Basalt heavy metal assessment

The weathering of mafic igneous rocks such as basalt, and silicate minerals (e.g., olivine), is associated with release of heavy metals, especially nickel and chromium. Concentrations of heavy metals above a certain threshold may cause contamination of soil, surface and groundwater, as well as crops, which might have a negative ecotoxicological impact on organisms, including animals and humans. The transport and mobility, and hence bioavailability and toxicity of the heavy metals depends on their speciation, which are influenced by processes such as i) adsorption and desorption; ii) oxidation and reduction; iii) dissolution and precipitation (Alloway, 2012). Due to the complexity of modelling the transport and bioavailability of heavy metals under varying soil, land use and crop types, we have chosen to apply a limit for the maximum permissible heavy metal concentrations of the basalt or silicate minerals applied to soils. If the materials exceed these values, they will be discounted for use in enhanced weathering activities.

To date, there are no environmental regulations around heavy metal limits for addition of basalt to agricultural land (Suhrhoff, 2022). Soil guideline values vary from country to country, and in some cases, the use of soil guideline values (SGVs) is only advised, and not obligatory. In many instances, there are no agricultural SGVs. In order to ensure best practice we apply the European SGVs, which are more stringent than others, on a global basis, even in countries where there are no such guidelines (Carlon, 2007).

Compared to olivine, basalts typically have lower heavy metal concentrations, and thus pose fewer environmental risks. To minimise any potential risk of heavy metal contamination, we screen our basalts to ensure that the heavy metal concentrations are well below levels that could pose any ecological or environmental risk. We are screening for arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), antinomy (Sb), and zinc (Zn). The concentration of heavy metals in the basalt is determined using Inductively Coupled Plasma - Mass Spectroscopy (ICP-MS) at an internationally ISO accredited lab. The basalt heavy metal composition is reanalysed every 3k tonnes to assess any heterogeneity in the source rock.

Prior to spreading, we estimate the concentration of the heavy metal in the top 30 cm of topsoil after addition of the basalt using equation 1. This is compared with EU agricultural SGVs to ensure that the concentrations of any potentially toxic heavy metals do not exceed acceptable limits.

$$C_{Soil\ after} = \frac{(C_{soil\ before} * \rho b * 0.3) + (C_{basalt} * m_{basalt})}{\rho b * 0.3 + m_{basalt}} \leq SGV \quad (1)$$

Where:

$C_{Soil\ before}$ is the heavy metal topsoil concentration before application of basalt [μg/g]

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ρ_b is the soil bulk density [kg/m^3], multiplied by 0.3 m to get 30 cm of topsoil
C_{basalt} is the heavy metal concentrations in the basalt
m_{basalt} is the mass of basalt applied [kg/m2]
SGV is the EU agricultural soil guideline value for a given heavy metal [μg/g]

The soil background concentration of heavy metals in a region of interest is extracted from open source published spatial datasets (e.g., 1000 m resolution for the EU from Tóth et al. 2016, and at 500 m resolution for the US, Smith et al., 2019). To ensure agreement between the published datasets and measured concentrations, a subset of soil samples are analysed for heavy metal concentration for a small number of farms within each region of interest.

The main factor controlling soil concentrations is the composition of the parent bedrock material. Localised naturally elevated background soil, surface and groundwater concentrations can sometimes occur when soils are formed in regions with metal-rich bedrock compositions, or localised hotspot contamination. Where $C_{Soil\ after}$ is predicted to exceed SGVs, additional soil samples will be analysed to ensure any enhanced weathering activities will not exceed SGVs.

Case Study: UK and US

The following is a case study showing our approach to calculate the change in heavy metal concentration to the topsoil after spreading. For both the UK and US, the maximum heavy metal concentration across three quarries is assessed in relation to the maximum soil background concentration ($C_{Soil\ after}$) in a 50 mile radius from the quarry (Table 1). Basalt heavy metal concentrations (C_{basalt}) are shown for the Tams Loup, Floak and Hillend quarries for the UK, and Riley Goldendale, Nobles and Rowley quarries for the US (Table 1).

