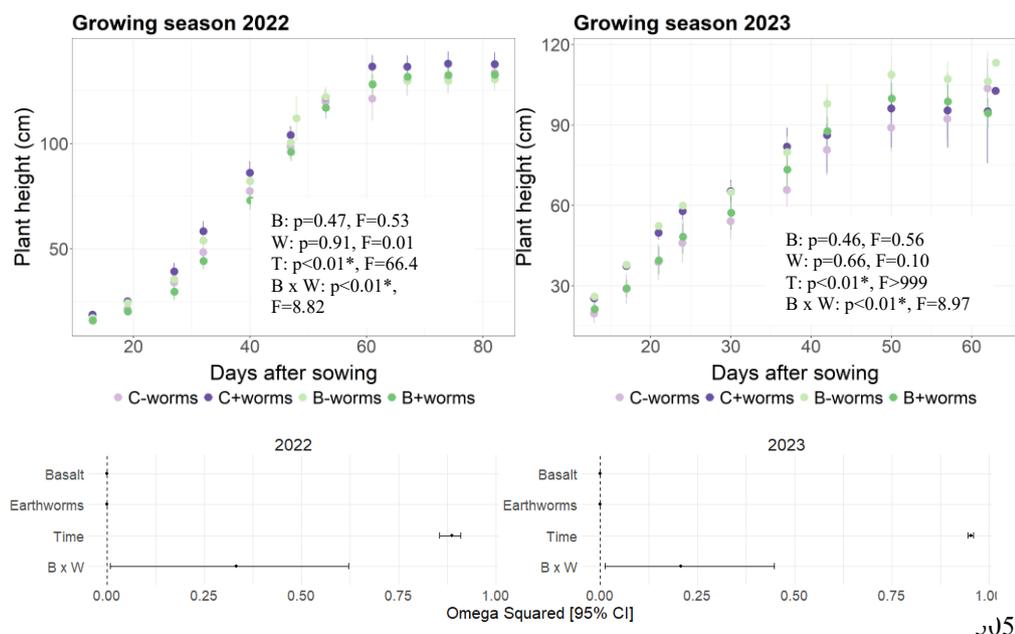


Figure 8: Plant height during the experiment of the four treatments (C-worms= control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) for growing season 2022, and 2023. p- and F-values are shown for a linear regression analysis with plant height as fixed effect and basalt (B), earthworms (W), time (days after sowing, T) and their interaction as covariables. Interactions that were not statistically significant and were excluded from the model. Statistically significant relationships are indicated by an asterisk (*). Forest plots of the effect sizes of basalt, earthworms, time, growing season and the statistically significant interaction are shown (Ω^2) with 95% confidence interval [CI] for both growing seasons.

Basalt application significantly affected plant nutrient concentrations in both growing seasons, with especially increasing concentrations of Mg and Si (Fig 9, Fig 10, Fig S8, Fig S9). As expected, basalt application significantly increased Mg concentrations in the stem after the first growing season, and in the leaves and roots after both growing seasons (Fig 9, Fig 10). This influence was not affected by earthworms, and no significant effect of basalt on corn and tassel Mg concentrations was found. Si concentrations also increased with basalt in the stem, leaves and tassel after the first growing season. In 2023, a significant basalt x earthworm interaction effect was observed on tassel Si concentrations. With earthworms, basalt increased tassel Si concentrations, but not without earthworms (Fig 9, Fig 10).

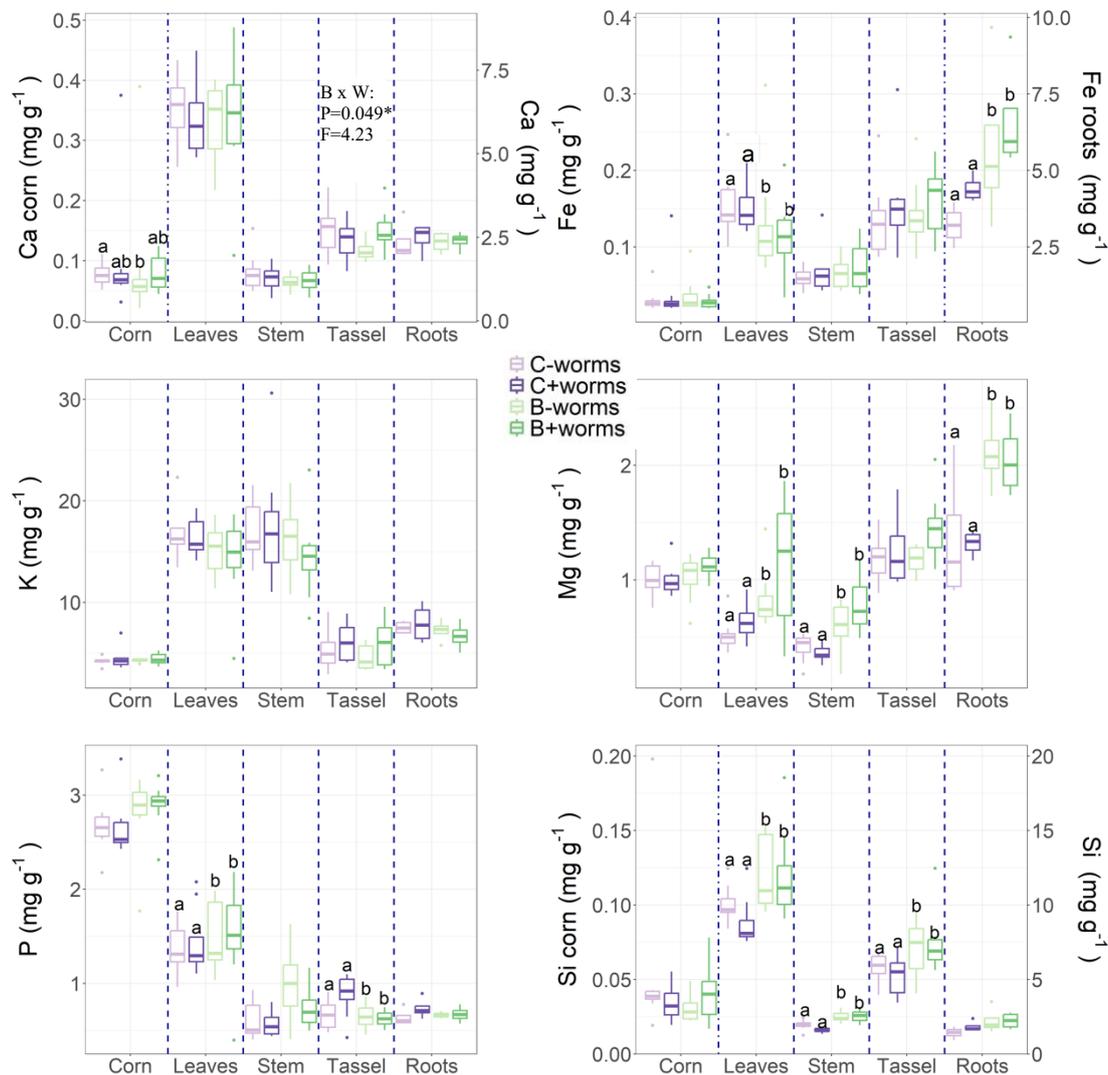
While Mg and Si increased, corn Ca concentrations decreased with basalt when earthworms were present, but only in 2022. Furthermore, a significant basalt x earthworm interaction effect was found on tassel Ca in 2022, and corn Ca concentrations in 2023. For both, earthworms increased their Ca concentration when basalt was added, while without basalt, earthworms decreased or had no influence on Ca concentrations (Fig 9, Fig 10, Table S3, Table S4).



Basalt decreased leaf Fe concentrations in 2022, while increasing Fe concentrations in the roots in 2022 and 2023, and in the stem and tassel in 2023 were found (Fig 9, Fig 10, Fig S8, Fig S9, Table S3, Table S4). These effects were not affected by earthworms. Furthermore, P concentrations increased in leaves, but decreased in the tassel in 2022 without any effect of earthworms. In 2023, a basalt x earthworm interaction effect was found on leaf P concentrations (Table S4). These increased with earthworms when basalt was applied, while no effect of earthworms was found without basalt (Fig 10). In 2023, basalt significantly decreased stem K concentrations in the treatment without earthworms, but no effect was found of basalt in the presence of earthworms (Fig 10, Table S4).

535 Lastly, earthworms increased C concentrations in leaves, while C concentrations in the tassels, and roots decreased with worms. Basalt did not affect plant C concentrations in 2022 (Fig 11, Table S3). On the contrary, in 2023, a significant basalt x earthworm interaction effect was found on stem C concentrations, with an increase with basalt but only without earthworms, and an increase with earthworms but only without basalt (Fig 11, Table S4).

