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Metal Accumulation Risks in Enhanced Rock Weathering:

Risk Assessment Framework and Recommendations

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Abstract (<300 words):

Enhanced rock weathering (ERW) has emerged as a promising carbon dioxide removal (CDR) pathway that could mitigate climate change while improving agricultural soils. However, as the rocks used in ERW weather, metals posing an environmental safety risk can also be released. The nascency of ERW, complex dynamics of metal release and availability, and heterogeneity of global soil regulations make it difficult for practitioners to determine accumulation risks for many metals. To systematically evaluate these risks, we created the ERW Metal Accumulation Calculator (ERW-MAC), a conservative mass-balance model that combines global feedstock and soil datasets to estimate post-ERW deployment soil concentrations for 16 metals across a variety of baseline conditions, agricultural practices, and a range of basalt and peridotite application rates. Under deployment conditions for basalt feedstocks, modeled post-application soil metal concentrations remain below the majority of regulatory thresholds despite 8 metals displaying potential to become elevated above baseline concentrations. Under deployment conditions for peridotite feedstocks, Ni and Cr soil concentrations often surpass the median regulatory threshold. Finally, we show that the metal concentration per unit of potential CDR (metal intensity) varies by roughly an order of magnitude across the metals and feedstocks considered. Peridotite has 7-11x Ni and Cr intensity compared to basalt, whereas basalt has higher intensities, and greater variability in intensities, across a larger suite of metals (e.g., Cu, V, Co, and Mn). We conclude that given the current status of regulations and ERW deployments, soil metal accumulation risk assessment can be most effective when following a 3-part sequence: 1) characterizing feedstock composition and baseline soil conditions, 2) mass balance modeling of accumulation under maximally conservative assumptions, and 3) evaluating results against local regulations. All of these risk assessment activities should continue to be followed by in-field monitoring to ensure soil concentrations do not exceed regulatory requirements.

1.0. Introduction

Carbon dioxide removal (CDR) strategies deployed at a large scale will be needed amongst the greater portfolio of emission reductions to mitigate climate change resulting from anthropogenic carbon dioxide (CO_2) emissions (IPCC 2023). Agricultural enhanced rock weathering (ERW) is a promising CDR strategy that involves spreading crushed silicate rocks (i.e., feedstocks) on cropland soils to accelerate the inorganic carbon cycle and remove carbon dioxide from the atmosphere (e.g., Renforth 2012, Beerling *et al* 2018, Hartmann *et al* 2013). On geologic timescales, the weathering of silicate rocks naturally removes CO_2 from the atmosphere by converting CO_2 into alkalinity in the form of stable bicarbonate ions (HCO_3^-) which are eventually transported to the ocean (e.g., Berner 2004, Martin 2017, Penman *et al* 2020).

ERW has the potential to sequester 0.7-1.1 Gt CO_2 yr^{-1} while also providing agronomic co-benefits such as micronutrient fertilization and soil pH management (Tu et al., 2026, Goll *et al* 2021). Feedstocks used for ERW are inherently variable in their compositions of both beneficial base cations and mineral-bound metals that may pose environmental safety risks (Dupla *et al* 2023, Levy *et al* 2024). As these feedstocks weather, they release their elements in varying ways, dependent on the weatherability of the host mineral assemblage (Heřmanská *et al* 2022, Lewis *et al* 2021), but predicting how, when, and which metals will be released is often a challenge. This risk is influenced by feedstock bulk and mineralogical composition, climate and soil conditions, and farming practices, which are all factors that can affect feedstock dissolution rate, bio-availability of metals, and rate of metal migration through the soil (e.g., Roberts *et al* 2005, Parvin *et al* 2022, Dupla *et al* 2023, Zhang *et al* 2024).

The environmental safety risks posed by metal release can come in the form of reduced crop health and yield, human and animal consumption of toxic elements, and groundwater contamination (e.g., Anjum *et al* 2015, Buch *et al* 2021, Hamels *et al* 2014, Hou *et al* 2025). Further complicating risk characterization, the existing distribution of metals in cropland soils are often horizontally, vertically, and temporally heterogeneous. The origin of these metals can be from anthropogenic sources such as atmospheric deposition, the use of sewage fertilizers, the application of other metal-bearing soil amendments such as phosphate or micronutrient fertilizers, or from natural weathering of the soil's parent material (Wan *et al* 2024, Rashid *et al* 2023). It is estimated that 14 to 17% of global cropland exceeds agricultural thresholds for at least one toxic element (Hou *et al* 2025).

One response to these risks has been the development of suites of regulations which set threshold values that limit the concentrations of specific contaminants in soils, waters, and crops (e.g., US EPA 2015, Carlon *et al* 2007, Tóth *et al* 2016). Here we focus specifically on soil regulations, however in some jurisdictions threshold levels also exist for metal concentrations in crushed silicate rock feedstocks or agricultural soil amendments (European Parliament and Council of the European Union 2019, MAPA 2016). These thresholds exist to ensure that feedstocks do not have dangerously high concentrations of any potential contaminants, however feedstock thresholds alone are not considered sufficient to be solely relied upon without an accompanying soil threshold due to the strong impact of baseline soil concentrations on post-feedstock-application soil concentrations.

