

Trace Metal Mobility in Post-mining Soils: An Integrated Risk Assessment

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Abstract

Trace metal (TM) contamination in post-mining soils represents a long-term environmental risk due to potential leaching into groundwater. This study applied an integrated risk assessment approach—combining sequential extraction, *in situ* soil solution sampling, and HYDRUS-1D modelling—to evaluate TM behaviour along the soil–groundwater pathway at a recently abandoned bauxite mining site in the Central Highlands of Vietnam, currently used for cassava cultivation. Our results revealed that less than 1% of the total TM concentrations (As, Cu, Zn, Pb) are mobilizable, indicating a negligible risk of groundwater contamination under the current conditions. This low mobility is primarily attributed to strong sorption by Fe- and Al-(hydr)oxides, despite the moderately acidic soil pH (5.3 ± 0.2). With the exception of Pb, the *in situ* soil solution samples showed consistently higher TM concentrations than predicted by sequential extraction (1.1–4.9-fold higher). This trend suggests that natural complexation with dissolved organic matter and minor redox fluctuations may enhance TM mobility more than estimated by lab experiments under controlled conditions. Simulation of the soil water balance indicated an annual infiltration of 3,654mm, evapotranspiration of 845mm, and seepage of 2,809mm, with TM loads far below admissible regulatory limits. However, continuous monitoring is recommended, as potential changes in pH, organic matter, or precipitation patterns could alter TM solubility and increase leaching risks in the future. These findings demonstrate that total TM concentrations may serve as valid first-order approximation for risk assessments in similar tropical post-mining soils, though site-specific conditions should always be considered.

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Keywords

In situ soil solution sampling, trace metal mobility, soil water balance simulations, HYDRUS 1-D, Lam Dong province

Introduction

The contamination of soils with pollutants such as trace metals (TMs) is one of the major threats to the functions of soil and is largely driven by human activities (Nguyen *et al.*, 2020). Post-mining landscapes are particularly vulnerable to TM enrichment due to ore processing and mineral residues (Chileshe *et al.*, 2019; Sahu & Basti, 2020). When present in concentrations exceeding natural background levels, TMs can impair land-use options, as soils become unsuitable for agriculture once toxic thresholds are surpassed (Moschner *et al.*, 2020). In tropical regions, however, the behaviour of TMs in contaminated soils remains far less studied compared to other parts of the world, such as European temperate zones (Rieuwerts, 2007).

For managing post-mining sites with TM contamination, environmental risk assessment plays a central role (Opara *et al.*, 2022). Many countries have established threshold values—referred to as “screening values” (Carlson *et al.*, 2007), “test values” (BBodSchV, 2021), or “limit values” (QCVN 03:2023/BTNMT, 2023)—to regulate soil pollution. Yet, these limits are commonly derived from total TM concentrations, which provide little insight into environmental behaviour and mobility (Rennert, 2019; Opara *et al.*, 2022), and are mainly determined by physicochemical characteristics (Crespo-Toledo *et al.*, 2025). Since mobility determines whether TMs may leach through soils and threaten groundwater, more refined methods of assessment are needed. Importantly, recent work in mining-affected systems has increasingly applied integrated risk assessment, combining complementary indicators or “lines of evidence” (e.g., contamination indices, mobility/speciation metrics, and pathway-based risk measures), because no single metric adequately captures risk in highly heterogeneous post-mining substrates (Crespo-Toledo *et al.*, 2025). In addition, for massively disturbed post-mining sites, TM behaviour may deviate from well-known mechanisms in undisturbed soils, calling for a cautious application and careful validation of standard total-concentration-based risk assessments.

Sequential extraction schemes allow mobility to be estimated by simulating natural

processes that can mobilise metals under changing conditions (Zeien & Brümmer, 1989; Bacon & Davidson, 2008; Nassiri *et al.*, 2022; Opara *et al.*, 2022). Of particular concern for the soil–groundwater pathway are water-soluble and easily soluble fractions, as these are most susceptible to transport by seepage water. While sequential extractions provide indirect estimates, direct sampling of the soil solution—such as through suction cups (Weihermüller *et al.*, 2005)—offers complementary insights into TM concentrations in soil water (Wiggenhauser *et al.*, 2024). To robustly assess potential risks to groundwater, these chemical approaches must be combined with knowledge of the soil water balance in order to calculate TM fluxes reaching groundwater bodies (Reck, 2021). This type of integration is consistent with recent studies in mine-affected environments that jointly evaluate mobility/speciation and risk metrics, and in some cases integrate additional evidence streams (e.g., hydrogeochemical monitoring or human/ecological risk characterisation) to better constrain real-world exposure (Nassiri *et al.*, 2022).