540



585 **Figure 9:** Concentrations of Ca, Fe, K, Mg, P, and Si in the corn, leaves, stem, tassel, and roots for the four treatments (C-worms= control
 without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) in
 maize of growing season 2022. Note that for Ca and Si, corn concentrations are shown on the primary y-axis, while concentrations in the
 other parts are shown on the secondary y-axis. Root Ca concentrations are shown on the secondary y-axis, and concentrations in the other
 plant parts on the primary y-axis. p- and F-values are shown in table S3. Different letters indicate significant differences between treatments.
 590 P- and F-values are shown of a significant interaction when this did not lead to clear differences among treatments. If no letters are shown
 for a combination of plant part and element, this means that there was no statistically significant influence of basalt or earthworms. Effect
 sizes (Ω^2) of statistically significant differences can be found in Fig S8.

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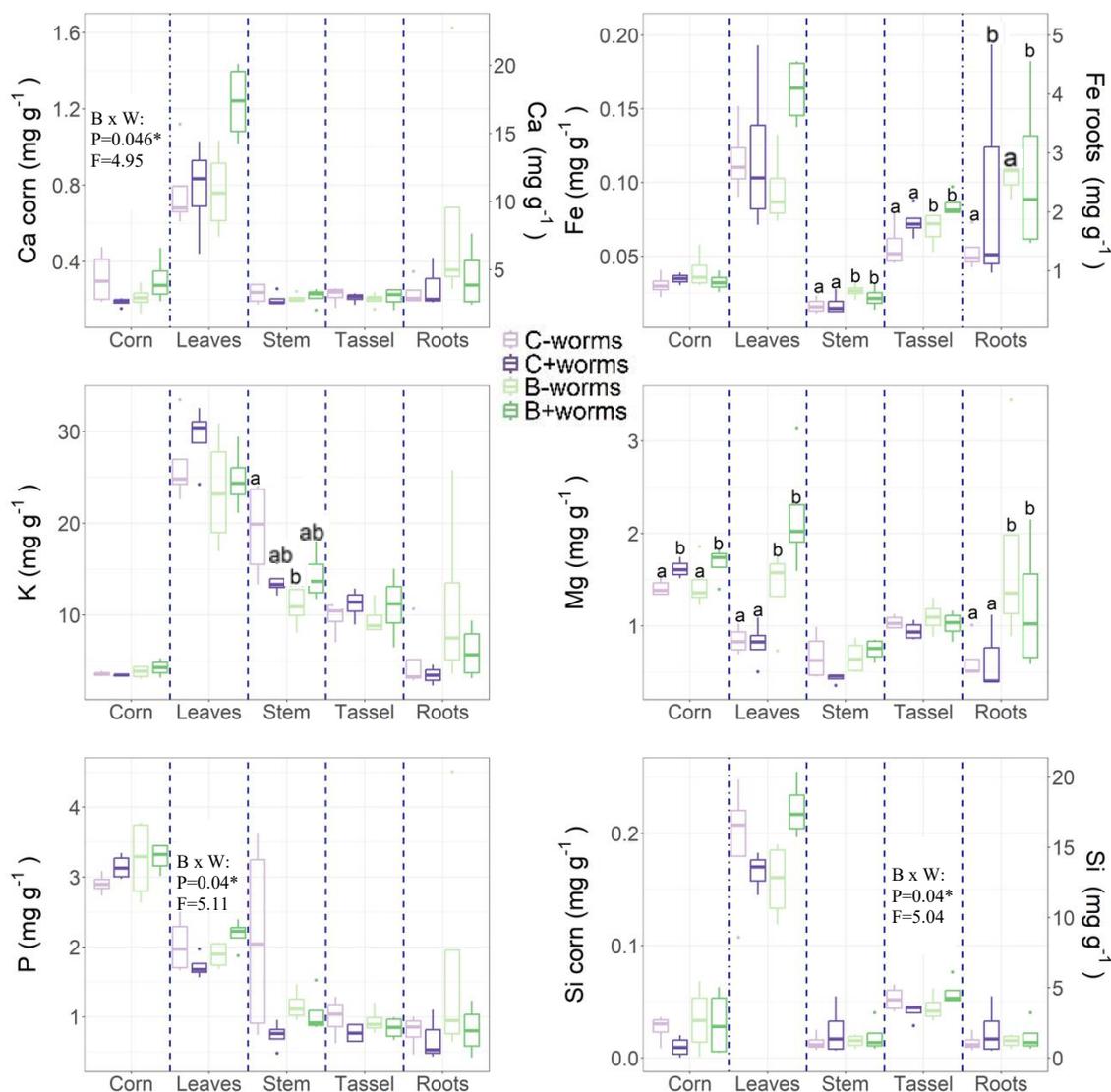


Figure 10: Concentrations of Ca, Fe, K, Mg, P, and Si in the corn, leaves, stem, tassel, and roots for the four treatments (C-worms= control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) in maize of growing season 2023. Note that some concentrations are shown on the secondary y-axis. p- and F-values are shown in table S4. Different letters indicate statistically significant differences between treatments. P- and F-values are shown of a statistically significant interaction when this did not lead to clear differences among treatments. If no letters are shown for a combination of plant part and element, this means that there was no statistically significant influence of basalt or earthworms. Effect sizes (Ω^2) of statistically significant differences can be found in Fig S9.

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Tassel N concentrations were significantly higher in the control treatment with earthworms compared to the other treatments in 2022. In 2023, stem N concentrations significantly increased with basalt (Fig 11). A borderline significant basalt x earthworms interaction effect was found for leaf N concentrations in 2023 (Table S4). The treatment with basalt and earthworms showed significantly higher N concentrations compared to the other treatments, while basalt or earthworms alone did not affect leaf N concentrations (Fig 11).

Basalt and earthworms also significantly altered nutrient ratios in the plants. The C/N ratio significantly decreased with earthworms in the tassel in 2022, and in leaves in 2023 (Fig 12, Table S3, Table S4). Basalt significantly decreased the stem C/N ratio. The N/P ratio in the corn, leaves, and stem significantly decreased with basalt in 2022. In 2023, on the other hand, basalt did not affect the N/P ratio, while earthworms decreased N/P ratios in the leaves, and stem. Furthermore, Ca/Mg ratios significantly decreased with basalt in all plant parts in 2022, while these were not affected by earthworms. Also in 2023, basalt significantly decreased Ca/Mg ratios in the leaves, stem, and roots. In the stem, this decrease only occurred when earthworms were present. A significant basalt x earthworm interaction effect was observed for the Ca/Mg ratio in the corn; the Ca/Mg ratio increased with basalt in the presence, but not in the absence of earthworms. Except for a significant increase in the Ca/Mg ratio in the tassel, earthworms did not affect the Ca/Mg ratio (Fig 12, Table S3, Table S4).