There are several environmental and methodological factors that contribute to the development of locally-applicable soil metal regulations, such as background metal concentration of a jurisdiction, the physico-chemical properties of the soils, and the choice of methods used to set regulations for a jurisdiction. As an example of an environmental factor that influences soil regulation development, high chromium concentrations can occur in regions with serpentinite-derived soils (e.g., McClain *et al* 2017; Oze *et al* 2004), high nickel concentrations can occur in soils derived from mafic material (e.g., Kumar *et al* 2019), and soils with low pH can lead to higher bioavailability and solubility of many metals (e.g., Alloway 2013). Local regulations often take into account baseline soil metal concentrations (e.g., MEF 2007), and some regulatory agencies publish thresholds that vary based on soil pH and soil type (e.g., Carlon *et al* 2007). Digestion methods also shape thresholds; see Methods 2.1.

Previous studies have assessed the risk of specific metals in specific regions (Dupla *et al* 2023, Haque *et al* 2020, Flipkens *et al* 2021, Suhrhoff 2022, Vink *et al* 2022, Sun *et al* 2022), however there is a need for more comprehensive analyses to standardize our base of knowledge. Due to the early stage of the ERW field and the complex regulatory landscape, the long-term risk of metals reaching harmful concentrations from ERW deployments still remains largely unexplored via systematic research. Here, we compile a suite of global feedstock and soil concentrations together with soil regulations for as many metals as possible given availability of global data. In this work, we present a conservative mass-balance model (ERW-MAC) using global feedstock and soil datasets to screen 16 metals for accumulation risk. We then contextualize model outputs against regulations, highlighting the heterogeneity that complicates their use as universal benchmarks for ERW deployment safety. We also compare the metal loading per unit of potential carbon removal between feedstock types. This work is a global analysis that intentionally considers a wide array of metals, as we intend it to serve as a potential basis for future metal-, region-, and condition-specific questions and analyses that may not have previously been identified.

2.0. Methods

2.1. Data

Feedstock and soil metal concentration data were collected for the following 16 metals: Nickel (Ni), Antimony (Sb), Beryllium (Be), Silver (Ag), Selenium (Se), Barium (Ba), Chromium (Cr), Copper (Cu), Manganese (Mn), Vanadium (V), Cobalt (Co), Zinc (Zn), Arsenic (As), Cadmium (Cd), Lead (Pb), and Mercury (Hg). Feedstock elemental and major oxide composition data were compiled from the GEOROC (Geochemistry of Rocks of the Oceans and Continents) database for both basalt and peridotite rock formations (DIGIS Team 2025). We constrained our analysis to basalt and peridotite to capture the most common ERW feedstock types (Hartmann *et al* 2013, Suhrhoff *et al* 2024). Soil data were obtained from the United States Geological Survey (USGS) (Smith *et al* 2013) and the Forum of the European Geological Surveys (FOREGS) (Salminen *et al* 2005). We also compiled data for additional regions from the supplementary sections of peer-reviewed literature for Brazil (Campos *et al* 2003), China (Wang *et al* 2020), and India (Kumar *et al* 2019). Data was compiled exclusively from agricultural soils.

We compiled soil metal concentration regulatory thresholds from 13 countries: United States, Germany, Czech Republic, Lithuania, Slovakia, Finland, Austria, Belgium, France, Italy, Portugal, Brazil, and Australia (Table S1). A total of 165 threshold values were compiled across 16 metals, and the acid digests were distributed among: aqua regia (*n*=150), total digest (*n*=13), very strong acid (*n*=2). These threshold values are predetermined concentrations above which soil contaminants are deemed unsafe for the general environment, plants, invertebrates, or humans. We recognize that these search parameters may have led to data gaps, and the obtained regulations likely do not represent a fully comprehensive global set.

In our analysis, we only include regulations that prescribed either a total acid or aqua regia digest for measurement of metal concentrations in soil. Total digests (e.g., 4-acid digest, lithium borate fusion) mobilize the entirety of the metals present in a soil sample, whereas weak acid digests (e.g., ammonium acetate, mobile metal ion (MMI)) mobilize only a portion of the total metal content of a soil sample. However, very few regulations (<13 in our dataset) explicitly specify a total digest method. To maintain a usable point of comparison, we also included thresholds developed using aqua regia digests. This choice is conservative because aqua regia recovers less metal than a total digest (e.g., Taraškevičius *et al* 2013, Dupla *et al* 2023), and thresholds derived from aqua regia are set at lower concentration values than equivalent total-digest thresholds would be. Therefore, if a modeled concentration falls below an aqua-regia-derived threshold, it can reasonably be assumed to also fall below the corresponding (higher) total-digest-derived threshold. This exclusion criteria was implemented to ensure that the comparison of concentration limit values to modeled concentration values was realistic.

2.2 Model

Post-application soil concentrations were modeled using a mixing approach that combined randomly sampled values from fitted feedstock and soil distributions. For each simulation iteration (n = 10,000) a concentration was drawn from each of the fitted soil and feedstock concentrations. The model produces kernel density estimates (KDEs) of soil metal concentrations under specified conditions which are visualized as a probability density function describing the relative likelihood of different post-deployment soil concentrations.

The modeled feedstock application rates were scaled dependent on feedstock type. For basalt, cumulative application rates of 25t/ha, 50t/ha, 75t/ha, 100t/ha, and 125t/ha were modeled, as in-field application rates are commonly between 20-50 t/ha (e.g., Wang and You 2025, Power *et al* 2025) and re-applications of feedstock are not uncommon. For peridotite, application rates of 5t/ha, 10t/ha, 15t/ha, 20t/ha, and 25t/ha were modeled, as recommendations for peridotite application rates are lower than basalt due to its elevated CO_2 removal capacity and greater potential contamination by Ni in particular (e.g., Iff *et al* 2024, Pogge Von Strandmann *et al* 2022, Taylor *et al* 2016).