This study addressed these aspects through a pilot investigation in the Central Highlands of Vietnam. The study site was a freshly abandoned former bauxite mining area, which is currently cultivated with cassava for bioenergy production. In such post-mining landscapes in Vietnam, TM contamination is a recognised environmental concern due to the country’s strong reliance on mineral resource extraction (Chu, 2011; Nguyen *et al.*, 2020) as mining residues often lead to elevated TM concentrations and altered soil conditions that influence TM mobility in the environment. As a result, numerous post-mining sites in Vietnam pose risks to food safety (Brömme *et al.*, 2018) and, because soils act as critical filters for groundwater, also to drinking water quality (Van *et al.*, 2023).

Against this background, the present study pursued three main objectives focused on the altered soil conditions in early post-mining landscapes: (i) the determination of solid-phase TM concentrations, (ii) the evaluation of TM mobility through sequential extractions and soil solution analyses, and (iii) the incorporation of soil water balance modelling to calculate TM fluxes. Characterising these disturbed soils is essential, as

they govern trace metal partitioning and mobility, root-zone exposure for cassava, and long-term ecosystem recovery. Together, these approaches can provide an integrated assessment of potential TM dispersion through the soil–groundwater pathway at post-mining sites under energy crop cultivation. We hypothesised that the Fe- and Al-oxide rich ferralsol mineralogy, together with its low soil organic carbon (SOC), would constrain TM mobility through strong sorption and limited dissolved organic carbon-mediated complexation and transport, leading to sub-threshold groundwater loads under cassava cultivation.

Materials and Methods

Study site

The study site was located near Bao Loc city (890 m a.s.l.), Lam Dong Province, southern Vietnam, within the Bao Lam district. It covered 1.6 ha in a post-mining area of an active open-cast bauxite mine managed by the state-owned company VINACOMIN. Mining activities, which targeted bauxite beds (2–8m thick) within the laterite weathering crust of the Pleistocene age, ceased at the site in 2020. Prior to mining, the topsoil (0.2–2m cover over the bauxite bed, encompassing the A and partial B horizons) was removed. Following the mine's closure, the original topsoil (a mixture of A and B horizons) was reapplied. According to the World Reference Base (WRB) classification (IUSS Working Group WRB, 2022), the original soil type before mining was a Xanthic Ferralsol (Brömmé *et al.*, 2018). Post-mining, the soil was classified as a Relocatic Regosol, as the material consists primarily of natural mineral soil.

At the time of sampling, the field was being prepared for cassava (*Manihot esculenta* Cranz). Cassava had already been cultivated in a first cycle (planted in April 2021 and harvested in January 2022), and between cycles the soil was bare, covered mainly by grasses. The climate at the study site is Tropical Monsoon (Am; Köppen–Geiger), with distinct wet and dry seasons (Brömmé *et al.*, 2018).

Baseline soil data from Environmental Impact Assessment (EIA) reports were not available for this post-mining site. No quantitative EIA information on soil chemical properties (e.g. TM concentrations, pH, and

SOC) could be obtained from the operator or authorities, so all soil characteristics and TM concentrations used in this study were based on the field sampling and laboratory analyses specified in the field sampling section.

Field sampling

Sampling was conducted in April 2023 by selecting two representative plots in order to assess the trace metal mobility. At each plot, a 1-m³ soil profile was excavated, enabling soil profiling and sampling. Disturbed soil was collected at depths of 15, 35, and 45cm (1kg per depth). Additionally, six undisturbed soil ring samples were taken per plot at depths of 15 and 45cm (12 per plot).

The soil solution was sampled using suction cups (ecoTech Umwelt-Messsysteme, Bonn, Germany) installed at ~30cm depth (limited by the augering depth). Cups were installed in pre-drilled holes, stabilized with soil slurry, and connected to glass collection bottles under manual vacuum. The soil solution was collected for four days; the first sample (24h) was discarded to avoid contamination, leaving six repetitions per plot for analysis. Samples were acidified immediately after excavation from the sampling bottles (HNO₃).

Fieldwork was conducted during the dry season, with each plot receiving daily irrigation of ~5L of tap water per cup to simulate planned irrigation and maintain consistent sampling conditions. This irrigation rate was designed to sustain soil moisture near field capacity, ensuring that the soil solution sampling targeted the mobile water fraction—the component contributing to seepage and potential groundwater changes.

Chemical analyses

Disturbed samples were air-dried (one week), sieved (< 2mm), and 10g of each sample was ground for 30s (MM400). Undisturbed samples were analysed directly without further pre-treatment. The following chemical analyses were conducted in the laboratory using the disturbed samples:

Soil standard properties: Total C and N were measured by dry combustion at 1,200°C (Vario EL Cube). pH was determined in H₂O and KCl suspensions (DIN ISO 10390, 2005).

Solid phase TM concentrations: Total TM concentrations were analysed by X-ray fluorescence spectroscopy (XRF). Milled soil was mixed with a resin binder, pressed into pellets, and measured in duplicate (SpectroXepos).