Baseline concentrations of the heavy metals in the topsoil before application of basalt ($C_{Soil\ before}$) for a 50 mile radius from the UK Tams Loup quarry were obtained from published spatial background datasets from Tóth et al. (2016) and JHI (2022). Topsoil baseline concentrations for a 50 mile radius from the US Riley Goldendale quarry were extracted from 72 point measurements from the USGS national soil geodatabase (Smith et al., 2019). The mass of basalt (m_{basalt}) assumes an application density of 20 tonnes per hectare, or 2 kg/m^2.

Due to the low heavy metal concentrations in the basalt, and low application densities, the increase in heavy metal concentrations for published baseline soil values ($C_{Soil\ after}$) generally do not exceed the EU agricultural SGVs. For all heavy metals, the percent relative change between $C_{Soil\ before}$ and $C_{Soil\ after}$ is within a few percent, and is deemed of low risk for heavy metal contamination.

Furthermore, in the UK, the soil concentration was measured at the Abbey Mains Farm three months after application. The maximum concentration is shown in Table 1 ($C_{Soil\ Max\ t\ =\ 3\ months}$). All values are below the EU SGV's, except for arsenic, which is elevated due to a naturally high background. None of the quarries have detectable levels of arsenic, including the basalt spread at that farm, consequently the elevated concentrations cannot be due to contamination from the basalt. In the US, the soil from Norris Farm was sampled prior to basalt spreading. All heavy metal concentrations were well below the EU SGVs, both in the measured ($C_{Soil\ before}$) and the calculated potential increase after basalt application ($C_{Soil\ after}$).

Table 1: Calculations of increase in soil heavy metal concentrations after basalt addition, and comparison to EU soil guideline values (SGVs)

	As [ug/g]	Cd [ug/g]	Co [ug/g]	Cr [ug/g]	Cu [ug/g]	Hg [ug/g]	Ni [ug/g]	Pb [ug/g]	Sb [ug/g]	Zn [ug/g]
EU Agricultural SGV	**5**	**1**	**20**	**100**	**100**	**0.5**	**50**	**60**	**2**	**200**
Basalt concentrations (C_{basalt}) in UK										
Tams Loup	<5	0.9	44	79	58	0.008	57	4.5	<5	165
Floak	<5	1.3	40	55	63	<0.005	53	3	<5	132
Hillend	<5	0.7	54	296	52	0.011	282	<2	20	114
Maximum published topsoil concentrations (C_{soil}) in 50 mile radius from Tams Loup Quarry										
$C_{Soil\ before}$	10.5	0.2	17	64	30	0.45	43	82	1	171
$C_{Soil\ after}$	-	0.20	17	64	30	0.45	43	82	-	171
% change to $C_{Soil\ before}$	-	2.1	1.0	0.1	0.6	-0.6	0.2	-0.6	-	-0.02
Maxium measured topsoil concentrations at Abbey Mains Farm										
$C_{Soil\ t\ =\ 3months}$	8.1	0.93	nd	43.8	23	<DL	26	32	-	87
Basalt concentrations (C_{basalt}) in US										
Riley Goldendale	<5	0.6	42	16	24	<0.005	17	6	<5	157
Nobles	1	0.1	42	111	63	<0.01	51	4.6	0	88
Rowley	<1	0.1	44	124	50	<0.01	55	8.5	0.08	107
Maximum published topsoil concentrations (C_{soil}) in 50 mile radius from Riley Goldendale Quarry										
$C_{Soil\ before}$	9.3	<1	32	150	89	0.1	56	30	0.001	200
$C_{Soil\ after}$	-	-	32	149	89	-	56	30	-	200
% change to $C_{Soil\ before}$	-	-	0.2	-0.5	-0.4	-	-0.4	-0.5	-	-0.1
Maxium measured topsoil concentrations at Norris Farm										
$C_{Soil\ before\ (measured)}$	<DL	<DL	15	nd	nd	0.009	9	<DL	nd	40
$C_{Soil\ after}$	-	-	15	-	-	-	9	-	-	41
% change to $C_{Soil\ before}$	-	-	1.1	-	-	-	0.5	-	-	1.8

<DL = Less than detection limit
nd = not determined
UK topsoil datasets from Tóth et al. (2016) and JHI (2022).
US topsoil datasets from Smith et al. (2019).
EU Agricultural soil guideline values (SGVs) from Carlon (2007).

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