Soil depth and soil bulk density were selected randomly for each simulation. Soil depth values were drawn randomly from a uniform distribution with a defined range of 0.05 m to 0.3 m to simulate different potential soil/feedstock mixing depths. Soil bulk density values were drawn randomly from a truncated normal distribution with a defined mean of 1250kg/m^3, standard deviation of 250kg/m^3, and a range of 800kg/m^3 to 1700kg/m^3 (Panagos *et al* 2024).

The basic mass-balance equation underlying the ERW-MAC is:

(1) $$HM_{conc(baseline\ soil)} + \frac{HM_{conc(feed)} * app\ \ rate * n_{applications}}{Depth * BD} = HM_{conc(final\ soil)}$$

The key variables in the function are defined as follows:

Table 1: Defined variables in the mass balance equation for the ERW-MAC model.		
Variable	**Unit**	**Definition**
$HM_{conc(baseline\ soil)}$	(mg/kg_{soil})	Concentration of element in baseline soil
$HM_{conc(feed)}$	(mg/kg_{feed})	Concentration of element in feedstock from GEOROC database
$app\ rate$	$(kg_{feed}/m^2/application\ event)$	Application rate of the feedstock in a given ERW deployment
$Depth$	(m)	Soil depth at which the feedstock will be incorporated
BD	(kg_{soil}/m^3)	Bulk density of the soil the feedstock is being deployed on
$HM_{conc(final\ soil)}$	(mg/kg_{soil})	Calculated concentration of an element after complete dissolution of the feedstock and accumulation into the soil

The modeling approach was designed to be maximally conservative to provide an upper-bound risk scenario for environmental safety risk with respect to metal accumulation. Site-specific scenarios that fall below modeled thresholds would be expected to present lower accumulation risk, though site-specific factors not captured by the model may warrant additional consideration.

The key assumptions of the model include: 1) full, instantaneous dissolution of the feedstock over one application event with full metal release from the feedstock; 2) no export of metals from soil after deposition (e.g., by plant uptake or transport through the soil column beyond the specified soil depth)and; 3) homogenous vertical and lateral soil metal concentrations throughout the soil.

This approach excludes risk-reducing dynamics such as metal complexation with organic matter and metal export from the soil column. The approach also does not account for certain risk-elevating dynamics relevant to specific metal species such as the presence of Mn oxides or oscillating redox conditions, which are factors that contribute to Cr(VI) formation. The model therefore represents a conservative baseline for total metal accumulation rather than a comprehensive treatment of metal speciation dynamics.

To determine the significance of the shifts in soil concentrations resulting from feedstock addition, Cohen's d, Mann-Whitney U, and Kolomogorov-Smirnov statistical tests were used (See Supplemental Text). A shift in soil concentrations was defined as significant when both the Cohen's D value was >0.2 and either the Mann-Whitney U or the Kolomogorov-Smirnov p value was <0.05. The Cohen's d threshold of 0.2 represents a conventional boundary for small effect sizes (Cohen 1988). Several metal-feedstock combinations fall just below this threshold (e.g., peridotite Cr at 5 t/ha, d = 0.18), meaning the list of metals identified as significant is sensitive to this choice. The comprehensive results of these tests are included in Table S2.

2.3 Metal intensity per unit of CDR

To compare metal loading between feedstock types on a common basis, we calculated the metal intensity per unit of theoretical maximum carbon dioxide removal (CDRmax). CDRmax was estimated for each GEOROC feedstock sample using the modified Steinour equation (Renforth 2019), which computes the maximum CO_2 sequestration potential from the major oxide composition (CaO, MgO, Na_2O, K_2O) assuming complete dissolution at a given soil pH of 6.0 (DIGIS Team 2025). Metal intensity was calculated as the feedstock metal concentration (mg/kg rock) divided by CDRmax (tCO_2/tROCK), yielding units of ppm metal per tCO_2 removed per ton of feedstock applied.

3.0. Results and Discussion

This analysis considers a suite of 16 metals present in ERW feedstocks and soils globally. In Table 2, we present feedstock:soil concentration ratios and data showing when statistically significant soil baseline shifts occur post-deployment. Although this analysis does not address the question of regulatory compliance, the results serve as a useful first-order approximation for which metals may elevate baseline soil concentrations at specific application scenarios. Intuitively, metals with higher feedstock:soil ratios show a statistically significant increase at lower cumulative application scenarios.

Under the conservative assumptions of the ERW-MAC model, basalt application can produce statistically significant but modest increases in soil metal concentrations above baseline for 8 of the 16 metals analyzed at ≥50t/ha, however for peridotite only Ni and Cr lead to elevation above baseline at ≥5t/ha. However, when global regulatory thresholds are overlaid (Figures 1 - 3), the post-application concentration distributions for both feedstock types remain largely below the range of regulatory concern for most metals analyzed. It is worth noting that, for example, the model assumes that two 50 t/ha application events is the same as one 100 t/ha application, which is varyingly defensible based on the mobility of the element considered. Additionally, bulk density and mixing depth are key variables that affect the relative toxicity of a metal in soil, and should be considered

Table 2: Median metal concentration in basalt and peridotite feedstocks and in baseline cropland soil, with feedstock:soil concentration ratios for all 16 metals analyzed. The peridotite ratio is normalized to basalt application rates (divided by 5). Asterisked ratios indicate metals that significantly elevate soil baseline concentrations in the model.

