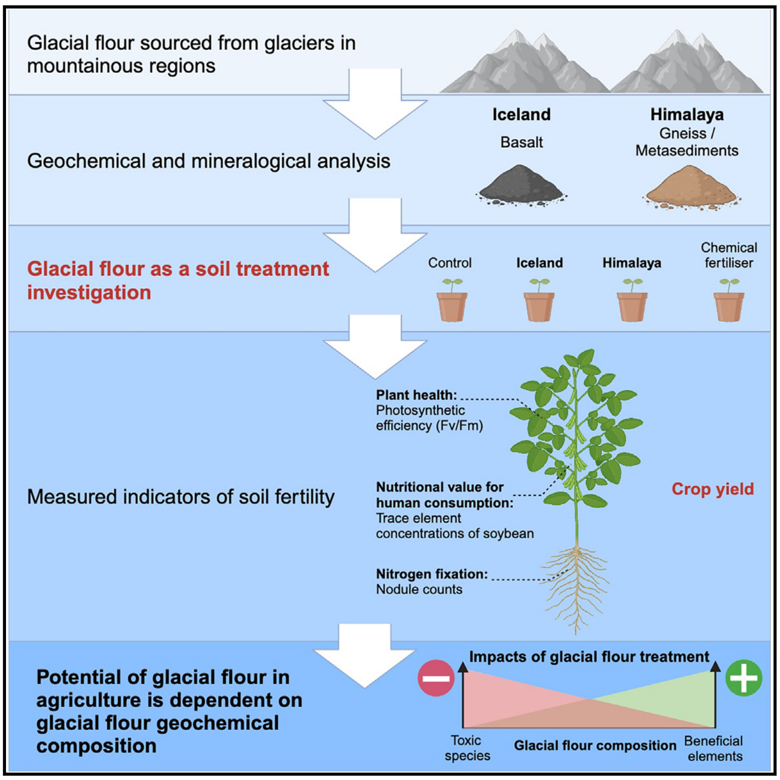
iScience

Article

The potential for glacial flour to impact soil fertility, crop yield and nutrition in mountain regions

Graphical abstract



Highlights

- Glacial flour sourced from two different mountainous regions significantly enhanced soybean crop yield acting as a source of macro and micronutrients
- Glacial flour treated crops benefited from improved plant health, nitrogen fixation, and plant biomass
- Nutritional value to humans is determined by geological composition and trace element availability e.g. toxic arsenic

Authors

Sarah Tingey, Jemma L. Wadham, Jonathan Telling, ..., Antony N. Dodd, Xuan Liu, Fotis Sgouridis

Correspondence

sarah.l.tingey@uit.no (S.T.),
jemma.l.wadham@uit.no (J.L.W.)

In brief

Soil science; Glacial processes; Glacial landscapes; Soil chemistry; Soil ecology.

Tingey et al., 2025, iScience 28, 111476
January 17, 2025
https://doi.org/10.1016/j.isci.2024.111476

CellPress

iScience

CellPress
OPEN ACCESS

Article

The potential for glacial flour to impact soil fertility, crop yield and nutrition in mountain regions

Sarah Tingey,[1,2,11,*] Jemma L. Wadham,[1,3,*] Jonathan Telling,[4] Shannon Flynn,[4] Jonathan R. Hawkings,[1,5] Sabina Strmic Palinkas,[1,2] Yulia Mun,[1,2] Christopher A. Yates,[3,6] Guillaume Lamarche-Gagnon,[1] Rory Burford,[1] Al L. Ramanathan,[7] Alistair Hetherington,[8] Antony N. Dodd,[9] Xuan Liu,[10] and Fotis Sgouridis[3]

[1]IC3: Centre for Ice, Cryosphere, Carbon and Climate, Department of Geosciences, UiT The Arctic University of Norway, Tromsø, Norway
[2]Department of Geoscience, UiT - The Arctic University of Norway, Tromsø, Norway
[3]School of Geographical Sciences, University of Bristol, Bristol, UK
[4]School of Natural and Environmental Sciences, Newcastle University, Newcastle, UK
[5]Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA, USA
[6]AtkinsRéalis, The Hub, 500 Park Avenue, Aztec West, Bristol, UK
[7]School of Environmental Sciences, Jawarlahal-Nehru University, New Delhi, India
[8]School of Biological Sciences, University of Bristol, Bristol, UK
[9]Department of Cell and Developmental Biology, John Innes Centre, Norwich, UK
[10]Geological Survey of Finland, Espoo, Finland
[11]Lead contact
*Correspondence: sarah.l.tingey@uit.no (S.T.), jemma.l.wadham@uit.no (J.L.W.)
https://doi.org/10.1016/j.isci.2024.111476