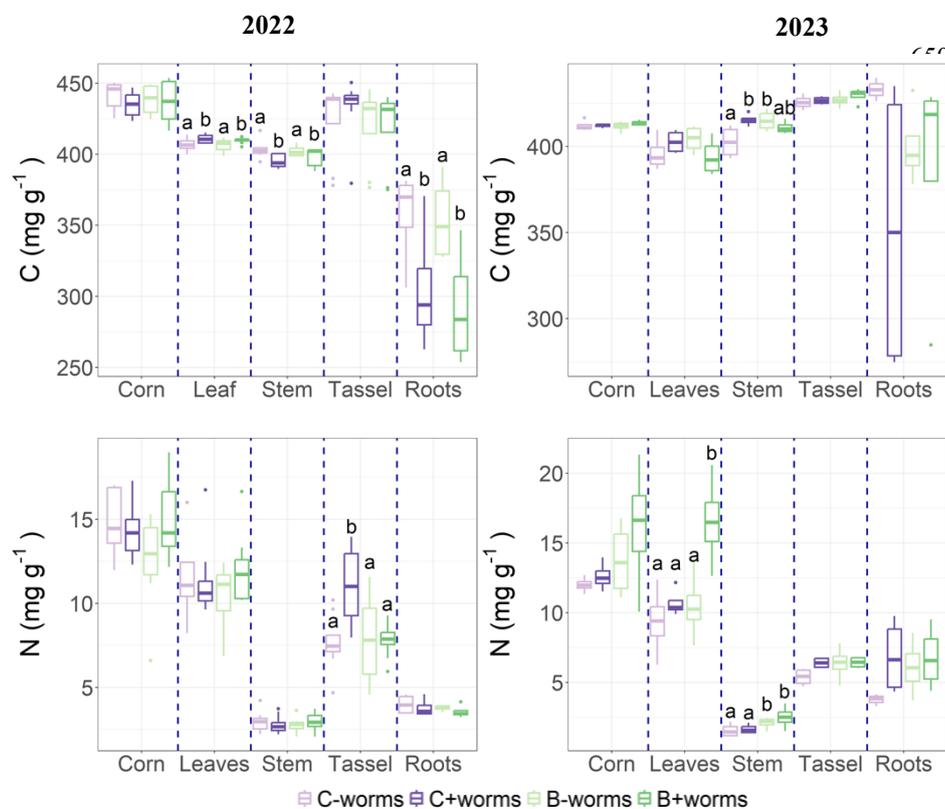
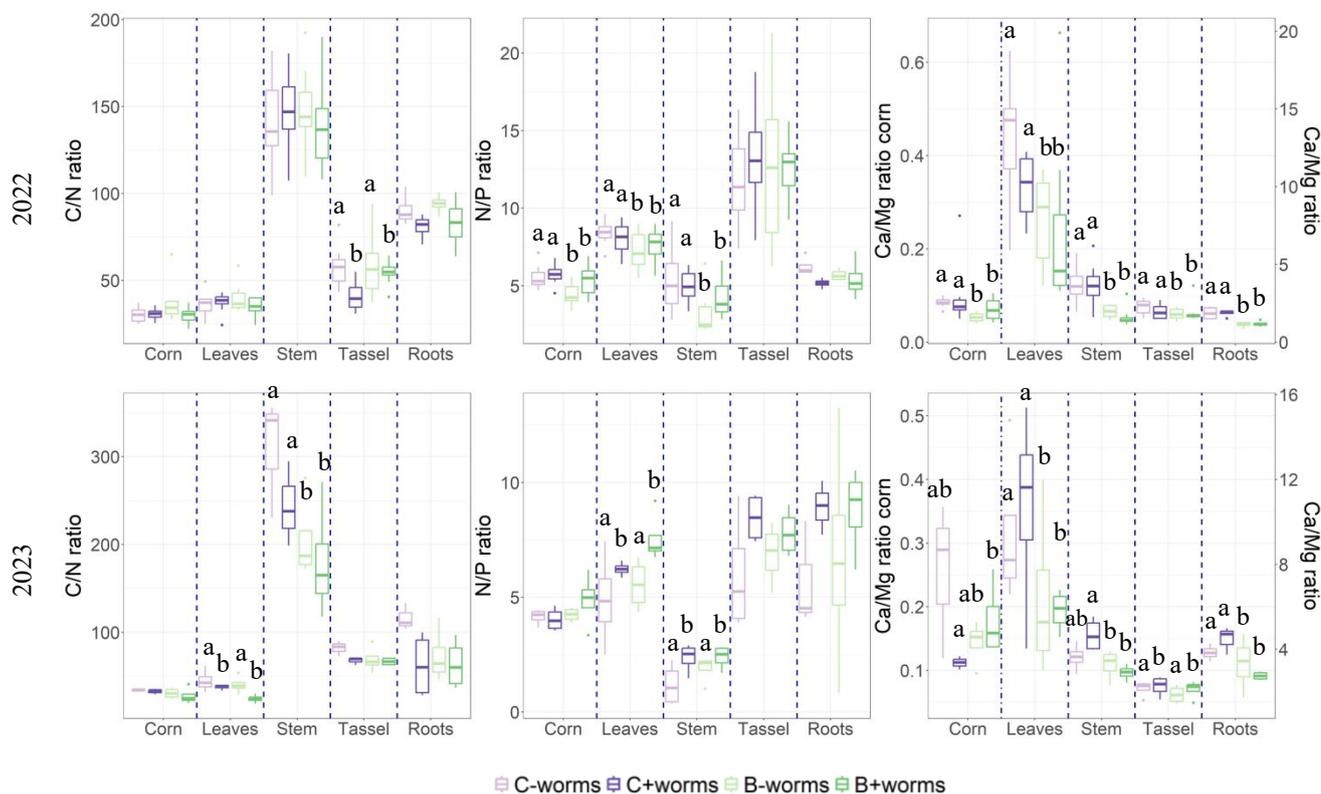


Figure 11: Concentrations of C and N in the corn, leaves, stem, tassel, and roots for the four treatments (C-worms = control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) for both growing seasons. p- and F-values are shown in table S3 and S4 and effect sizes (Ω^2) of statistically significant differences can be found in Fig S8 and S9. Different letters indicate statistically significant differences between treatments.

670



675 **Figure 12:** C/N, N/P, and Ca/Mg ratios in the corn, leaves, stem, tassel, and roots for the four treatments (C-worms= control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) for both growing seasons. p- and F-values are shown in table S3 and S4. Different letters indicate statistically significant differences among treatments. Effect sizes (Ω^2) of statistically significant differences can be found in Fig S8 and S9.

3.4 Plant heavy metals

Basalt application influenced heavy metal concentrations in above- and belowground plant parts, especially in the first growing season. In 2022, basalt affected concentrations of Al, Cr, Cd, and V in the plant parts, while earthworms did not. Basalt significantly decreased leaf Al concentrations, and corn and tassel Cd concentrations, but tassel Cr, and roots Al and V concentrations significantly increased with basalt (Fig 13, Table S5). In 2023, plant concentrations of Al, Cr, Cd, and V were not affected by basalt or earthworms (Fig 14, Table S6). Concentrations of Ni, Pb, and Zn were affected by basalt in both growing seasons. Basalt significantly increased root Ni concentrations, and decreased leaf Ni concentrations in both growing seasons. In 2022, tassel Ni concentrations increased significantly with basalt as well (Fig 13, Table S5). Concentrations of Zn decreased significantly with basalt application compared to without basalt in all plant parts in 2022, while in 2023 Zn concentrations increased only in the roots and stems. Earthworm presence did not affect plant Zn concentrations.

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Lastly, a significant basalt x earthworm interaction effect was found on Pb concentrations in the roots in 2022, while in 2023, this was the case for leaves and corn Pb concentrations (Fig 13, Fig 14, Table S5, Table S6). In 2022, basalt did not affect root Pb concentrations when earthworms were present, while without earthworms, Pb concentrations were significantly higher with basalt application. In 2023, leaf Pb concentrations increased with basalt application in the presence of earthworms, while in the absence of earthworms, basalt decreased leaf Pb concentrations. Corn Pb concentrations were significantly higher in the treatment with basalt and earthworms (Fig 14, Table S6).