Mobile TM fractions: Steps 1 (NH_4NO_3 extraction) and 2 (NH_4OAc extraction, pH 6) of the Zeien & Brümmer (1989) sequential extraction were applied to the disturbed samples. These steps of the sequential extraction protocol equaled the easily soluble and exchangeable TM fractions.

Soil solution and extracts: Liquid samples were analysed by ICP-MS (Agilent 7900). Elements with > 70% of values below the Limit of Quantification by ICP-MS were omitted from the results, as summary statistics derived from such censored data yield imprecise estimates (Antweiler & Taylor, 2008). In this study, Cd was the only element meeting this exclusion criterion.

Soil hydrological analysis

Undisturbed samples were analysed at the Vietnam National University of Agriculture (VNUA), Hanoi, following DIN EN ISO 11274 (2014) to establish soil water retention at five matric potentials (pressure stages of pFs of 0, 1.5, 1.8, 2.0, and 2.5). Additional high matric potential data (> pF 3) were measured on disturbed samples using a WP4C device (Meter Group). This device uses the chilled mirror dew point technique to measure the texture-related water potential of porous media. Retention curves were fitted to the Mualem–van Genuchten model; fitted parameters are shown in **Table 1**.

Soil water modelling

The HYDRUS-1D model (Šimůnek *et al.*, 2008) was used to simulate soil water flow and calculate TM fluxes. The soil profile was represented by two layers (0–25 and 25–200cm depths, 200 nodes with increasing density towards boundaries). Simulations extended two years, with the first year serving as spin-up for numerical equilibrium. The upper boundary condition was atmospheric (precipitation, evapotranspiration), while the lower boundary was free drainage (water table > 10m). Daily precipitation data were obtained from the Bao Loc station, and potential evapotranspiration

(ET_0) was calculated with the Penman–Monteith equation based on Singer *et al.* (2021). Cassava crop dynamics were parameterised with a leaf area index (LAI) series derived from Phoncharoen *et al.* (2019). Radiation extinction by the canopy was set to 0.57 (Mwamba *et al.*, 2021). Root distribution was set to 50% at the surface and decreased linearly to the field-observed maximum rooting depth of 40cm. In HYDRUS-1D, root depth and distribution define the spatial domain of water uptake, while the Feddes parameters govern the reduction of uptake under water stress. Since cassava-specific Feddes parameters are not available, we used the default values for potatoes (Feddes *et al.*, 1978) as a pragmatic proxy for the stress-response function. This approach is consistent with previous HYDRUS applications where crop-specific parameters were missing (Gregory & Wojciechowski, 2020). We acknowledge that cassava and potato exhibit distinct root architectures: cassava develops deeper adventitious and storage roots, whereas potato roots are generally shallower and associated with stolons (Khan *et al.*, 2016). However, the use of potato parameters here was not intended to represent cassava root morphology, but rather to approximate the stress-response function in the absence of cassava-specific data. The soil hydraulic properties were derived from retention data (see previous section).