SUMMARY

Novel sustainable agricultural strategies that enhance soil nutrients and human nutrition are crucial for meeting global food production needs. Here, we evaluate the potential of "glacial flour," a naturally crushed rock produced by glaciers known to be rich in nutrients (P, K, and micronutrients) needed for plant growth. Our proof-of-concept study, investigated soybean (*Glycine max.* var. Black jet) growth, yield, and nutrient content with soil supplementation from glacial flour sourced from Himalayan glaciers (meta-sediment gneiss bedrock) and Icelandic glaciers (basaltic bedrock). Glacial flour treatment enhanced crop yields by 85% (Himalayan) and 135% (Icelandic), compared to controls. Additionally, glacial flour fortified crops with beneficial micronutrients zinc and selenium. However, the application of Himalayan flour led to arsenic bioaccumulation in the crop, underscoring the importance of catchment geology. This study supports using glacial flour as a soil remediation strategy for sustainable agriculture but emphasizes the need to consider potential toxicity risks.

INTRODUCTION

Agriculture in the 21st century faces a global challenge to sustainably meet the needs of a predicted world population of 9 billion by 2050.[1] It is proposed that meeting these future food demands will require investment in smallholder practices[2] and a global shift toward sustainable intensive agriculture,[3] whilst improving crop nutritional content.[4] One potential method of rejuvenating soils to enhance productivity is the application of fresh mineral material,[5] such as crushed rock (e.g., rock dust or flour). Existing studies have shown that ground rock particles can be a source of phosphorus (P),[6] potassium (K),[7] and micronutrients (iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn)[8]) to soils, enhancing crop yields,[9] plant health,[10] soil water retention,[11] and soil carbon dioxide (CO_2) sequestration capacity.[12] However, the impact of crushed rock on crop growth within typical agricultural soils is constrained by its mineralogical composition, particle size, and soil pH.[13] The adoption of crushed rock soil amendments is limited by the need to selectively mill rocks (<150 μm)[14] of desired mineralogical properties[13] and sourcing of pre-milled material,[15] both of which have a non-trivial carbon footprint and high economic costs.[16] The soil geochemical environment should also be considered with regard to whether it is suitable for promoting chemical weathering, or the applied crushed rock and associated nutrient release.[17]

A novel alternative to the application of mechanically crushed rocks is to employ material that has been naturally crushed by erosional agents, the most powerful of which are glaciers. Glaciers are "sediment factories," efficiently eroding and crushing their underlying bedrock to highly reactive, fine particles,[18] hereafter referred to as glacial flour. Recent work has shown that glacial rock flour sourced from Greenlandic glaciers overlying felsic bedrock (quartz, feldspars, biotite, and minor amphiboles), to experimental and native soils within Danish organic agriculture[19] has successfully increased crop yields. This is due primarily to the provision of K[19,20] and magnesium (Mg),[20] improved water retention[21] and has also shown potential to sequester CO_2[22]. However, although these preliminary investigations have shown positive impacts on crop yields, we identify two key research gaps.

First, the impact of geologically alternative glacial flours sourced from contrasting bedrocks upon crop yield and growth is unknown. Past research into the use of crushed rock for agriculture has concluded that plagioclases from basalts are among the fastest weathering silicate minerals, enhancing nutrient provision[22] and sequestering up to 0.8–0.9 tCO_2 per ton of rock dissolved.[9,23] However, despite being identified as the "ideal" rock type for large-scale enhanced weathering application, the effectiveness of basaltic glacial flour, such as Icelandic glacial flour, as a soil treatment has not yet been established.