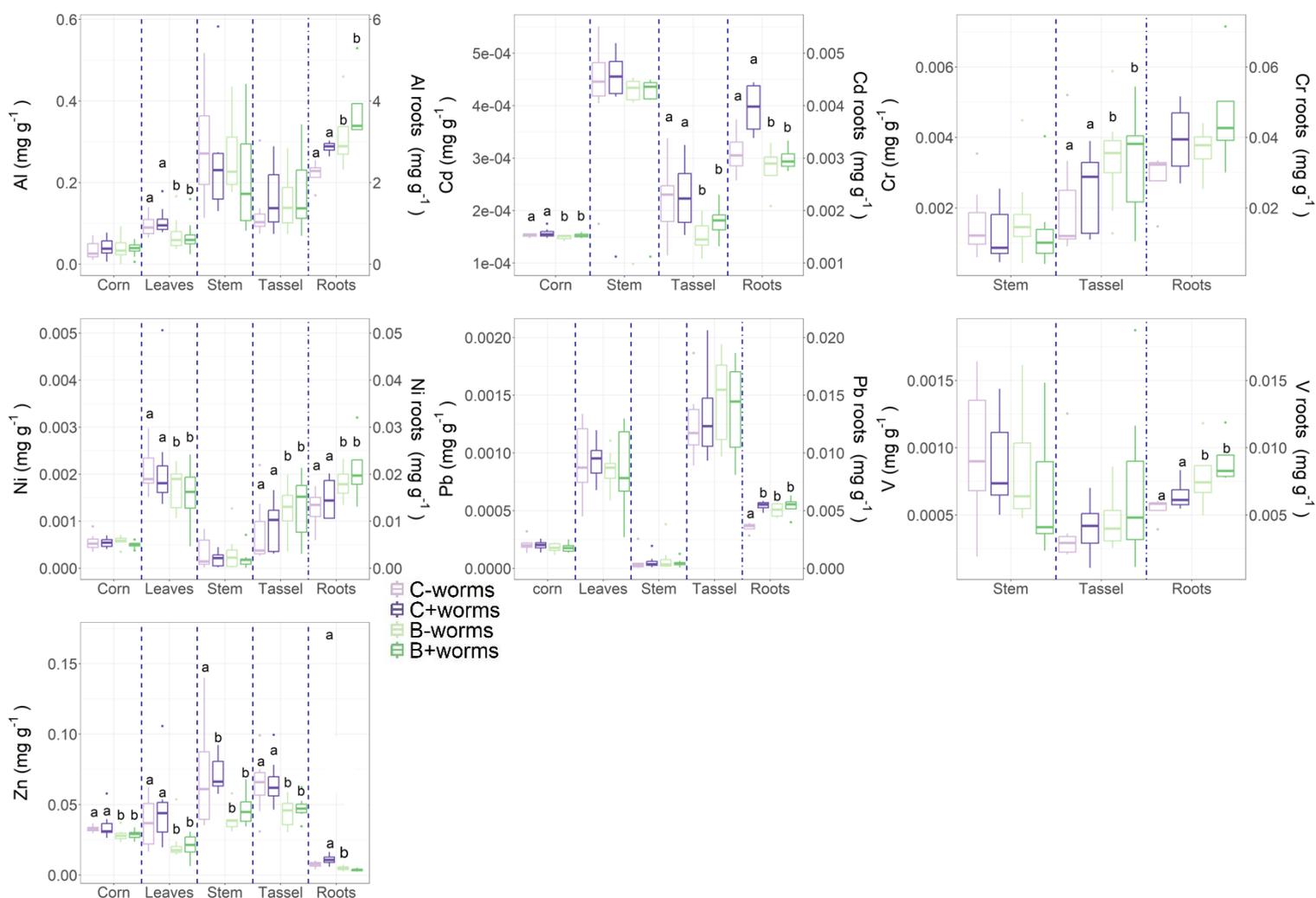


Figure 13: Concentrations of Al, Cd, Cr, Ni, Pb, V, and Zn in the corn, leaves, stem, tassel, and roots for the four treatments (C-worms= control without earthworms, C+worms = control with earthworms, B-worms = basalt without earthworms, B+worms = basalt with earthworms) in maize of growing season 2022. Note that for Al, Cd, Cr, Ni, Pb, and V, root concentrations are shown on the secondary y-axis, while concentrations in the other plant parts are shown on the primary y-axis. p- and F-values are shown in table S5. Different letters indicate statistically significant differences between treatments. Effect sizes (Ω^2) of statistically significant differences can be found in Fig S10a.

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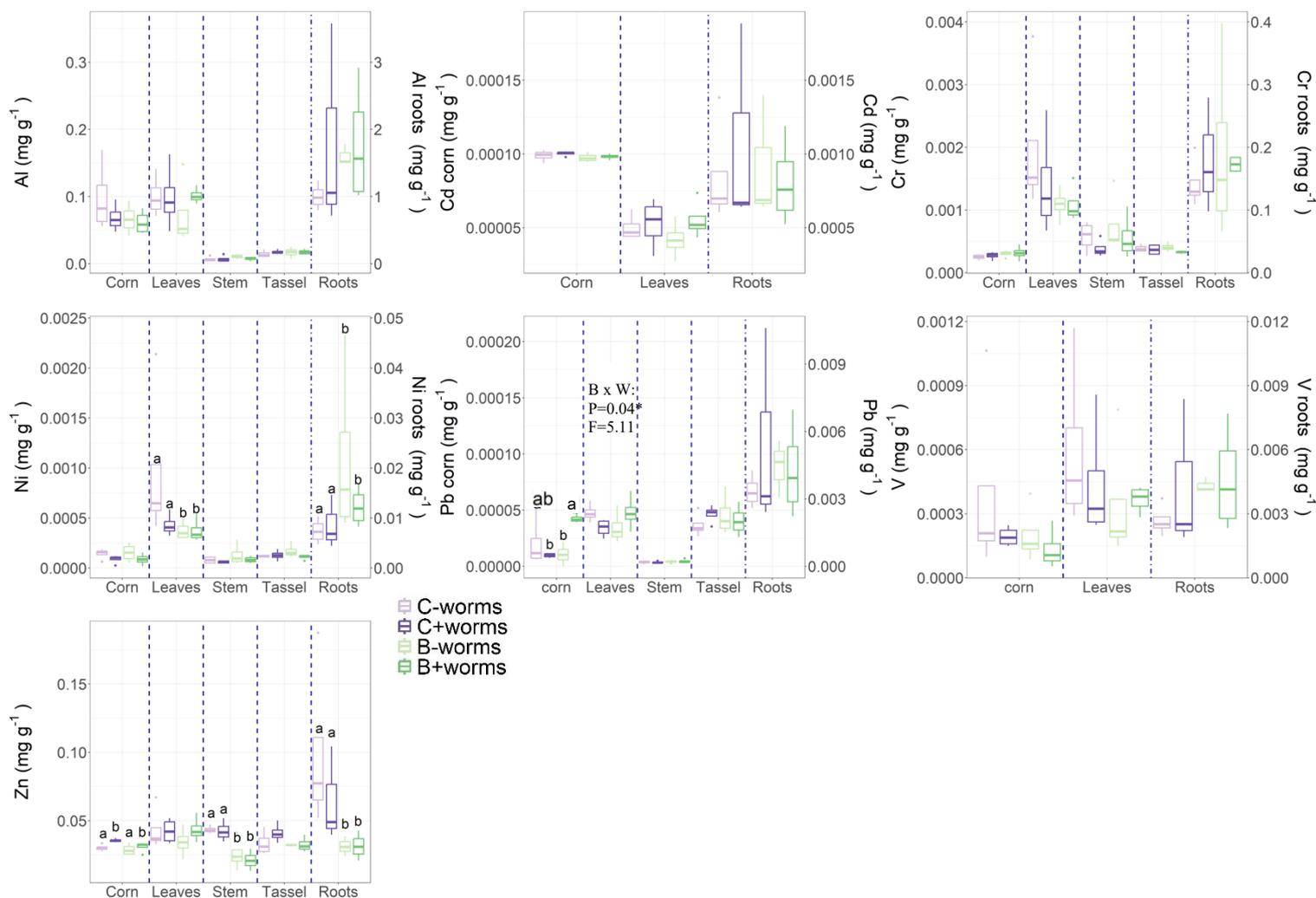


Figure 14: Concentrations of Al, Cd, Cr, Ni, Pb, V, and Zn in the corn, leaves, stem, tassel, and roots for the four treatments (C-worms= control without worms, C+worms = control with worms, B-worms = basalt without worms, B+worms = basalt with worms) in maize of growing season 2023. Note that for Al, Cd, Cr, Ni, Pb, and V, root concentrations are shown on the secondary y-axis, while concentrations in the other plant parts are shown on the primary y-axis. p- and F-values are shown in table S6. Different letters indicate statistically significant differences between treatments. P- and F-values are shown of a significant interaction when this did not lead to clear statistically significant differences among treatments. Effect sizes (Ω^2) of statistically significant differences can be found in Fig S10b.

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4. Discussion

715 4.1 Soil properties

Porewater pH and concentration of Ca, Mg, Na, and Si – elements that were abundant in fast weathering minerals of the basalt - increased with basalt application. This confirms our hypothesis that basalt improves nutrient availability. Earthworms decreased the porewater pH, but not when basalt was added, suggesting that basalt counteracted the soil acidification effect of the earthworms. Decreased porewater pH with earthworms could be related to the production of organic acids by earthworms and to increased microbial activity in the presence of earthworms, acidifying the surrounding soil (Atiyeh et al., 2002; Canellas et al., 2002; Kögel-Knabner & Amelung, 2021; Lubbers et al., 2017).

720 In line with our hypothesis, earthworms reinforced the basalt-induced increases in porewater nutrient concentrations (Ca, Mg, Na, and Si), confirming a positive synergistic relationship between earthworms and basalt. The burrowing activity of earthworms can mechanically break down the silicate materials, while also increasing soil porosity and water infiltration (Six et al., 2004). Along with increased microbial activity and production of organic acids, these processes can stimulate weathering of basalt (Bayon et al., 2021). This contrasts with findings of Calogiuri et al. (2025), where alive earthworms did not affect weathering parameters in column experiments. On the other hand, dead earthworms significantly increased weathering products, potentially related to the associated microbial processes.

730 In contrast to these increases, porewater Fe, K, Al, Ni, and Zn concentrations decreased with basalt, even though the basalt used in this study contained trace amounts of these elements (Table S1). The lower Fe, Al, and Zn concentrations are presumably due to the increase in pH. With increasing pH, formation of insoluble Fe compounds is stimulated, reducing Fe availability (Lindsay & Schwab, 1982; Shenker & Chen, 2005). The availability of Al, Ni, and Zn also decreases drastically when soils become more neutral or alkaline (Malekzadeh et al., 2015; Suganya et al., 2020; Yusuf et al., 2011). Potentially, 735 the tendency of elevated Ni concentrations in the first growing season did not persist because of increases in pH, and a reduced weathering rate of basalt in the second growing season. Next, the release of Mg, Ca, and K from basalt can cause leaching of K present in the topsoil (Jalali, 2008). Furthermore, clay formation can affect the availability of elements, for example Fe, Al, and also K. Al and Fe are constituents of a variety of clay minerals and/or (hydr)oxides, whereas K is often fixed in clay interlayers (Kome et al., 2019). In the same experiment, Steinwider et al. (2025) found indications of enhanced clay formation 740 in the basalt treatments, thus potentially decreasing Al, Fe, and K in the porewater.