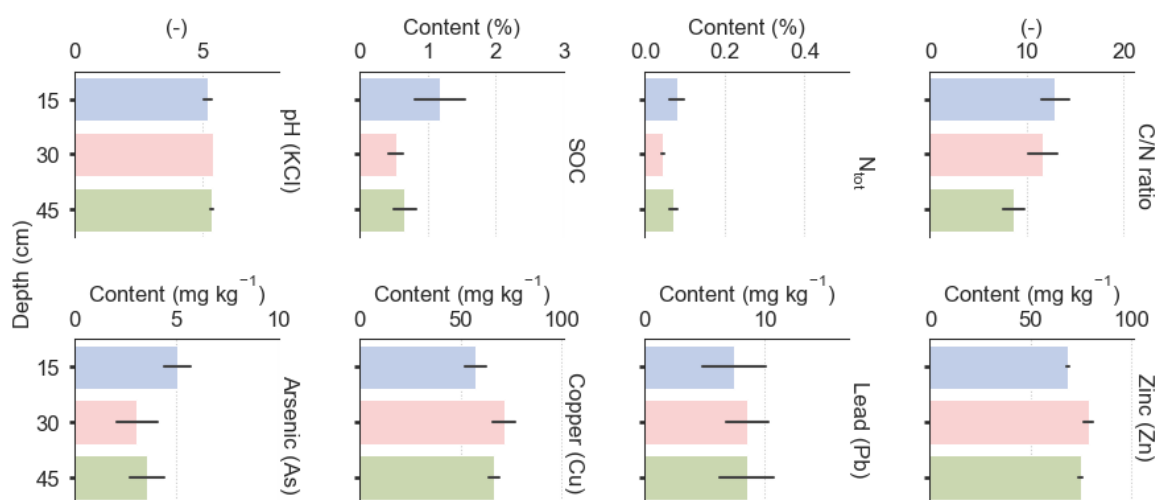
Results and Discussion

Physicochemical soil properties

Figure 1 summarises the physicochemical soil properties of both plots. The soils were moderately acidic, with an average pH of 5.3 ± 0.2 . The soil organic carbon (SOC) peaked at $1.18 \pm 0.96\%$ in the topsoil, then declined sharply with depth except for a slight increase from 30 to 45cm. Total nitrogen (N_{tot}) decreased less abruptly, yielding the widest C/N ratio near the surface that narrowed downward. At this early post mining site (< 3 years cultivation), mining disturbances—mixing the A/B horizons—dominated the vertical SOC patterns, although cassava is known to deplete SOC over time through root nutrient export and tillage exposure primarily in the 0–30cm zone (Adjei *et al.*, 2023). The 30–45cm SOC increase likely

Table 1. Mualem-van Genuchten parameters used for modelling. The soil water retention parameters were obtained by measurements with suction plates and WP4C on a drying branch.

Depth (cm)	Θ_{sat} (-)	Θ_{res} (-)	A (-)	N (-)	K_{sat} (cm day ⁻¹)
0-30	0.413	0.012	0.021	1.145	100
30-45	0.417	0.169	0.001	1.952	100

**Figure 1.** Selected physicochemical soil properties for the experimental site constrained by variable and depth. C and N were determined in triplicate and the remaining variables in duplicate, resulting in six and four values per bar, as values were combined for both examined profiles. The black line per bar represents the standard error for each subsample. Note the different scaling on the x-axes. Vietnamese Class 3 soil limits (QCVN 03:2023/BTNMT) exceed plotted TM ranges and are omitted.

reflected subsoil heterogeneity from mining rather than cultivation impacts confined above the primary rooting depth.

Trace metal (TM) concentrations were relatively uniform across depths, with lower values for As and Pb (3.88 ± 1.76 and $8.16 \pm 4.09 \text{ mg kg}^{-1}$, respectively) and higher values for Cu and Zn (65.15 ± 10.55 and $73.99 \pm 5.17 \text{ mg kg}^{-1}$, respectively). Standard errors were larger for these low-level elements, reflecting greater uncertainty. All measured TMs were well below the maximum permissible limits of the Vietnamese National Technical Regulation on Soil Quality (QCVN 03:2023/BTNMT, 2023) for all land-use classes, indicating no acute soil contamination. This finding aligns with international benchmarks as the As, Cu, and Zn levels fall below the German precaution values for soils (BBodSchV, 2021). While Cu concentrations slightly exceeded this precautionary threshold, these values do not indicate an immediate health risk, as precautionary thresholds are designed to prevent future contamination rather than signal acute hazards. The SOC values are consistent with

previous studies on tropical soils (Hung *et al.*, 2016; Nguyen *et al.*, 2020). Under current conditions, the soil properties favour the immobilisation of As, Cu, Pb, and, to a lesser extent, Zn through element-specific physicochemical processes: (i) the moderately acidic pH decreases the solubility of Cu and Pb and somewhat reduces Zn mobility by enhancing sorption to mineral and organic surfaces; (ii) organic matter provides high-affinity binding sites, sorption sites with Cu and Pb predominantly form inner-sphere complexes and Zn is more weakly bound (Mansfeldt, 2011; Seidl *et al.*, 2021); and (iii) the Ferralsol parent material is rich in Fe and Al (hydr)oxides that further immobilise metals via inner-sphere adsorption (As, Pb), surface complexation (Zn), and co-precipitation (Pb) (Mendez *et al.*, 2022). The considerable scatter in variables is likely attributable to soil disturbances and topsoil reapplication after mining in 2020. Consequently, the current data reflect only a snapshot of post-disturbance conditions, which may not fully represent the long-term equilibrium state.