Furthermore, metasedimentary bedrock types are widely found beneath glaciers in mountain regions such as the Alps,[24,25] Andes,[26,27] Canadian Rockies,[28] Caucasus Georgia,[29] Hindu-Kush Himalaya (HKH),[30,31] Karakoram,[32] Rwenzori,[33] Scandinavia and Svalbard,[34] but the potential of glacial flour as a soil amendment is untested. Past investigations into enriching soils with crushed rock have sourced metamorphic and sedimentary crushed rock from quarry and mining practices have shown varied impacts upon crop yields.[35] High glacier coverage over metasedimentary rocks in some regions, such as the HKH[36] and the Karakorum[37] intersects with widespread food security issues,[38,39] and highlights an important area for the investigation of glacial flour effectiveness on crop yields. For example, in the HKH, concentrations of glacial flour can reach up to 0.5 g L^{-1} in mountainous valley glacier-fed rivers during peak summer discharge, with monitored glaciers having sediment export of 120 T yr^{-1}.[40] In the HKH, increased runoff and sediment loads are predicted to increase with continued glacier retreat under climate warming.[41] An increase in sediment deposition on agricultural floodplains[42] and the potential for agricultural expansion into deglaciating landscapes, makes it important to determine the wider impacts of geologically diverse glacial flour on crops.[43]

Second, although glacial flour has previously been shown to be rich in bioavailable nutrients[44] such as nitrogen (N),[45] P[47], K[19], carbon (C),[46] Fe[47] and trace micronutrients,[48] and has the potential to enhance crop yields,[19,20] the uptake of these elements by crops and the impact on their nutritional value is unknown. The addition of beneficial geogenic micronutrients (Fe, Ca, Mg, Zn) to soils has the potential to enrich crops by "biofortification."[49] Concurrently, glacial flour treatment may increase geogenic trace elements to potentially toxic concentrations, e.g., elements (As, Cd, Co, Cr, Ni, and Pb), in soils.[50] It is therefore important to determine the impact of lithologically contrasted glacial flours on crop nutrition and its relevance for public health.

Here, we assess the potential of two geologically contrasted glacial flours to support soil fertility, crop growth, and the nutritional content of the widely cultivated legume soybean (*Glycine max* var. Black jet), in a controlled glasshouse investigation using an artificial soil matrix as a proof-of-concept study. The legume soybean was selected as a model crop in this investigation, as it eliminates the need for N fertilization since it fixes N through its symbiotic relationship with rhizobia in root nodules.[45] Despite some sedimentary bedrocks being N-rich,[51] it is unlikely that rock N transfers directly to the plant in significant amounts.[38] Soybeans are also one of the most commercially valuables, widely cultivated global crops: they are important as an oil seed; a component of human diets; and are used as biofuels and feedstocks.

Himalayan glacial flour was chosen because of the presence of metasedimentary bedrocks beneath glaciers, and because it is agriculturally relevant for the region, due to a reliance on smallholder agriculture,[52] rising food security demands,[53] and increasing threats from climate change.[54] Icelandic flour was selected due to the basaltic geology underlying the glaciers, with basalts being previously highlighted as having potential for crop fertilization and carbon capture via enhanced weathering.[12] The glacial flours investigated in this study were sourced from contrasting bedrocks to previous studies, which have focused on the application of Greenlandic glacial flour from granitic bedrock.[19–21,55,56]

Our proof-of-concept results document the response of crop yield, plant health, and nutrition following the addition of glacial flour to a low-nutrient, artificial soil matrix, in comparison to controls (no treatment) alongside traditional chemical fertilizer addition experiments. The results from our controlled investigation across one growth cycle rapidly highlight the impacts of glacial flour upon crops and provide compelling evidence that glacial rock flour has the potential to be both a source of fertility and toxicity to agricultural croplands.

RESULTS AND DISCUSSION

Glacial flour mineralogy

Icelandic glacial flour was collected from Sólheimajökull glacier, Iceland (63.4 °N, 19.4 °W) and originates from flood basaltic terrain.[57] Himalayan glacial flour was sourced from Chhota Shigri glacier, India (32.3 °N, 77.7 °E) that overlies a metamorphic complex, predominantly composed of migmatites and gneisses locally penetrated by granitic rocks and overlayed by metasediments, mostly black slates, phyllites and fine-grained biotite-schists.[58,59] In both cases, the glacial flour was collected from recently deposited glaci-fluvial material close to the glacier terminus.