In the treatments without basalt, earthworms had minimal effects on nutrient or heavy metal concentrations in porewater. Generally, earthworms are expected to increase nutrient availability for plants by breaking down organic matter and by stimulating microbial activity, further increasing decomposition (Bertrand et al., 2015; Blouin et al., 2013). However, the 745 organic content of the initial soil was relatively low (0.8%) (Rusco et al., 2001), providing limited material for earthworms to digest and thereby potentially diminishing their impact on porewater nutrient concentrations (Lentiri et al., 2014). Even though

plants increased C inputs into the soil, endogeic earthworms are specialized in consuming older, stabilized soil carbon (Ferlian et al., 2014). This might also explain the lack of influence of earthworms on heavy metal availability in our study, as decomposition of organic material can also release heavy metals into the porewater (Nyiramigisha et al., 2021; Parvin et al., 2022). Furthermore, the high variability of the effect sizes of basalt and earthworms on porewater chemistry is probably due to the highly fluctuating nature of porewater dynamics. Previous studies have reported both positive and negative effects of earthworms on heavy metal availability (Karaca et al., 2010; Ma et al., 2002; Sizmur & Hodson, 2009; Wen et al., 2004). The high variability in the effects of basalt and earthworms on porewater chemistry, likely due to the highly dynamic nature of porewater processes, makes it difficult to draw firm conclusions.

4.2 Plant growth and nutrients

The higher biomass in 2022 compared to 2023 can likely be related to environmental factors such as precipitation and temperature. While the summer of 2022 was sunny, warm and dry, the summer of 2023 was more cloudy, less warm and wetter (Fig S1). Given that plants were irrigated to avoid drought stress, growing conditions were thus more favourable in 2022. Like plants, earthworms were unaffected by basalt application in our study, This contrasts with the field experiment of Dupla et al. (2024), where earthworm abundance increased in response to basaltic rock powder. Dupla et al. (2024) suggested this may be due to increased microbial activity (evidenced by higher soil respiration) attracting earthworms. In our mesocosms, however, lateral movement toward treated plots was not possible, preventing such responses. Nonetheless, also in our experiment, soil respiration increased during the first year following basalt application (Boito et al., 2025), indicating increased microbial activity. This suggest that under field conditions where earthworms can migrate, similar responses to those reported by Dupla et al. (2024) could occur.

Overall, plant biomass was not affected by basalt or earthworms, contradicting the hypothesis of increased biomass with basalt. In fact, leaf biomass even decreased with basalt in combination with earthworms in the second growing season. To explain the limited impact on biomass, we examined porewater nutrient dynamics. The PCA revealed that biomass was positively associated with PC2, which is positively correlated with porewater concentrations of Ca, K, N, and Mg, and negatively with porewater P concentrations and alkalinity. Basalt increased porewater Ca, N, and Mg but reduced K concentrations. However, the latter was not statistically significantly related to aboveground plant biomass. Instead, biomass was positively correlated with porewater Fe and Ca concentrations, and negatively with porewater Zn concentrations. Basalt altered porewater chemistry in opposing ways: increases in Ca and decreases in Zn were associated with higher aboveground biomass, but simultaneous reductions in Fe were associated with lower biomass. These constraining effects may explain why basalt did not consistently increase aboveground biomass. Nevertheless, the model selected using AIC only explained 40% of the variance in biomass, suggesting that other factors might have played a role as well.



780 Whereas plant biomass did not differ among the treatments, plant nutrient concentrations were significantly affected by basalt
and earthworms. In general, basalt increased plant concentrations of Mg, and Si in both growing seasons. These increases can
be directly linked with increased concentrations in the porewater. On the contrary, corn Ca concentrations decreased, which is
inconsistent with porewater Ca concentrations. The decrease of the porewater Ca/Mg ratio with basalt application can
potentially explain this inconsistency, as Ca and Mg compete for binding sites at the plant root (Kopsell et al., 2013). This
finding aligns with results of ten Berge et al. (2012) and Rijnders et al. (2024).

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Basalt application increased Fe and P concentrations in some plant parts, especially in 2023, despite a decrease in porewater
Fe and P concentrations. This suggests that Fe and P release during basalt weathering may have elevated the exchangeable Fe
and P levels in the soils, improving the soil's capacity to supply these nutrients when they are taken up by the crops. The higher
acidity of the rhizosphere and excretion of siderophores can also make Fe and P more soluble in proximity to the roots,
790 improving the uptake by the plants (Hochmuth, 2011; Mcnear, 2013; Morrissey & Guerinot, 2009; Penn & Camberato, 2019).

There was almost no effect of earthworms on plant nutrients, except for increased corn Mg concentrations in 2023. Earthworms
did increase tassel Ca concentrations in 2022, and leaf P, corn Ca, and tassel Si concentrations in 2023, but only with basalt.
This means that the combined effect of earthworms and basalt had a positive influence on nutrient uptake by plants, which can
795 be attributed to increased availability of these nutrients when both earthworms and basalt were added. Earthworms also
alleviated the negative effect of basalt on stem K concentrations in 2023, which decreased with basalt but only without
earthworms. Earthworms digest organic matter and leave casts behind that are rich in exchangeable nutrients, also K (Lemtiri
et al., 2014; Van Groenigen et al., 2019). These casts are local nutrient-rich hotspots, and even though K from casts is available
for plants, this does not per se translate into higher porewater K concentrations.

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Although we added earthworms to mimic a typical density in agricultural soils, earthworms may occur in much higher
numbers, typically ranging from 100 to 500 individuals per m², and can go as high as 2000 individuals per m² (Lavelle et al.,
1997). When more sustainable agricultural practices are applied with less disturbing tillage practices, a higher diversity and
density of earthworms, covering endogeic and anecic earthworms, is expected (Spurgeon et al., 2013), likely improving their
805 influence on nutrient availability and soil characteristics and also plant growth (Bertrand et al., 2015; Blouin et al., 2013; Six
et al., 2004).

4.3 Plant heavy metals

The release of heavy metals during basalt weathering poses a risk for heavy metal accumulation in plants, but in contrast to
our hypothesis, basalt mostly decreased heavy metal concentrations in the aboveground plant parts with the exception of
810 increased tassel Cr and Ni concentrations.



Even though our basalt contains Al, Ni, and Zn, some aboveground plant parts showed significant decreases in the concentrations of these heavy metals with basalt application. The negative basalt effect on plant Zn concentrations aligns with the reduced Zn availability that may be attributed to the pH increase. In contrast, basalt increased porewater Ni concentrations, leading to accumulation of Ni in the plant roots. Accumulation of heavy metals, such as Al, Ni, and V, in the roots is a common defense mechanism of plants, limiting their transport to the aboveground plant parts (Baccouch et al., 2001). Additionally, some heavy metals are also transported through bivalent cation transporters (Shen et al., 2016). Hence, higher Mg^{2+} concentration in the roots can prevent heavy metals transport to aboveground tissue. This may explain the lack of increased Ni concentrations in aboveground tissue with the exception of increased tassel Ni concentrations. The latter might reflect the high mobility of Ni in the phloem, and the redistribution of Ni from older vegetative tissues like leaves to reproductive organs (Page & Feller, 2015).

The decreased leaf Al concentrations align with decreases in porewater Al concentrations, but Al significantly accumulated in the roots in 2022, indicating that Al availability increased in the proximity of the rhizosphere. Excretion of organic acids and protons by plants and associated AMF, and rhizosphere respiration can locally decrease soil and porewater pH in comparison to the bulk soil (Mcneer, 2013), potentially increasing Al availability in proximity of the roots. Plants can accumulate Al in their roots, and as Al is released with basalt weathering, this was likely more bio-available in the basalt treatments compared to the control.

Like Al, Cd availability was probably affected by pH as well, as basalt significantly reduced plant Cd concentrations. Whether this is in alignment with porewater Cd concentrations could not be verified because Cd was below LOQ in all porewater samples, but the increased pH with basalt application potentially decreased Cd availability (Xian & Shokohifard, 1989). Decreased plant Cd levels were also found in rice upon steel slag application (He et al., 2020).