Element	Global Baseline Soil Median Conc. (mg/kg)	Basalt Median Conc. (mg/kg)	Peridotite Median Conc. (mg/kg)	Basalt Conc./Baseline Soil Conc.	Peridotite Conc./Baseline Soil Conc. Normalized to basalt app. rate	Application rate that triggers significant baseline elevation (Basalt; Peridotite) in t/ha
Ag	0.27	0.05	0.00	0.20	0.00	N/A
As	6.09	1.44	0.00	0.24	0.00	N/A
Ba	474.00	250.00	15.00	0.53	0.01	N/A
Be	1.10	1.04	0.06	0.95	0.01	N/A
Cd	0.20	0.10	0.02	0.52	0.02	N/A
Co	7.93	44.00	109.00	5.55**	2.75	50 ; N/A
Cr	34.00	158.00	2587.00	4.65**	15.22**	50 ; 10
Cu	14.89	71.00	14.40	4.77**	0.19	50 ; N/A
Hg	0.03	0.00	NA	0.00	NA	N/A
Mn	479.00	1325.00	979.50	2.77**	0.41	75 ; N/A
Ni	16.00	80.00	2086.00	5.00**	26.08**	75 ; 5
Pb	18.90	3.40	0.40	0.18	0.00	N/A
Sb	0.58	0.10	0.00	0.17	0.00	N/A
Se	0.40	0.39	0.02	0.98**	0.01	100 ; N/A
V	55.00	259.00	53.10	4.71**	0.19	50 ; N/A
Zn	58.00	95.00	51	1.64**	0.18	100 ; N/A

For basalt, four metals (Cu, Cr, Co, V) show a statistically significant increase at 50 t/ha cumulative application, all with feedstock:soil ratios >4.5. At 75 t/ha, Mn (ratio 2.77) and Ni (ratio 5.00) show the potential to elevate baseline soil concentration. At 100 t/ha, Zn (ratio 1.64) and Se (ratio 0.98) elevate soil baseline concentrations. For Se, the feedstock concentration is roughly equal to the soil baseline, so the additive term in the mass-balance equation contributes only a marginal shift regardless of application rate. The resulting significance at 100 t/ha reflects the statistical power of n=10,000 iterations detecting a small effect (Cohen's d = 0.23) rather than a meaningful relative enrichment. The remaining 8 metals (Ag, As, Ba, Be, Cd, Hg, Pb, Sb) do not significantly elevate soil baselines at any application rate modeled, and all have feedstock:soil ratios below 1. Unexpectedly, Ni concentrations significantly shift above baseline at 75t/ha for basalt, when a shift at 50t/ha would be expected based on its feedstock:soil ratio. However, Ni has an exceptionally high baseline soil variability (coefficient of variability = 599%), which potentially contributes to this result.

When normalized to basalt application rates (dividing by 5 to account for the ~5× lower peridotite application rate), the feedstock:soil ratios for Ni (26.1) and Cr (15.2) far exceed even the highest ratio for a metal in basalt (4.77 for Co). A unique case occurs in Co, as despite peridotite's high Co concentrations (median 109 mg/kg), high variability in baseline soil Co (CV = 228%) may prevent consistent elevation of baseline concentrations across a majority of scenarios. However, all other peridotite metals have normalized ratios below 1, indicating that peridotite's risk profile may be mostly concentrated in two metals rather than distributed broadly as it is for basalt.

A number of factors limit the reliability of the ratios as a broadly-applicable proxy to assess environmental safety risk: 1) high baseline soil variability can delay or mask the expected shift (as with Ni); 2) metals with ratios near 1 can reach statistical significance from a small shift given the statistical power of n=10,000 iterations, without meaningful relative enrichment (as with Se) and; 3) it assumes constant bulk density and tillage depth. The combination of these factors underscore the importance of site-specific soil characterization and consideration of agronomic practices across a broad suite of scenarios and therefore motivated the development and application of our more comprehensive ERW-MAC model.

3.1 Global soil metal concentrations and regulations

To visualize shifting soil metal concentrations for multiple application scenarios (inclusive of variability in soil bulk density and tillage practices), the ERW-MAC model produces values visualized as curves of the probable distribution of soil concentrations for each metal after incremental increases in application amount. The height of the curve at any given point corresponds to how many scenarios led to a particular final soil concentration. That is, the higher the curve at a given point, the more likely the soil concentration of the chosen element is to fall near that concentration. The overlain regulatory box can be used to evaluate post-application soil metal concentrations against a subset of global regulations, however any visual comparison is not to be interpreted as a formal compliance assessment given the spatial and methodological heterogeneity of regulations.

The curves for metals which elevate baseline concentrations at application scenarios below 100 t/ha are shown in Figures 1-3, and the full suite of curves for all metals across both feedstocks can be found in Figures S1-S7. When interpreting the individual KDE curves against the metal-specific regulatory overlays, the key metric is the proportion of each distribution that exceeds the median regulatory threshold. This proportion estimates the likelihood that a randomly selected feedstock:soil combination would produce a post-application soil concentration that would exceed the median regulation value. For example, 10.7% of the integrated area under the peridotite 10 t/ha curve falls above (to the right of) the median regulation value for Cr, which means that 10.7% of the the modeled deployment scenarios would exceed the median regulatory value (Figure 3B).

Regulatory coverage is uneven across the metals analyzed (Figure S8). Several metals identified by the ERW-MAC model as leading to significant elevation of soil baseline concentration (e.g. V (n = 6), Mn (n = 2), and Se (n = 3)) have little regulatory coverage. Therefore, the regulatory overlay on Figures 1-3 for these metals should be interpreted with caution.