Grain size analysis showed a significant ($p < 0.05$) difference between the Icelandic and Himalayan glacial flour. The Icelandic particle size diameter was 33.7 ± 1.7 μm, compared to 112.4 ± 2.3 μm for Himalayan flour (Table S1). Both flours are coarser than previous glacial flour crop work, e.g., the Greenlandic glacial flour used by Gunnarsen et al.[20] had a median particle size diameter of 2.6 μm[19]. The glacial flour used in these experiments is nevertheless within the range of particle sizes investigated with crushed rock for crop work.[13–15,35]

Mineral analysis via light microscopy indicated that Icelandic glacial flour primarily comprised fine grained olivines and pyroxenes, some plagioclase feldspars, clay minerals, and iron oxides weathering crusts. Himalayan glacier flour appeared as medium grained sand, containing mostly quartz and minor amounts of biotite, feldspars, iron oxides, and oxyhydroxides indicated via weathering crusts, ilmenite, and rutile. Scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) analysis of iron oxyhydroxides in Himalayan glacial flour indicated they were predominantly oxidation products of sulfides, as

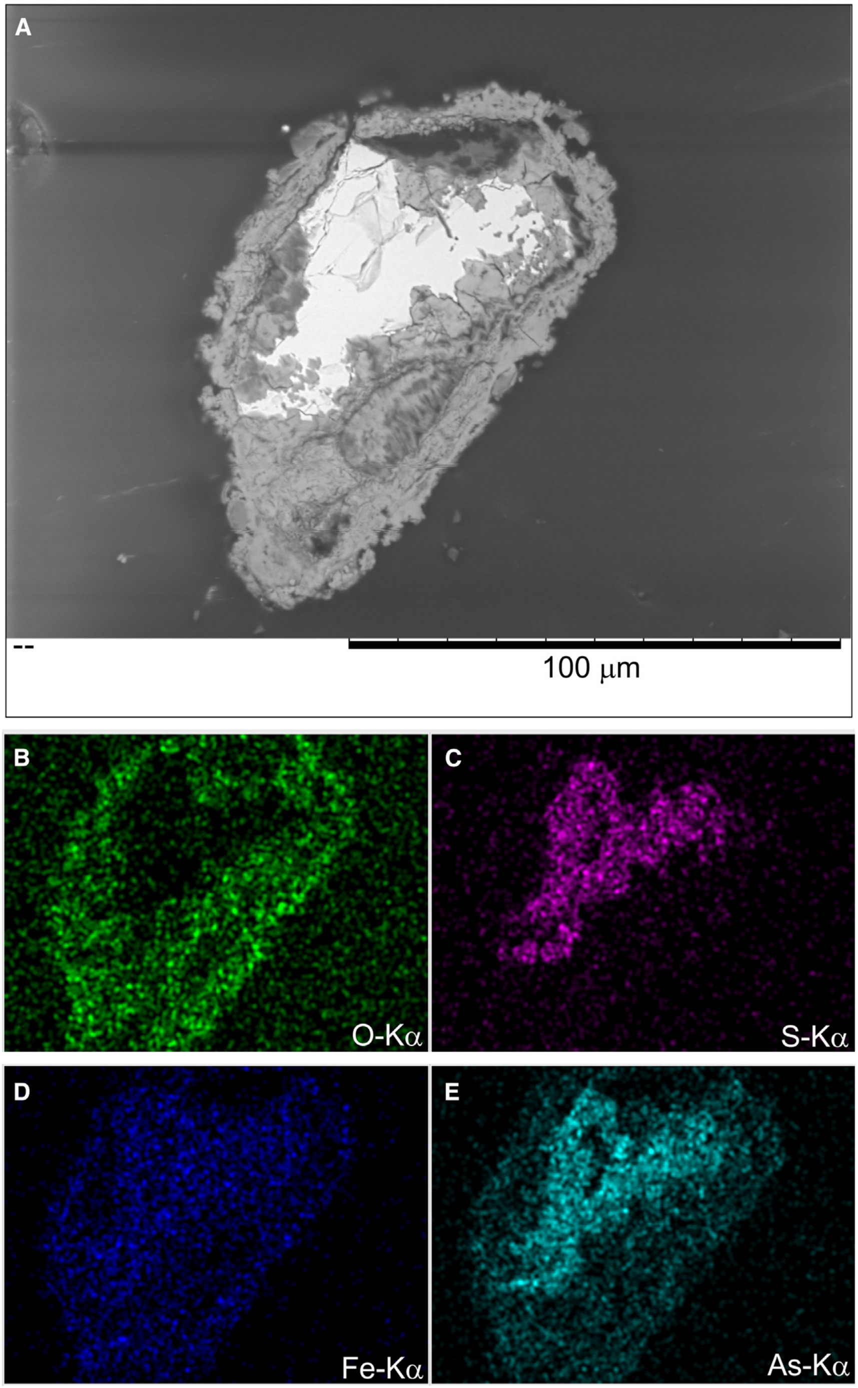


Figure 1. Himalayan glacial four arsenopyrite grain analysis, scale of 100 μm shown is applicable to all images