Trace metals in soil solution

TM mobility was assessed both in situ (soil solution sampling) and in the laboratory (sequential extractions) (**Figure 2**) as static extractions do not necessarily reflect field TM mobility due to methodological limitations (Sutherland & Tack, 2003; Zimmerman & Weindorf, 2010). Except for Pb, the in-situ mobilities were consistently higher than the laboratory-derived values, despite step 1 of the extraction protocol being designed to mimic water-soluble fractions. This suggests that dynamic field conditions enhance release compared to static extractions. While the watering procedure around the suction cups may have altered the ionic strength, pH, and complexation—potentially biasing TM concentrations upward relative to natural conditions—this effect only partially accounts for the observed differences, as Pb concentrations were lower in the in-situ investigations. The exchangeable fractions of As and Pb were notably higher than the water-soluble fractions, while for Cu and Zn, both fractions were of comparable magnitude. Overall, the fraction of the mobile metals was very small (< 1% of the total concentration). The relative contributions of Pb and Zn were the highest ($\leq 0.5\%$), whereas Cu was particularly immobile (< 0.05%), consistent with earlier findings (Wiggenhauser *et al.*, 2024). From an environmental perspective, the mobile and easily exchangeable fractions are most critical (Opara *et al.*, 2022). Their low share at this site suggests little risk of TM transfer to groundwater under the present conditions. As such, using cassava as energy plants seems a suitable soil rehabilitation practice in questions of land management of post-mining sites to force land recycling. However, future changes in soil chemistry, particularly declines in pH or alterations in organic matter due to land management, could increase metal mobilisation (Filipović *et al.*, 2016; Gul *et al.*, 2019; Moschner *et al.*, 2020). This highlights the dynamic nature of TM stability in tropical post-mining soils. As irrigation water chemistry might have influenced metal speciation, future work should use low-ionic-strength deionised water (similar

to the chemistry of rainwater) or avoid irrigation when feasible.

Simulated soil water balance and metal loads

To the best of our knowledge, no prior studies have reported on soil and water quality data from early post-mining bauxite sites under cassava cultivation in Vietnam's Central Highlands, limiting direct site-specific comparisons. Our findings thus establish a critical baseline for TM concentrations, mobility, and fluxes in this context. The simulated soil water balance (**Figure 3a**) revealed an annual infiltration of 3,654mm, with 845mm (23%) lost to evapotranspiration (ET) and 2,809mm (77%) exiting the profile as deep seepage. A distinct dry season occurs from November to April, characterised minimal infiltration and seepage. Although direct validation was not possible, simulated ET fell within reported ranges for the region (Ha *et al.*, 2023; Tran *et al.*, 2023; Sayyadi *et al.*, 2025), lending confidence to the model. To assess the groundwater risk, field- and laboratory-derived TM mobilities were multiplied by annual seepage to estimate potential TM loads (**Figure 3b**). For instance, German environmental legislation defines the maximum allowable annual TM loads in Annex 1 of the Federal Soil Protection and Contaminated Sites Ordinance of Germany (BBodSchV, 2021). In all cases, the estimated annual loads remained far below these limits of 35, 300, 200, and 1,200 g ha⁻¹ yr⁻¹ for As, Cu, Pb, and Zn, respectively (cf. **Figure 3b**). The highest relative loads were obtained from the field-based mobility data, which better represent natural conditions. Even in this conservative scenario, the Pb, Cu, Zn, and As loads remained negligible. Moreover, since the groundwater level lies deeper than 10m, additional retention processes within the vadose zone are expected to further attenuate fluxes prior to water table recharge (El-Aassar *et al.*, 2023).

Conclusions

The integrated risk assessment, combining sequential extraction, in situ soil solution sampling, and HYDRUS-1D modelling, revealed a negligibly low risk of TM contamination along

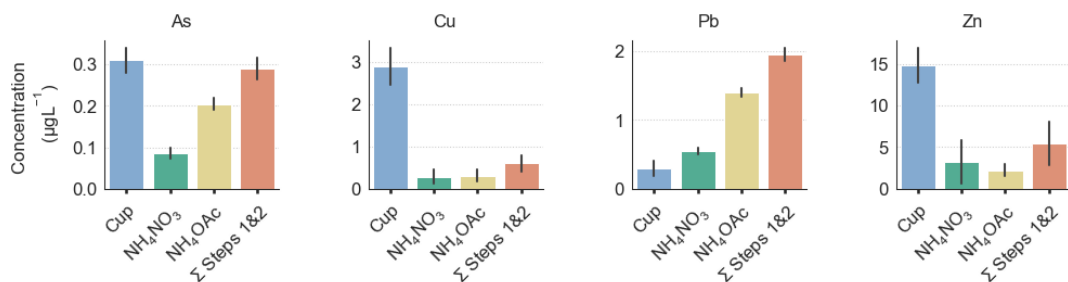


Figure 2. Differently determined trace metal mobilities with “Cup” = in situ sampled soil solution using suction cups as well as the first two steps of the extraction protocol following Zeien & Brümmner (1989), NH₄NO₃ = easily soluble TM fraction, NH₄OAc = exchangeable TM fraction, and “Σ Steps 1&2” = sum of NH₄NO₃ and NH₄OAc. The black line per bar represents the standard error for each subsample. Subsample populations were n = 12 for the “Cup” fraction and n = 36 for the other two fractions. Note the different scaling on the y-axes.