The compiled thresholds also show wide heterogeneity in both scope and stringency that are often the result of specific local environmental factors (see section 1.0 and 3.2). For example, the compiled thresholds for Ni range from 30 mg/kg (Brazil prevention value; CONAMA 2009) to 150 mg/kg (Finland higher guideline value; MEF 2007). This heterogeneity is visible in the regulatory box-and-whisker overlays on Figures 1–3, where the interquartile range alone often spans a factor of 2–3x.

Finally, the type of digest that a regulation used to derive its threshold is important information for measuring a sample for comparison and compliance, but is not always obvious. The digest type dictated by the threshold should match the digest used to analyze the sample (see Methods 2.1 and SI).

Despite these regulatory limitations, mass-balance-based approaches and their comparison against existing thresholds remain amongst the most comprehensive risk-screening approaches ERW practitioners can use.

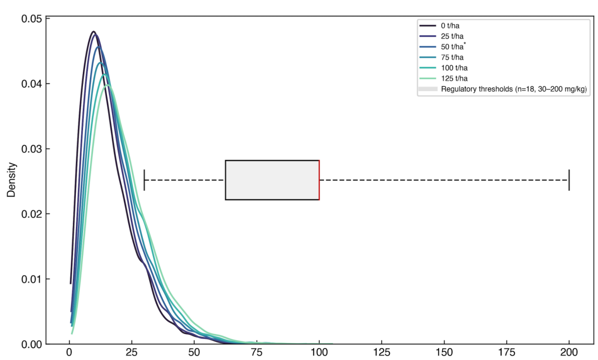
3.2. Metal accumulation scenarios and regulatory environment for basalt feedstocks

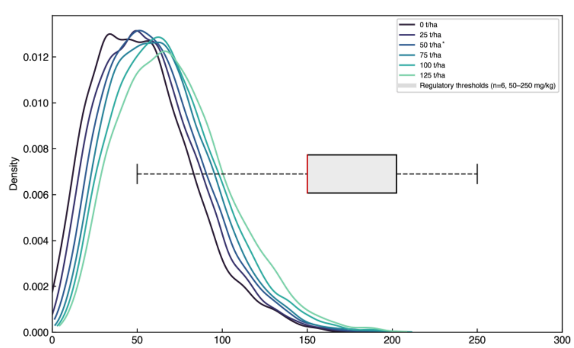
Figures 1 and 2 show the KDE curves for the 8 metals in basalt that show a statistically significant shift above baseline, with compiled regulatory thresholds overlaid as box-and-whisker plots. For the metals that show a statistically significant elevation above baseline at the lower application volumes (Cu, Cr, Co, V at 50 t/ha), the post-application distributions remain below the regulatory median even at the highest application scenario which indicates a substantial divergence between regulatory risk and baseline elevation. For instance, for Cr, the median post-application concentration at the highest basalt application scenario (~45 mg/kg) still falls below the 25th percentile of compiled thresholds (n = 16, range 50–300 mg/kg). For Ni at the highest basalt application scenario, the median post-application concentration (~21 mg/kg) likewise remains below the regulatory range (n = 19, 30–150 mg/kg).

For Mn, the basalt post-application distributions overlap heavily with the regulatory range. However, this range is derived from only 2 thresholds (220, 1500 mg/kg) so this likely reflects sparse regulatory coverage as opposed to truly elevated risk. The lower threshold (220 mg/kg) is from the US EPA, and specifies the limit to be detrimental for plants, whereas the higher threshold (1500 mg/kg) is from Lithuania, and is designated for agricultural soils. This highlights that regulations for a given metal can be exceedingly (~7x) different based on unknown factors. Similarly, the range of regulatory thresholds (n=9) found for Co spanned 13-250 mg/kg, which is a 19x difference in limit value.

In many areas globally, cropland soil metal concentrations in one jurisdiction can exceed regulatory thresholds from other jurisdictions due to local geogenic or anthropogenic impacts on soils (Campos 2003, Kumar 2019, Wang 2020, Salminen 2005). This is in part because soil thresholds are often calibrated to local geogenic and land-use baselines rather than universal toxicity limits. For example, soil regulations that are created by the Ministry of the Environment of Finland (MEF 2007, Table S1) are bespoke to Finnish soils. Finland's Co thresholds, which are very high (100-250 mg/kg) compared to other countries' regulations (13-50 mg/kg), are better understood when considering that areas of Finland are naturally enriched in Co and Finland has the largest known Co resources in Europe (Konnunaho *et al* 2023). Therefore, using a Co threshold from India, for example, to regulate a Finnish soil would be inappropriate, and the reverse is also true. Alternatively, if a deployment in India (where we could not find readily-accessible national regulations) were to attempt to adhere to Finland's Ni regulations, the baseline soil concentrations would sometimes exceed Finnish limits because portions of Indian soils are derived from Deccan traps parent material (e.g., Sayyed and Hundekari 2006, Tandon 2002) which are mafic rocks that can lead to elevated concentrations of some heavy metals in soils. Of all the Ni soil values for India in our database (n=111), 6.3% exceed Finland's lower guideline value (100 mg/kg), and 7.2% exceed Finland's higher guideline value (150 mg/kg) (Table S3; Kumar *et al* 2019).