Unlike other heavy metals, Ni and Zn are essential micronutrients required at very low concentrations for various physiological and biochemical processes in plants. Ni is a key component of enzymes involved in the N cycle, such as urease, and its deficiency can lead to accumulation of urea in plants (Kamboj et al., 2018; Yusuf et al., 2011). Zn is involved in physiological pathways and ensures membrane integrity (Mattiello et al., 2015; Suganya et al., 2020). Deficiency of Ni and Zn can result in reduced crop growth, lower yield and lower quality of crops (Mattiello et al., 2015; Suganya et al., 2020). Like deficiency, excess concentrations of both elements are toxic for plants and can reduce crop growth (Abedi et al., 2022; Hassan et al., 2019). However, plant Ni and Zn concentrations in our study ($Ni < 0.003 \text{ mg g}^{-1} \text{ dw}$, and $Zn < 0.15 \text{ mg g}^{-1}$) were well below phytotoxic thresholds for Ni ($0.01 - 0.05 \text{ mg g}^{-1} \text{ dw}$ (Amjad et al., 2020)) and Zn ($\geq 0.2 \text{ mg g}^{-1}$ in a study of Baran (2012)). Plant Cd, Ni, and Pb concentrations did not exceed the European maximum allowance in corn (Table S10).



845 Besides decreases in plant heavy metal concentrations with basalt application, tassel Cr and root V concentrations increased
with basalt application compared to the control treatment in 2022. This was not surprising, as basalt contains Cr and V.
Nonetheless, the increased plant Cr and V concentrations occurred only in 2022 and did not persist in 2023. This temporal
decrease may indicate a gradual decline in the release of Cr and V. Alternatively, it may be related to differing weather
conditions. The higher amount of precipitation during the summer of 2023 compared to 2022 (Fig S1) may have increased
850 downward movement and leaching of heavy metals, as indicated by the larger volume of collected leachates (Fig S12, Table
S8). Nevertheless, Cr and V leaching in our experiment during the growing season of 2023 could not be quantified; Cr
concentrations were below the LOQ, likely due to excessive dilution from the large volume of leachates. V was not measured
in the leachates. This is in line with results of Rijnders et al. (2023), where plants accumulated more heavy metals when they
were subjected to a dry period, followed by heavy precipitation. Another study showed the opposite, with higher accumulation
855 of heavy metals in plants in the wet season compared to the dry season in the Enuga State, South East Nigeria (Ogbonna et
al., 2018). How precipitation affects heavy metals is thus not straightforward and depends on various factors such as
precipitation amount and frequency, heavy metal species, plant species, and soil type (Naeem et al., 2020; Ogbonna et al.,
2018).

860 Additionally, earthworms only marginally affected heavy metal concentrations, which is in line with their influence on heavy
metal availability in the porewater. However, earthworms increased corn Zn concentrations, while porewater Zn concentrations
were not affected by earthworms. Earthworms also increased root Pb concentrations, and also corn Pb concentrations when
basalt was applied. Potentially, earthworms could have increased dissolved organic carbon, which can form complexes with
heavy metals and make them more available for plants (Sizmur & Hodson, 2009).

865 5. Conclusion

This study investigated how basalt application and earthworms affect porewater chemistry, plant nutrients, and heavy metal
dynamics in *Zea mays*. Basalt was the main driver of changes in soil chemistry, increasing porewater pH, alkalinity and the
availability of several nutrients (Mg, Ca, Na and Si), while earthworms mainly reinforced these basalt-induced increases in
nutrient availability - consistent with a possible enhancement of weathering rates - despite having limited effects when applied
870 alone. Together, basalt and earthworms altered nutrient availability and plant nutritional composition but did not increase plant
biomass over the two growing seasons.

Basalt did not lead to harmful accumulation in aboveground plant tissues. Instead, concentrations of several metals (Al, Cd,
Zn) decreased, likely due to reduced availability at higher pH. Although basalt increased Ni, Cr, and V uptake in some plant
875 parts during the first growing season, these effects were transient and remained well below phytotoxic or regulatory thresholds.
Earthworms had only minor effects on heavy metal uptake.



Overall, our findings indicate that basalt amendment and earthworm activity can substantially modify soil chemistry and plant nutrient status, without increasing heavy-metal risks in edible maize tissues. In our experiment, these changes did not translate into higher biomass under the relatively nutrient-rich conditions tested here. Benefits of basalt and earthworms may therefore be more pronounced in nutrient-poor or degraded soils.

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

SV designed the research. LB, LS, JR and JR conducted the experimental work. JR did the data analysis and drafted the paper. PF conducted the elemental analysis and helped designing the methodology. All authors reviewed the manuscript and contributed to data interpretation.

Competing interests

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

Disclaimer

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Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees
900 according to their status anonymous or identified.

References

- Abedi, T., Gavanji, S., & Mojiri, A. (2022). Lead and Zinc Uptake and Toxicity in Maize and Their Management. *Plants*, 11(15), 1922. <https://doi.org/10.3390/plants11151922>
- Amjad, M., Raza, H., Murtaza, B., Abbas, G., Imran, M., Shahid, M., Naeem, M. A., Zakir, A., & Iqbal, M. M. (2020). Nickel
905 toxicity induced changes in nutrient dynamics and antioxidant profiling in two maize (*Zea mays* L.) hybrids. *Plants*, 9(1).
<https://doi.org/10.3390/plants9010005>
- Arunachalama, A., & Entoori, K. (2022). Role of earthworms in soil fertility and its impact on agriculture: A review. *International Journal of Fauna and Biological Studies*, 9(3), 55–63. <https://doi.org/10.22271/23940522.2022.v9.i3a.907>
- Atiyeh, R. M., Lee, S., Edwards, C. A., Arancon, N. Q., & Metzger, J. D. (2002). The influence of humic acids derived from
910 earthworm-processed organic wastes on plant growth. *Bioresource Technology*, 84, 7–14.
- Baccouch, S., Chaoui, A., & El Ferjani, E. (2001). Nickel toxicity induces oxidative damage in *Zea mays* roots. *Journal of Plant Nutrition*, 24(7), 1085–1097. <https://doi.org/10.1081/PLN-100103805>
- Baran, A. (2012). Assessment of *Zea mays* Sensitivity to Toxic Content of Zinc in Soil. *Polish Journal of Environmental Studies*, 22, 77–83.
- 915 Bayon, R. C. Le, Bullinger, G., Schomburg, A., Turberg, P., Brunner, P., Schlaepfer, R., & Guenat, C. (2021). Earthworms, Plants, and Soils. In *Hydrogeology, Chemical Weathering, and Soil Formation* (pp. 81–103). Wiley.
<https://doi.org/10.1002/9781119563952.ch4>
- Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., Bird, M., Kantzas, E., Taylor, L. L., Sarkar, B., Kelland, M., DeLucia, E., Kantola, I., Müller, C., Rau, G., & Hansen, J. (2018). Farming with crops and rocks to address
920 global climate, food and soil security. *Nature Plants*, 4(3), 138–147. <https://doi.org/10.1038/s41477-018-0108-y>
- Ben-Shachar, M., Lüdtke, D., & Makowski, D. (2020). effectsize: Estimation of Effect Size Indices and Standardized Parameters. *Journal of Open Source Software*, 5(56), 2815. <https://doi.org/10.21105/joss.02815>
- Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., & Roger-Estrade, J. (2015). Earthworm services for cropping systems. A review. *Agronomy for Sustainable Development*, 35(2), 553–567. <https://doi.org/10.1007/s13593-014-0269-7>
925 7
- Blouin, M., Butt, K. R., & Profile, S. (2013). A review of earthworm impact on soil function and ecosystem services. *Article in European Journal of Soil Science*, 64, 161–182. <https://doi.org/10.1111/ejss/12025>