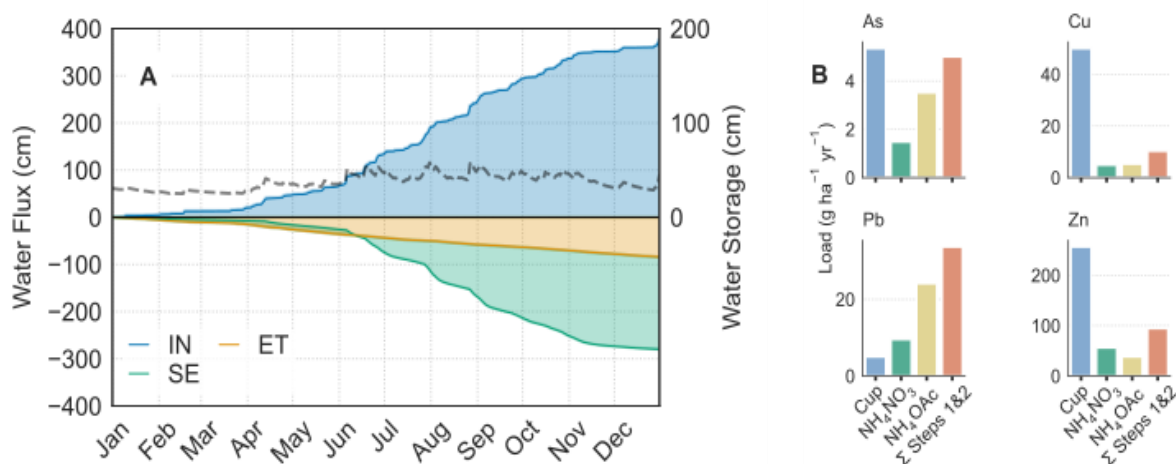


Figure 3. (A) Simulated annual water balances throughout the year 2023. Positive values indicate fluxes into the soil profile and vice versa for negative values. “IN” and “ET” denote the infiltration and evaporation at the upper boundary and, “SE” fluxes through the lower boundary (deep seepage). The dashed line illustrates the total water volume in the soil profile (storage). (B) Calculated annual loads of trace metals derived by multiplying the field- and lab-determined mobilities (cf. Figure 2) with the annual cumulative seepage water simulated for 2023.

the soil–groundwater pathway at this post-mining site in Vietnam’s Central Highlands under the current conditions.

The results confirmed this low risk for two key reasons: (i) only a very small fraction of the total solid-phase TM concentration is mobilizable (< 1%); and (ii) the annual TM loads are well below internationally recognised thresholds, including legislatively admissible limits under German environmental standards.

Overall, the very low risk is primarily attributable to the limited mobility of TMs at the site, which is strongly influenced by the soil characteristics. The abundance of Fe and Al oxides effectively immobilise TMs through sorption, although the slightly acidic pH poses a moderate risk of trace metal mobilisation.

Additionally, the high clay content of the subsoils provides further sorption capacity, thereby reducing TM leaching potential.

Nevertheless, it should be emphasised that this risk assessment applies only to current site conditions. Future changes, such as land-use shifts that alter soil pH or increases in annual precipitation that enhance seepage, could modify TM mobility and thereby increase the risk of groundwater contamination. Since risk assessments typically rely on total soil TM concentrations, our results indicate that this common approach may also be valid as a first-order approximation for highly disturbed tropical Ferralsol post-mining soils, although its applicability should be further evaluated in other sites and settings. We, thus, recommend

extending multi-tiered assessments, integrating either site-specific soil solution monitoring or sequential extraction with HYDRUS-1D modeling for flux predictions, to outperform total concentration screenings by incorporating bioavailability and hydrological dynamics, especially in disturbance-prone tropical post-mining contexts.