Soil thresholds are therefore not consistently inter-comparable, and treating them as such can lead to mischaracterization of risk profiles for ERW deployments. However, this analysis illustrates that, for basalt distributions, the majority of scenarios for most metals stays below the regulatory range at all application scenarios (Figures S1-S7).





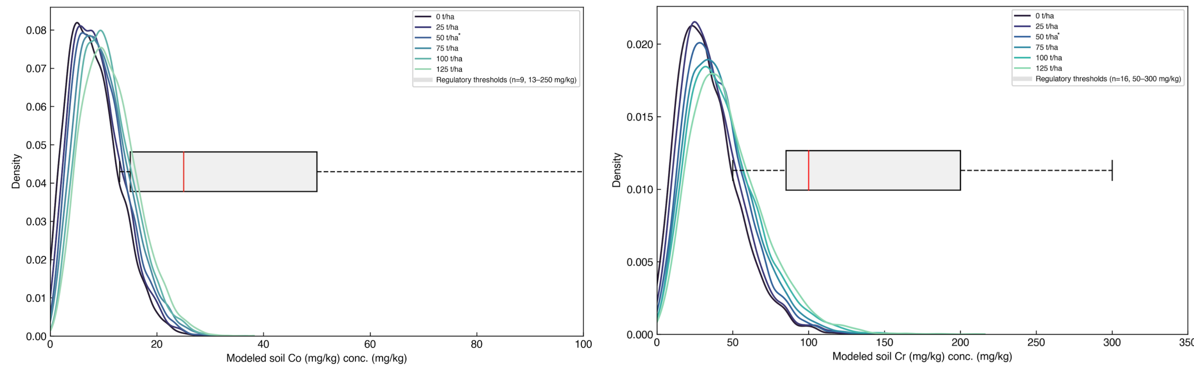


Figure 1: Modeled evolution of soil concentrations for metals which exceed baseline at application rates at or above 50 t/ha (Cu, V, Co, and Cr) as a result of cumulative basalt applications. The application rate curves range from a minimum of 0 t/ha (dark purple) to a maximum of 125 t/ha (light green). The red lines mark the median regulatory value in the range. An asterisk next to an application rate in the top right key indicates a statistically significant increase in soil metal concentration above baseline. Note the different x and y axis scales between the four graphs.

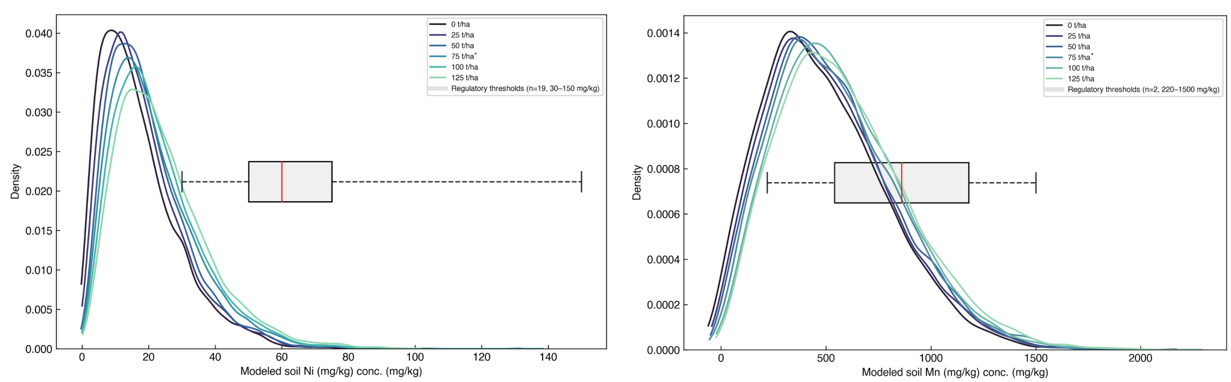


Figure 2: Modeled evolution of soil concentrations for metals which exceed baseline at application rates above 75 t/ha (Ni and Mn) as a result of cumulative basalt applications. The application rate curves range from a minimum of 0 t/ha (dark purple) to a maximum of 125 t/ha (light green). An asterisk next to an application rate in the top right key indicates a statistically significant increase in soil metal concentration above baseline. Note the different x and y axis scales between the four graphs.

3.3 Metal accumulation scenarios and regulatory context for peridotite feedstocks

For peridotite, only Ni and Cr significantly elevate soil baseline concentrations (Table 2; Figure 3). Ni shows a statistically significant elevation above baseline at all modeled application rates (≥5 t/ha) and Cr beginning at 10 t/ha. However, no other metal consistently elevates baselines at cumulative peridotite applications up to 25 t/ha.

Figure 3 shows the peridotite KDE curves with regulatory overlays. For Ni, the 25 t/ha distribution overlaps substantially with the interquartile range of compiled thresholds (n = 19, 30–150 mg/kg), with the upper end of the distribution extending beyond the high end of the regulatory range. For Cr, the 25 t/ha distribution approaches the lower quartile of thresholds (n = 16, 50–300 mg/kg).

For peridotite, a much larger proportion of the distributions for Ni and Cr sits within the regulatory range compared to basalt. This relationship has previously been identified for peridotite and is one reason why peridotite feedstocks are applied at lower rates (e.g., Schiedung *et al* 2025). Ultramafic (e.g., peridotite) feedstocks also have higher CDR potential (~0.8 tCO_2/tROCK) relative to mafic (e.g. basalt) feedstocks (~0.3 tCO_2/tROCK) which also allows for lower application rates (Schiedung *et al* 2025).