- Boito, L., Steinwigger, L., Rijnders, J., Berwouts, J., Janse, S., Niron, H., Roussard, J., Vienne, A., & Vicca, S. (2025). Enhanced Rock Weathering Altered Soil Organic Carbon Fluxes in a Plant Trial. *Global Change Biology*, 31(8).
930 <https://doi.org/10.1111/gcb.70373>
- Brown, I. C. (1943). A rapid method of determining exchangeable hydrogen and total exchangeable bases of soils. *Soil Science*, 56(5). <https://doi.org/10.1097/00010694-194311000-00004>
- Calogiuri, T., Janssens, I., Vidal, A., Van Groenigen, J. W., Verdonck, T., Corbett, T., Hartmann, J., Neubeck, A., Niron, H., Poetra, R. P., Rieder, L., Servotte, T., Singh, A., Van Tendeloo, M., Vlaeminck, S. E., Vicca, S., & Hagens, M. (2025a).
935 How earthworms thrive and drive silicate rock weathering in an artificial organo-mineral system. *Applied Geochemistry*, 180. <https://doi.org/10.1016/j.apgeochem.2024.106271>
- Calogiuri, T., Janssens, I., Vidal, A., Van Groenigen, J. W., Verdonck, T., Corbett, T., Hartmann, J., Neubeck, A., Niron, H., Poetra, R. P., Rieder, L., Servotte, T., Singh, A., Van Tendeloo, M., Vlaeminck, S. E., Vicca, S., & Hagens, M. (2025b).
940 How earthworms thrive and drive silicate rock weathering in an artificial organo-mineral system. *Applied Geochemistry*, 180. <https://doi.org/10.1016/j.apgeochem.2024.106271>
- Canellas, L. P., Olivares, F. L., Okorokova-Façanha, A. L., & Façanha, A. R. (2002). Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma membrane H⁺-ATPase activity in maize roots. *Plant Physiology*, 130(4), 1951–1957. <https://doi.org/10.1104/pp.007088>
- Cipolla, G., Calabrese, S., Noto, L. V., & Porporato, A. (2021). The role of hydrology on enhanced weathering for carbon
945 sequestration I. Modeling rock-dissolution reactions coupled to plant, soil moisture, and carbon dynamics. *Advances in Water Resources*, 154. <https://doi.org/10.1016/j.advwatres.2021.103934>
- Curry, J. P. (2004). *6 Factors Affecting the Abundance of Earthworms in Soils*.
- Dupla, X., Claustre, R., Bonvin, E., Graf, I., Le Bayon, R. C., & Grand, S. (2024). Let the dust settle: Impact of enhanced rock
950 weathering on soil biological, physical, and geochemical fertility. *Science of the Total Environment*, 954. <https://doi.org/10.1016/j.scitotenv.2024.176297>
- Ferlian, O., Cesarz, S., Marhan, S., & Scheu, S. (2014). Carbon food resources of earthworms of different ecological groups as indicated by ¹³C compound-specific stable isotope analysis. *Soil Biology and Biochemistry*, 77, 22–30. <https://doi.org/10.1016/j.soilbio.2014.06.002>
- Gee, G. W., & Bauder, J. W. (1986). Particle-size Analysis. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical
955 Methods* (2nd ed., 15). <https://doi.org/10.2136/sssabookser5.1.2ed.c15>
- Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., Dürr, H. H., & Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, 51(2), 113–149. <https://doi.org/10.1002/rog.20004>
- Hassan, M. U., Chattha, M. U., Khan, I., Chattha, M. B., Aamer, M., Nawaz, M., Ali, A., Khan, M. A. U., & Khan, T. A.
960 (2019). Nickel toxicity in plants: Reasons, toxic effects, tolerance mechanisms, and remediation possibilities—a review.



In *Environmental Science and Pollution Research* (Vol. 26, Number 13, pp. 12673–12688). Springer Verlag.
<https://doi.org/10.1007/s11356-019-04892-x>

- 965 He, H., Xiao, Q., Yuan, M., Huang, R., Sun, X., Wang, X., & Zhao, H. (2020). Effects of steel slag amendments on accumulation of cadmium and arsenic by rice (*Oryza sativa*) in a historically contaminated paddy field. *Environmental Science and Pollution Research*, 27, 40001–40008. <https://doi.org/10.1007/s11356-020-10028-3>/Published
- Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, 25, 101–110.
- Hochmuth, G. (2011). Iron (Fe) Nutrition of Plants. *EDIS*, 2011. <https://doi.org/10.32473/edis-ss555-2011>
- 970 Jalali, M. (2008). Effect of sodium and magnesium on kinetics of potassium release in some calcareous soils of western Iran. *Geoderma*, 145(3–4), 207–215. <https://doi.org/10.1016/j.geoderma.2008.03.005>
- Kamboj, N., Dhanker, P., Kumar, A., & Malik, R. S. (2018). Importance of nickel in crops. ~ 3470 ~ *Journal of Pharmacognosy and Phytochemistry*, 7(3).
- Karaca, A., Kizilkaya, R., Turgay, O. C., & Cetin, S. C. (2010). Effects of Earthworms on the Availability and Removal of Heavy Metals in Soil. In *Soil biology* (Vol. 19, pp. 369–388). https://doi.org/10.1007/978-3-642-02436-8_17
- 975 Kögel-Knabner, I., & Amelung, W. (2021). Soil organic matter in major pedogenic soil groups. *Geoderma*, 384. <https://doi.org/10.1016/j.geoderma.2020.114785>
- Kome, G. K., Enang, R. K., Tabi, F. O., & Yerima, B. P. K. (2019). Influence of Clay Minerals on Some Soil Fertility Attributes: A Review. *Open Journal of Soil Science*, 09(09), 155–188. <https://doi.org/10.4236/ojss.2019.99010>
- 980 Kopsell, D. E., Kopsell, D. A., Sams, C. E., & Barickman, T. C. (2013). Ratio of calcium to magnesium influences biomass, elemental accumulations, and pigment concentrations in kale. *Journal of Plant Nutrition*, 36(14), 2154–2165. <https://doi.org/10.1080/01904167.2013.789108>
- Lavelle, P., Bignell, D., Roger, P. A., Lepage, M., Walters, V., Roger, P., Ineson, P., Heal, ? W., & Dhillion, S. (1997). Soil function in a changing world: the role of invertebrate ecosystem engineers. *European Journal of Soil Science*, 33(4), 159–193. <https://www.researchgate.net/publication/221754102>
- 985 Lemtiri, A., Colinet, G., Alabi, T., Cluzeau, D., Zirbes, L., Haubruge, É., & Francis, F. (2014). Impacts of earthworms on soil components and dynamics. A review. In *Biotechnol. Agron. Soc. Environ* (Vol. 18, Number 1, pp. 121–133).
- Lewis, A. L., Sarkar, B., Wade, P., Kemp, S. J., Hodson, M. E., Taylor, L. L., Yeong, K. L., Davies, K., Nelson, P. N., Bird, M. I., Kantola, I. B., Masters, M. D., DeLucia, E., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2021). Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. *Applied Geochemistry*, 132, 105023. <https://doi.org/10.1016/j.apgeochem.2021.105023>
- 990 Lindsay, W. L., & Schwab, A. P. (1982). The Chemistry of Iron in Soils and its Availability to Plants. *Journal of Plant Nutrition*, 5(5), 4–7. <https://doi.org/10.1080/01904168209363012>



- Lubbers, I. M., Pulleman, M. M., & Van Groenigen, J. W. (2017). Can earthworms simultaneously enhance decomposition and stabilization of plant residue carbon? *Soil Biology and Biochemistry*, *105*, 12–24.
995 <https://doi.org/10.1016/j.soilbio.2016.11.008>
- Luchese, A. V., Gutz de Castro Leite, I. J., da Silva Giaretta, A. P., Alves, M. L., Pivetta, L. A., & Missio, R. F. (2023). Use of quarry waste basalt rock powder as a soil remineralizer to grow soybean and maize. *Heliyon*, *9*(3).
<https://doi.org/10.1016/j.heliyon.2023.e14050>
- Ma, Y., Dickinson, N. M., & Wong, M. H. (2002). Toxicity of Pb/Zn mine tailings to the earthworm *Pheretima* and the effects of burrowing on metal availability. *Biology and Fertility of Soils*, *36*(1), 79–86. <https://doi.org/10.1007/s00374-002-0506-0>
1000
- Malekzadeh, P., Mehr, R. S., & Hatamnia, A. A. (2015). Effects of aluminum toxicity on maize (*Zea mays* L.) seedlings. *Iranian Journal of Plant Physiology*, *5*, 1289–1296.
- Mattiello, E. M., Ruiz, H. A., Neves, J. C. L., Ventrella, M. C., & Araújo, W. L. (2015). Zinc deficiency affects physiological and anatomical characteristics in maize leaves. *Journal of Plant Physiology*, *183*, 138–143.
1005 <https://doi.org/10.1016/j.jplph.2015.05.014>
- Mcneer, D. H. (2013). *The rhizosphere-roots, soil and everything in between*.
<https://www.researchgate.net/publication/303919396>
- Morrissey, J., & Guerinot, M. Lou. (2009). Iron uptake and transport in plants: The good, the bad, and the ionome. *Chemical Reviews*, *109*(10), 4553–4567. <https://doi.org/10.1021/cr900112r>
1010
- Naeem, M., Ansari, A. A., & Gill, S. S. (2020). Contaminants in agriculture: Sources, impacts and management. In *Contaminants in Agriculture: Sources, Impacts and Management*. Springer International Publishing.
<https://doi.org/10.1007/978-3-030-41552-5>
- Nguyen, K. S., Nguyen, H. T. K., Nguyen Ngoc Tri Huynh, Nguyen Vinh Phuoc, & Nguyen Khanh Son. (2024). comprehensive review of rock dust for soil remineralization in sustainable agriculture and preliminary assessment of nutrient values in micronized porous basalt rock from Nghe-An province, Vietnam. *Vietnam Journal of Science and Technology*, *62*. <https://doi.org/10.15625/2525-2518/18544>
1015
- Nyiramigisha, P., Komariah, & Sajidan. (2021). Harmful Impacts of Heavy Metal Contamination in the Soil and Crops Grown Around Dumpsites. *Reviews in Agricultural Science*, *9*, 271–282.
- Ogbonna, C. P., Nezebulu, E. C., & Okorie, E. P. (2018). Seasonal variation in heavy metal accumulation in plants at coal mine sites and possible health risk. *Nigerian Journal of Environmental Sciences and Technology*, *2*(2), 196–207.
www.nijest.com
1020
- Page, V., & Feller, U. (2015). Heavy metals in crop plants: Transport and redistribution processes on the whole plant level. In *Agronomy* (Vol. 5, Number 3, pp. 447–463). MDPI AG. <https://doi.org/10.3390/agronomy5030447>