(A) Backscattered electron (BSE) image of an isolate arsenopyrite grain from the Himalayan glacial flour showing a fresh core and weathering rim.

(B) Scanning electron microscopy (SEM)-EDS map of oxygen reflects that the rim is composed of oxides or oxyhydroxides.

(C) SEM-EDS map of sulfur confirms that the core is composed of a sulfide mineral phase.

(D) SEM-EDS map of iron shows that weathering did not affect the mobility of this element.

(E) SEM-EDS map of arsenic confirms that the core is composed of preserved arsenopyrite while arsenic was mobilized from the rim (that is composed of Fe-oxyhydroxides) during weathering (oxidation processes).

they formed weathering crusts around pyrite, pyrrhotite, and arsenopyrite particles (Figure 1). Visual inspection alongside thin section light microscopy of rocks collected from the Himalayan proglacial zone suggests that sulfides are associated with hydrothermal veins, which is consistent with the hydrothermal alteration of minerals in geothermal regions of the HKH.[60] The presence of sulfide minerals such as arsenopyrite in the Himalayan flour has the potential to act as a source of toxic trace elements, such as arsenic (As), to crops after weathering.[61] Investigating the accumulation of these potentially toxic elements from glacial flour by crops is therefore critical in assessing potential health risks to humans.

Glacial flour enhanced crop yields

Himalayan and Icelandic flour treatments increased soybean yield (dry weight (g)) above control experiments (no treatment) by 85% and 138% respectively ($p < 0.05$) (Himalaya; 36.0 ± 2.9 g m^{-2}, Iceland; 47.4 ± 2.1 g m^{-2}, Control; 19.9 ± 3.4 g m^{-2}) (Figure 2A; Table 1) when applied to a low nutrient soil matrix at a practical application rate (2 T ha^{-1}, equivalent to 0.125–0.146 mm covering farmland).[6,14] Furthermore, the glacial flour application rate, between 0.5 T ha^{-1} and 20 T ha^{-1}, was significantly positively correlated with soybean yield ($R^2 = 0.80$, $p < 0.05$, $n = 3$) (Figure 2B). The crop yield exceeded that of low-application rate chemical fertilizer treatments (N-P-K added at 10 kg ha^{-1} Figures 2A; Table 1). Crop yields achieved in this experiment are comparable to previous glacial flour crop yield gains for the same application range.[19,20]

The higher crop yield achieved when the soil matrix was supplemented with Icelandic flour ($p < 0.05$) compared with the Himalayan flour for the same application rate is likely due to two factors. First, Icelandic flour contained higher total concentrations of key plant nutrients (P, Fe, S, Mg, Ca, Mn; Table 2) than Himalayan flour – although it was depleted in K compared with the Himalayan flour, reflecting the different bedrock lithologies (Table 2). Concentrations of highly labile exchangeable nutrients