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References

- Adjei E. O., Ayamba B. E., Buri M. M., Biney N. & Appiah K. (2023). Soil quality and fertility dynamics under a continuous cassava-maize rotation in the semi-deciduous forest agro-ecological zone of Ghana. *Frontiers in Sustainable Food Systems*. 7. DOI: 10.3389/fsufs.2023.1095207.
- Antweiler R. C. & Taylor H. E. (2008). Evaluation of Statistical Treatments of Left-Censored Environmental Data using Coincident Uncensored Data Sets: I. Summary Statistics. *Environmental Science & Technology*. 42: 3732-3738.
- Bacon J. R. & Davidson C. M. (2008). Is there a future for sequential chemical extraction? *The Analyst*. 133: 25-46.
- BBodSchV (2021). Bundes-Bodenschutz- und Altlastenverordnung vom 9. Juli 2021 (BGBl. I S. 2598, 2716) [Federal Soil Protection and Contaminated Sites Ordinance]. Berlin: German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN).
- Brömme K., Mark H., Konopatzki P., Kovac S., Stolpe F., Weiland S. & Zschiesche M. (2018). Cultivation of energy crops on former mining sites on a pilot scale in Vietnam. Berlin/Hanoi: Independent Institute for Environmental Issues – UfU.
- Carlou C., D'Alessandro M. & Swartjes F. (2007). Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonization.. s.l.:European Commission, Joint Research Centre, Ispra, EUR 22805-EN.
- Chileshe M. N., Syampungani S., Festin E. S., Tigabu M., Daneshvar A. & Odén P. C. (2019). Physico-chemical characteristics and heavy metal concentrations of copper mine wastes in Zambia: implications for pollution risk and restoration. *Journal of Forestry Research*. 31: 1283-1293.
- Chu T. T. H. (2011). Survey on heavy metals contaminated soils in Thai Nguyen and Hung Yen provinces in Northern Vietnam. *Journal of Vietnamese Environment*. 1: 34-39.
- Crespo-Toledo T., Avelar-González F., Guerrero-Barrera A., Mitchell K., Yamamoto-Flores L. & Flores-Amaro O. (2025). Integrative assessment of heavy metal risks in mining polluted sediments and soils of Aguascalientes, Mexico. *Case Studies in Chemical and Environmental Engineering*. 11: 101130.
- DIN EN ISO 11274 (2014). Soil quality – Determination of the water-retention characteristic – Laboratory methods (ISO 11274:1998 + Cor 1:2009); German version EN ISO 11274:2014. Berlin, Germany: Beuth Verlag.
- DIN ISO 10390 (2005). Soil quality - Determination of pH (ISO 10390:2005). Berlin, Germany: Beuth Verlag.
- El-Aassar A.-H., Hagagg K., Hussien R., Oterkus S. & Oterkus E. (2023). Integration of groundwater vulnerability with contaminants transport modeling in unsaturated zone, case study El-Sharqia, Egypt. *Environmental Monitoring and Assessment*. 195(6): 722. DOI:10.1007/s10661-023-11298-3.
- Feddes R. A., Kowalik P. J. & Zaradny H. (1978). *Simulation of field water use and crop yield*. Wageningen: Centre for Agricultural Publishing and Documentation.
- Filipović V., Cambier P., Filipović L., Coquet Y., Pot V., Bodineau G., Jaulin A., Mercier V., Houot S. & Benoit P. (2016). Modeling copper and cadmium mobility in an Albeluvisol amended with urban waste composts. *Vadose Zone Journal*. 15: 1-15.
- Gregory P. J. & Wojciechowski T. (2020). Chapter One - Root systems of major tropical root and tuber crops: Root architecture, size, and growth and initiation of storage organs. In: Sparks D. L. (Ed.). *Agricultural and Food Sciences*. Academic Press: 1-25. DOI: 10.1016/bs.agron.2020.01.001.
- Gul I., Manzoor M., Hashmi I., Bhatti M. F., Kallerhoff J. & Arshad M. (2019). Plant uptake and leaching potential upon application of amendments in soils spiked with heavy metals (Cd and Pb). *Journal of Environmental Management*. 249: 109408.
- Ha P. T., Phuong D. N. D., Anh H. H., Tu L. H., Vuong N. D. & Loi N. K. (2023). Quantitative exploration of the innovative trend method for evapotranspiration and its sensitivity to climatic variables: The case study of Southeast Vietnam. *Earth Science Informatics*. 17: 299-314.
- Hung, T. T., Doyle, R., Eyles, A. & Mohammed, C., 2016. Comparison of soil properties under tropical Acacia hybrid plantation and shifting cultivation land use in