- 1025 Parvin, Afsana, Moniruzzaman, M., Hossain, M. K., Saha, B., Parvin, Afroza, Suchi, P. D., & Hoque, S. (2022). Chemical Speciation and Potential Mobility of Heavy Metals in Organic Matter Amended Soil. *Applied and Environmental Soil Science*, 2022. <https://doi.org/10.1155/2022/2028860>
- Penn, C. J., & Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil ph affects phosphorus availability to plants. *Agriculture (Switzerland)*, 9(6). <https://doi.org/10.3390/agriculture9060120>
- 1030 Pinheiro, J., Bates, D., Debroy, S., Sarka, D., & R Core Team, R. (2013). nlme: Linear and Nonlinear Mixed Effects Models. *R Package Version 3.1*, 109.
- Rijnders, J., Vicca, S., Struyf, E., Amann, T., Hartmann, J., Meire, P., Janssens, I., & Schoelynck, J. (2023). The effects of dunite fertilization on growth and elemental composition of barley and wheat differ with dunite grain size and rainfall regimes. *Frontiers in Environmental Science*, 11. <https://doi.org/10.3389/fenvs.2023.1172621>
- 1035 Rijnders, J., Vienne, A., & Vicca, S. (2024). Effects of basalt, concrete fines, and steel slag on maize growth and heavy metal accumulation in an enhanced weathering experiment. *Biogeosciences*. <https://doi.org/10.5194/egusphere-2024-3022>
- Rusco, E., Jones, R., & Bidoglio, G. (2001). *Organic Matter in the soils of Europe: Present status and future trends*.
- Shen, J., Song, L., Müller, K., Hu, Y., Song, Y., Yu, W., Wang, H., & Wu, J. (2016). Magnesium alleviates adverse effects of lead on growth, photosynthesis, and ultrastructural alterations of *Torreya grandis* seedlings. *Frontiers in Plant Science*, 7(NOVEMBER2016). <https://doi.org/10.3389/fpls.2016.01819>
- 1040 Shenker, M., & Chen, Y. (2005). Mini-Review Paper Increasing Iron Availability to Crops: Fertilizers, Organo-Fertilizers, and Biological Approaches. *Plant Nutr*, 5, 1–17. <https://doi.org/10.1111/j.1747-0765.2005.tb00001.x>
- Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, 79(1), 7–31. <https://doi.org/10.1016/j.still.2004.03.008>
- 1045 Sizmur, T., & Hodson, M. E. (2009). Do earthworms impact metal mobility and availability in soil? - A review. In *Environmental Pollution* (Vol. 157, Number 7, pp. 1981–1989). <https://doi.org/10.1016/j.envpol.2009.02.029>
- Skov, K., Wardman, J., Healey, M., McBride, A., Bierowiec, T., Cooper, J., Edeh, I., George, D., Kelland, M. E., Mann, J., Manning, D., Murphy, M. J., Pape, R., Teh, Y. A., Turner, W., Wade, P., & Liu, X. (2024). Initial agronomic benefits of enhanced weathering using basalt: A study of spring oat in a temperate climate. *PLoS ONE*, 19(3 March). <https://doi.org/10.1371/journal.pone.0295031>
- 1050 Spurgeon, D. J., Keith, A. M., Schmidt, O., Lammertsma, D. R., & Faber, J. H. (2013). *Land-use and land-management change: relationships with earthworm and fungi communities and soil structural properties*. <http://www.biomedcentral.com/1472-6785/13/46>
- Steinwider, L., Boito, L., Frings, P. J., Niron, H., Rijnders, J., de Schutter, A., Vienne, A., & Vicca, S. (2025). Beyond Inorganic C: Soil Organic C as a Key Pathway for Carbon Sequestration in Enhanced Weathering. *Global Change Biology*, 31(7). <https://doi.org/10.1111/gcb.70340>
- 1055



- Suganya, A., Saravanan, A., & Manivannan, N. (2020). Role of Zinc Nutrition for Increasing Zinc Availability, Uptake, Yield, and Quality of Maize (*Zea Mays* L.) Grains: An Overview. *Communications in Soil Science and Plant Analysis*, 51(15), 2001–2021. <https://doi.org/10.1080/00103624.2020.1820030>
- 1060 Swoboda, P., Döring, T. F., & Hamer, M. (2022). Remineralizing soils? The agricultural usage of silicate rock powders: A review. In *Science of the Total Environment* (Vol. 807). Elsevier B.V. <https://doi.org/10.1016/j.scitotenv.2021.150976>
- ten Berge, H. F. M., van der Meer, H. G., Steenhuizen, J. W., Goedhart, P. W., Knops, P., & Verhagen, J. (2012). Olivine weathering in soil, and its effects on growth and nutrient uptake in ryegrass (*Lolium perenne* L.): A pot experiment. *PLoS ONE*, 7(8). <https://doi.org/10.1371/journal.pone.0042098>
- 1065 Toor, M. D., Basit, A., Okorie, B., Nath, D., Din, M. M. U., Kumar Verma, P., Saleem Sajjad, Ullah, I., Yousef, H. N., & Mohamed, H. I. (2024). Earthworms as Catalysts for Climate-Resilient Agriculture: Enhancing Food Security and Water Management in the Face of Climate Change. *Water, Air, and Soil Pollution*, 235(12). <https://doi.org/10.1007/s11270-024-07576-6>
- Van Groenigen, J. W., Van Groenigen, K. J., Koopmans, G. F., Stokkermans, L., Vos, H. M. J., & Lubbers, I. M. (2019). How 1070 fertile are earthworm casts? A meta-analysis. *Geoderma*, 338, 525–535. <https://doi.org/10.1016/j.geoderma.2018.11.001>
- Van Groenigen, N., Thomasarrigo, L. K., Byrne, J. M., Kappler, A., Christl, I., & Kretzschmar, R. (2020). Interactions of ferrous iron with clay mineral surfaces during sorption and subsequent oxidation. *Environmental Science: Processes and Impacts*, 22(6), 1355–1367. <https://doi.org/10.1039/d0em00063a>
- Ven, A., Verlinden, M. S., Verbruggen, E., & Vicca, S. (2019). Experimental evidence that phosphorus fertilization and 1075 arbuscular mycorrhizal symbiosis can reduce the carbon cost of phosphorus uptake. *Functional Ecology*, 33(11), 2215–2225. <https://doi.org/10.1111/1365-2435.13452>
- Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A., Peñuelas, J., Poblador, S., Rijnders, J., Sardans, J., Struyf, E., Swoboda, P., van Groenigen, J. W., Vienne, A., & Verbruggen, E. (2022). Is the climate change mitigation 1080 effect of enhanced silicate weathering governed by biological processes? *Global Change Biology*, 28(3), 711–726. <https://doi.org/10.1111/gcb.15993>
- Vienne, A., Frings, P., Poblador, S., Steinwider, L., Rijnders, J., Schoelynck, J., Vinduskova, O., & Vicca, S. (2024). Earthworms in an enhanced weathering mesocosm experiment: Effects on soil carbon sequestration, base cation exchange and soil CO₂ efflux. *Soil Biology and Biochemistry*, 199, 109596. <https://doi.org/10.1016/j.soilbio.2024.109596>
- 1085 Walinga, I., Van Der Lee, J. J., Houba, V. J. G., Van Vark, W., & Novozamsky, I. (1995). Plant Analysis Manual. In *Plant Analysis Manual*. Springer Netherlands. <https://doi.org/10.1007/978-94-011-0203-2>
- Wen, B., Hu, X. Y., Liu, Y., Wang, W. S., Feng, M. H., & Shan, X. Q. (2004). The role of earthworms (*Eisenia fetida*) in influencing bioavailability of heavy metals in soils. *Biology and Fertility of Soils*, 40(3), 181–187. <https://doi.org/10.1007/s00374-004-0761-3>



- 1090 Xian, X., & Shokohifard, G. I. (1989). Effect of pH on chemical forms and plant availability of cadmium, zinc, and lead in polluted soils. *Water, Air, and Soil Pollution*, 45, 265–273.
- Yusuf, M., Fariduddin, Q., Hayat, S., & Ahmad, A. (2011). Nickel: An overview of uptake, essentiality and toxicity in plants. *Bulletin of Environmental Contamination and Toxicology*, 86, 1–17. <https://doi.org/10.1007/s00128-010-0171-1>