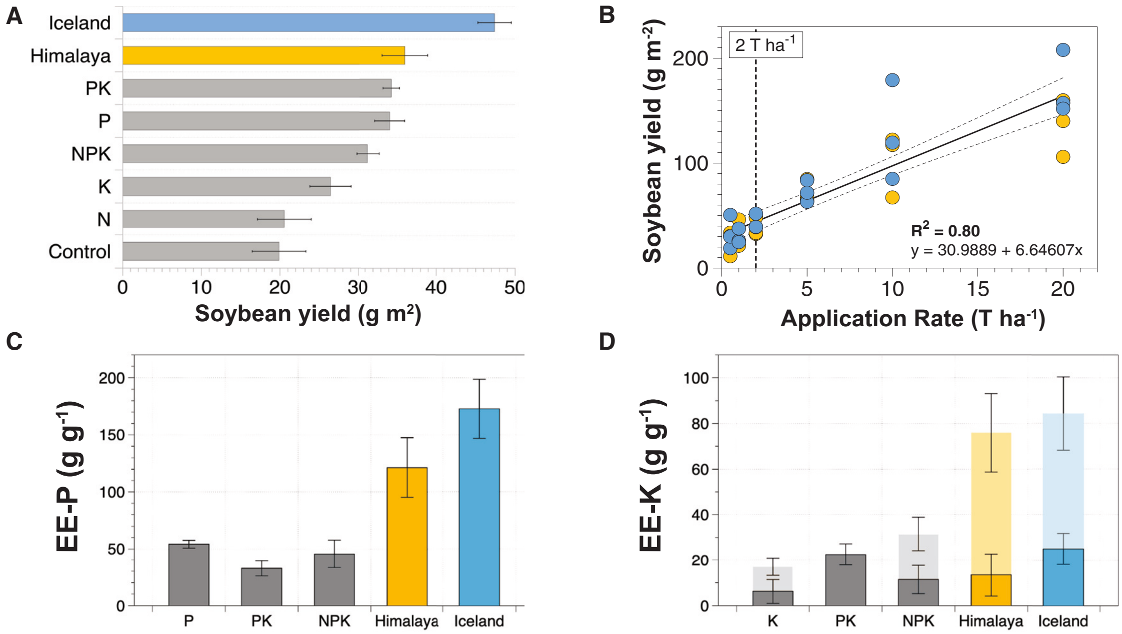


Figure 2. Soybean and glacial flour crop yield and efficiency results

(A) Soybean crop yield (g m^{-2}) across a range of treatments, including glacial flour applications at 2 T ha^{-1} (n = 12, error bars are SEM).
(B) rate relationship between soybean yield and glacial flour application rate (n = 3, 95% confidence intervals represented by dashed line).
(C) elemental efficiency (EE-P) of P (g g^{-1}).
(D) elemental efficiency (EE-K) of K (g g^{-1}). The gray shaded horizontal regions in (C and D) are regarded as the optimum AE in farming [1]. The darker colored bars in c and d are EEs calculated using the total K and P, and lighter colors are the EE calculated using the exchangeable EE-K values (these bars are not available for EE-P because the values calculated were beyond that of reasonable values, see main text). Agronomic efficiency calculations are calculated using the whole pot nutrient values of exchangeable or total nutrients, including the soil matrix.

(Ex-P; 24.6 ± 2.7 μg g^{-1}, Ex-K 1060 ± 94.6 μg g^{-1}, Ex-Fe 4.0 ± 0.08 mg g^{-1}) in Icelandic flour were more than double those in the Himalayan flour (Ex-P; 5.6 ± 0.8 μg g^{-1}, Ex-K 383 ± 67.7 μg g^{-1}, Ex-Fe 1.40 ± 0.02 mg g^{-1}) (Table 2; Table S2).[62] Second, Icelandic flour had a smaller mean particle size, suggesting a greater reactive surface area (mean p.s.d = 33.7 ± 1.7 μm), compared with Himalayan flour (mean p.s.d = 112.4 ± 2.3 μm) (Table S1).

We calculated experimental element efficiency (EE) indices (Figures 2C and 2D) to evaluate the effectiveness of glacial flours in increasing crop yield. These indices are analogous to the widely applied metric 'agricultural efficiency', which is used to assess the impact of applied elemental chemical fertilizers on crop yield.[63] Agricultural efficiency metrics (Equation 2) determine a rate between the difference in two yields (e.g., Treatment Yield – Control Yield) and the mass of nutrient applied (e.g., Chemical P applied (kg m^2)). A high EE score suggests high yields compared to the mass of nutrients applied, whilst low values indicate inefficient fertilization and yield response. EEs were calculated using both the exchangeable (Ex-P, Ex-K) and total P and K[65] concentrations associated with glacial flours with the latter used to infer potential enhanced mineral weathering in the experiment.