Overall, the comparatively fewer number of metals that can accumulate in soils from peridotite feedstock application may present opportunities for more targeted monitoring and specific research into Ni and Cr environmental safety risks.

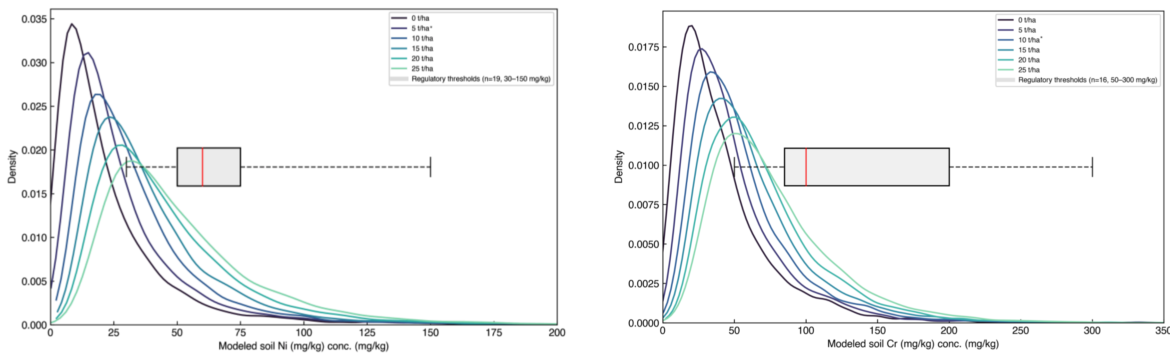


Figure 3: Modeled evolution of soil concentration levels for Ni (left) and Cr (right) as a result of cumulative peridotite applications. The application rate curves range from a minimum of 0 t/ha (dark purple) to a maximum of 25 t/ha (light green). An asterisk next to an application rate in the top right key indicates a statistically significant increase in soil metal concentration above the baseline. Note the different x and y axis scales between the two graphs.

3.4 Metal intensity per unit of carbon removal

To evaluate whether elevated accumulation risk for individual metals present in basalt and peridotite is a function of feedstock geochemistry or a consequence of typical application rates, we calculated the amount of each individual metal concentrated in each feedstock ("intensity") per unit of potential carbon removal ("CDRmax"). It is already clear that metals like Ni and Cr are present in much greater concentrations in peridotite feedstocks than basalt. However, because the CDRmax of peridotite feedstocks is higher than basalt, less feedstock is required to achieve the same amount of CDR. Figures 4 and S9 therefore directly compare metal intensity for each of the 16 metals analyzed and additionally provide a framework for understanding one practical implication of feedstock choice given potential variability in baseline soil conditions.

For Ni, peridotite's median intensity is approximately 11x that of basalt (Table 3). For Cr, peridotite's median intensity is roughly 7x that of basalt's (Table 3), which indicates that peridotite's Ni and Cr burden is a function of the rock's geochemistry rather than a consequence of application rates.

Table 3: Metal intensity per unit of carbon removal by rock type.			
Rock	**Metal**	**Median Intensity (ppm per tCO_2/tROCK)**	**Sample size (n)**
Peridotite	Ni	4,434	1580
Basalt	Ni	384	57,000
Peridotite	Cr	5,493	1,473
Basalt	Cr	744	54,402
Peridotite	Co	234	1,061
Basalt	Co	207	37,124
Peridotite	V	111	1,464
Basalt	V	1,183	49,095
Peridotite	Zn	111	1,036
Basalt	Zn	447	37,925
Peridotite	Cu	27	1,030
Basalt	Cu	311	36,068
Peridotite	Mn	2,051	153
Basalt	Mn	5,942	1,856
Peridotite	Sb	0	166
Basalt	Sb	0	3,536
Peridotite	Pb	1	894
Basalt	Pb	14	35,677
Peridotite	Cd	0	125
Basalt	Cd	1	2,159
Peridotite	Be	0	124
Basalt	Be	5	6,054
Peridotite	Ba	29	1,417
Basalt	Ba	1114	58,584
Peridotite	As	0	175
Basalt	As	5	3,437
Peridotite	Ag	0	57
Basalt	Ag	0	1,708

The pattern reverses for most other metals. Basalt generally carries a higher metal intensity per unit of carbon removal than peridotite, except for Co (Figure S9). For Co, peridotite's median intensity is slightly higher than basalt's (Table 3). Even though Co does not reach statistical significance in the modeled outputs for peridotite due to high baseline soil variability (CV=228%), the per-unit-CDR suggests that monitoring for Co is still warranted in peridotite-based deployments. Overall, peridotite metal intensity is primarily concentrated in Ni and Cr, with Co as a lower-magnitude concern, while basalt distributes a more moderate intensity across a broader suite of metals.