- northern Vietnam. *Southern Forests: a Journal of Forest Science*. 79: 9-18.
- IUSS Working Group WRB (2022). World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps (4th ed.). Vienna Austria: International Union of Soil Sciences (IUSS).
- Khan M. A., Gemenet D. C. & Villordon A. (2016). Root System Architecture and Abiotic Stress Tolerance: Current Knowledge in Root and Tuber Crops. *Frontiers in Plant Science*. 7. DOI: 10.3389/fpls.2016.01584.
- Mansfeldt T. (2011). Metalle [Metals]. In: Blume H., Horn R. & Thiele-Bruhn S. (Eds). *Handbuch des Bodenschutzes. Bodenökologie und -belastung: vorbeugende und abwehrende Schutzmaßnahmen [Soil protection manual. Soil ecology and contamination: preventive and defensive protection measures]* (4th ed.). Weinheim: Wiley-VCH: 287-313.
- Mendez J. C., Van Eynde E., Hiemstra T. & Comans R. N. J. (2022). Surface reactivity of the natural metal (hydr)oxides in weathered tropical soils. *Geoderma*. 406: 115517.
- Moschner C., Feuerstein U., Heilmeier H., Zaffar N. & Wiche O. (2020). Effect of substrate properties on the mobility of selected trace elements in soil and concentrations in shoots of *Phalaris arundinacea*. *Carpathian Journal of Earth and Environmental Sciences*. 15: 49-56.
- Mwamba S., Kaluba P., Moualeu-Ngangue D., Winter E., Chiona M., Chishala B. H., Munyinda K. & Stützel H. (2021). Physiological and Morphological Responses of Cassava Genotypes to Fertilization Regimes in Chromi-Haplic Acrisols Soils. *Agronomy*. 11: 1757.
- Nassiri O., Rhoujjati A., Moreno-Jimenez E. & Hachimi M. L. E. L. (2022). Assessment of metallic trace elements mobility from mine tailing and soils around abandoned Pb mine site in North East Morocco. *Journal of Taibah University for Science*. 16: 933-943.
- Nguyen T. T. H., Vuong H. N., Zhang W. G., Lai V. C., Nguyen V. H., Le B. B., Nguyen P. T. & Tran T. N., (2020). Distribution of heavy metals in the topsoil of agricultural land in Nam Dinh Province, Vietnam. *Applied Ecology and Environmental Research*. 18: 6793-6811.
- Opara C. B., Kutschke S. & Pollmann K. (2022). Fractionation of metal(loid)s in three European mine wastes by sequential extraction. *Separations*. 9: 67.
- Phoncharoen P., Banterng P., Vorasoot N., Jogloy S., Theerakulpisut P. & Hoogenboom G. (2019). Growth rates and yields of cassava at different planting dates in a tropical savanna climate. *Scientia Agricola*. 76: 376-388.
- QCVN 03:2023/BTNMT (2023). National technical regulation on soil quality. s.l.:Ministry of Natural Resources and Environment.
- Reck A. (2021). *Vadose zone water and contaminant transport*. Berlin: Technical University of Berlin.
- Rennert T. (2019). Wet-chemical extractions to characterise pedogenic Al and Fe species – a critical review. *Soil Research*. 57: 1-16.
- Rieuwerts J. S. (2007). The mobility and bioavailability of trace metals in tropical soils: a review. *Chemical Speciation & Bioavailability*. 19: 75-85.
- Sahu C. & Basti S. (2020). Trace metal pollution in the environment: a review. *International Journal of Environmental Science and Technology*. 18: 211-224.
- Sayyadi S., Nguyen V. D., Apel H., Haas J., Dang T. T., Than V. D., Nguyen N. H. & Güntner A. (2025). Observation-based analysis of groundwater storage in Vietnam's Central Highlands: influence of hydro-climatic variability. *Hydrological Sciences Journal*. 70: 2993-3012.
- Seidl M., Le Roux J., Mazerolles R. & Bousserhine N., 2021. Assessment of leaching risk of trace metals, PAHs and PCBs from a brownfield located in a flooding zone. *Environmental Science and Pollution Research*. 29: 3600-3615.
- Šimůnek J., van Genuchten M. T. & Šejna M. (2008). Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal*. 7: 587-600.
- Singer M. B., Asfaw D. T., Rosolem R., Cuthbert M. O., Miralles D. G., MacLeod D., Quichimbo E. A. & Michaelides K. (2021). Hourly potential evapotranspiration at 0.1° resolution for the global land surface from 1981-present. *Scientific Data*. 8: 224. DOI: 10.1038/s41597-021-01003-9.
- Sutherland R. A. & Tack F. M. G. (2003). Fractionation of Cu, Pb and Zn in certified reference soils SRM 2710 and SRM 2711 using the optimized BCR sequential extraction procedure. *Advances in Environmental Research*. 8: 37-50.
- Tran T. V., Tran D. X. & Nguyen D. B. (2023). Agricultural drought in the Vietnamese Central Highlands at 1-km resolution: Monthly and annual datasets. *Data in Brief*. 48: 109194.
- Van T. T., Tri D. T., Dinh G. N. N. & Vuong T. M. H., (2023). Evaluation of groundwater level, quality and recharge: a case study of Can Tho City, Viet Nam. *Vietnam Journal of Science and Technology*. 61: 120-136.
- Weihermüller L., Kasteel R., Vanderborght J., Pütz T. & Vereecken H. (2005). Soil water extraction with a suction cup. *Vadose Zone Journal*. 4: 899-907.
- Wiggenhauser M., Illmer D., Spiess E., Holzkämper A., Prasuhn V. & Liebisch F. (2024). Cadmium, zinc, and copper leaching rates determined in large monolith lysimeters. *Science of the Total Environment*. 926: 171482.
- Zeien H. & Brümmner G. W. (1989). Chemische Extraktion zur Bestimmung von Schwermetallbindungsformen in Böden [Chemical extraction for determining trace metal binding forms in soils]. s.l., s.n.: 505-510.
- Zimmerman A. J. & Weindorf D. C. (2010). Heavy Metal and trace metal analysis in soil by sequential extraction: A review of procedures. *International Journal of Analytical Chemistry*. 2010: 387803. DOI: 10.1155/2010/387803.