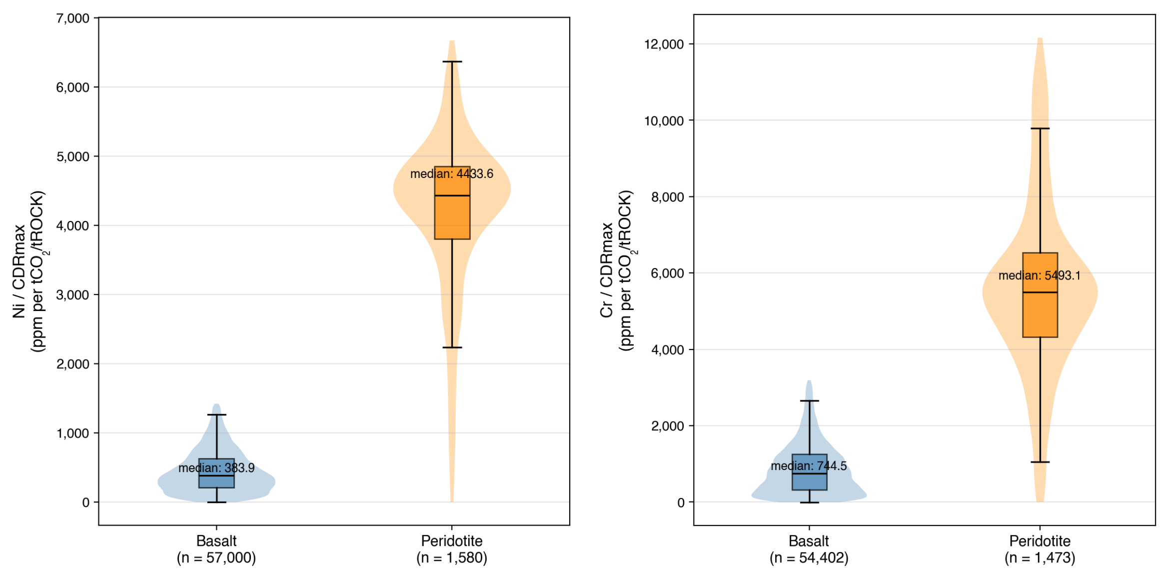


Figure 4: Metal intensity per unit of theoretical maximum carbon removal (ppm per tCO_2/tROCK) for basalt (blue) and peridotite (orange), shown for Ni (left) and Cr (right). Median values are labeled, the box spans the interquartile range, and the whiskers extend to 1.5x the interquartile range. CDRmax was calculated from major oxide compositions via the modified Steinour equation at pH 6.0 (Renforth 2019). Sample sizes vary by metal and feedstock due to data availability in the GEOROC database and are reported on each panel.

Per unit of CDR, basalt has a relatively higher burden of Cu, V, Zn, and Mn than other metals (Figure S9). These metals have received comparatively little attention in ERW environmental risk assessments, which have focused primarily on Ni and Cr. The combination of high per-unit-of-CDR loading and limited regulatory coverage (V: n=6, Mn: n=2) identifies these as priorities for future research in basalt-based deployments. In contrast, peridotite has a more acute burden of Ni and Cr, which allows for more targeted site selection during ERW deployments using these feedstocks.

4. Summary and Conclusions

Under maximally conservative assumptions, basalt application at rates common in current field deployments does not produce post-application soil metal concentrations that approach the majority of compiled global regulatory thresholds for any of the 16 metals analyzed. For peridotite, the modeled Ni and Cr post-application soil concentrations overlap with the median value of the compiled thresholds. Also, the Ni and Cr intensity per unit of peridotite CDR is 7–11x higher than that of basalt. These findings indicate that while peridotite concentrates its metal burden into two metals, basalt distributes a more moderate burden across a broader suite. Neither feedstock shows potential for widespread environmental harm in the model results at current average single deployment rates.

However, the robust regulatory landscape needed to confirm the lack of potential harm is fragmented by geography, extraction method, and metal coverage, which leaves the ERW field without a consistent basis for evaluating metal accumulation risk. Based on these findings, we recommend that for most effective risk assessment, ERW practitioners rigorously characterize both their feedstock and baseline soil concentrations ahead of deployment for all metals analyzed here. Additionally, because Cu, Co, V, and Mn have the potential to become elevated above baseline concentrations at realistic basalt application rates but have received less attention than Ni and Cr in previous risk assessments, continued in-field monitoring over multiple years of this suite of metals is also strongly encouraged.

Irrespective of individual metals, we take the position that given the current status of ERW-relevant regulations and scaling of deployments, maximally comprehensive risk consideration should include: 1) modeling the most conservative accumulation scenario prior to deployment using site-specific parameters; 2) exercising caution when applying regulatory thresholds across jurisdictions, given the spatial and methodological heterogeneity documented here; and 3) supporting the development of ERW-specific soil safety thresholds grounded in local soil type and geochemistry and 4) actively monitoring deployments for metal concentration changes and sharing that data publicly.

Until a more robust monitoring system is established for ERW , we recommend that ERW practitioners use tools like the ERW-MAC alongside site-specific soil and feedstock characterization to identify metals of concern prior to deployment, rather than relying solely on feedstock screening or cross-jurisdictional regulatory thresholds. By providing a transparent, conservative framework for evaluating metal accumulation risk, the ERW-MAC model can support both informed project design and the development of evidence-based policy as the ERW field continues to scale.

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Data Availability Statement

All data used throughout this research is publicly available. Code run for these analyses can be found at https://github.com/Cascade-Climate/ERW-MAC/tree/main. Compiled datasets (baseline soil, feedstock, and regulations) that were fed into the model can be found at https://zenodo.org/records/21419182 and https://zenodo.org/records/21418764.

Conflict of Interest

J.L. maintains un-exercised options in the carbon registry Isometric awarded during his employment there from 2023-2024. The remaining authors declare that they have no competing interests.

Author Contributions

N.O. led the conceptualization, data curation, project administration, and investigation of this research and manuscript. J.L. also contributed to conceptualization and investigation. N.O. and J.L. collaborated on formal analysis, methodology, visualization, writing – original draft, and writing – review & editing. N.A. contributed to formal analysis, methodology, visualization, and writing – review and editing. T.T. contributed to supervision, project administration, and writing – review and editing.

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