EEs calculated using only Ex-P (Ex-P EE: Himalaya flour EE = 3100 ± 212 g g^{-1}, Icelandic flour EE = 4609 ± 240 g g^{-1}) were two orders of magnitude higher than International Fertiliser Association (IFA) target AE values (15–40 g g^{-1}).[64] These values are unrealistically high and suggest that P is likely to be supplied from mineral P in glacial flours, Extractions performed on the glacial flours indicate the majority of P (>95% for both flours) is held in a HCl-extractable phase, which is commonly assumed to represent apatite-group minerals. Experimental EE scores using total P were closer to the recommended agricultural efficiency p values (Himalaya flour TP EE = 121 ± 26.1 g g^{-1}, Icelandic flour TP EE = 173 ± 25.9 g g^{-1}). Both glacial flours were more efficient per gram of Ex-K than chemical K treatments (Ex-K EE: K EE = 17.1 ± 3.9 g g^{-1}, PK EE = 8.1 ± 1.6 g g^{-1}, NPK EE = 31.5 ± 7.3 g g^{-1}, Himalaya EE = 75.9 ± 17.2 g g^{-1},

Table 1. Soybean crop yield results

Treatment	Soybean yield (g m^{-2})	Change in Fv/Fm (%)	Above ground biomass (g per plant)	Nodule count	n
Control	19.9 ± 3.4	−31.1 ± 1.5	1.24 ± 0.17	28.3	6
N	20.5 ± 3.4	−23.4 ± 2.7	1.56 ± 0.08	31.1	4
P	34.1 ± 1.9	−20.5 ± 1.8	1.95 ± 0.06	86.9	4
K	26.4 ± 2.6	−24.6 ± 1.2	1.84 ± 0.10	79.6	4
PK	34.3 ± 1.0	*NA*	1.71 ± 0.26	91.3	5
NPK	31.3 ± 1.5	−24.6 ± 1.9	1.91 ± 0.12	51.8	6
Himalaya flour	36.0 ± 2.9	−17.6 ± 2.1	1.92 ± 0.02	104.9	6
Iceland flour	47.4 ± 2.1	−16.2 ± 1.9	2.20 ± 0.16	149.8	6

Glacial flour treatments shown are those for 2 T ha-1 application rate. Results shown are the mean and the standard error of the mean.

Table 2. Measured mean glacial flour concentrations of plant essential exchangeable (uncrushed, labile extractions) and total nutrients (crushed, total extraction)

Glacial flour	Exch-N	Total-P(Exch-P)	Total-K(Exch-K)	Total-Fe (Exch-Fe)	Total-Ca	Total-Mg	Total-Mn	Total-S	Total-Si	Total-Zn	Total-Ni	Total-As
				($mg\ g^{-1}$)							($ug\ g^{-1}$)	
Iceland	<LOD	2.85 a± 0.04 (0.024 ± 0.003)	6.76 ± 0.15(1.07 ± 0.09)	152 ± 3 (4.05 ± 0.08)	27.4 ± 0.08	33.5 ± 0.09	2.50 ± 0.04	3.56 ± 0.04	< LOD	232 + 2.2	86.9 + 2.9	2.59 + 0.03
Himalaya	<LOD	2.24 ± 0.10 (0.006 ± 0.001)	8.41 ± 0.26(0.38 ± 0.07)	20.5 ± 0.2(1.49 ± 0.02)	2.35 ± 0.06	3.47 ± 0.06	< LOD	< LOD	1.02 ± 0.17	114 + 3.1	12.8 + 0.2	73.8 + 8.0

Exch, exchangeable; LOD, limit of detection.
Values from this study are presented to three significant figures.

Table 3. Element efficiency of P (EE-P) and K (EE-K)

Treatment	EE-P	EE-K	EE-ExchK	n
		($g\ g^{-1}$)		
P	54.3 ± 3.46	–	–	12
K	–	6.15 ± 5.15	17.1 ± 6.15	12
PK	32.5 ± 6.59	22.5 ± 4.73	8.11 ± 0.56	12
NPK	45.5 ± 12.3	11.4 ± 6.21	31.6 ± 7.28	12
Himalaya (2 T ha^{-1})	121 ± 26.1	13.4 ± 9.34	75.9 ± 17.2	12
Iceland (2 T ha^{-1})	173 ± 25.9	24.9 ± 6.72	84.3 ± 16.1	12
FAO recommendations	15–40	16–20		

AE, agronomic efficiency; Exch, exchangeable; SD, standard deviation of the mean.
Relevant efficiency data is presented. EE-P was calculated based on Total P concentrations. EE-K was calculated from Total K, EE-Exch-K is presented based on sequential K extractions. Values from this study are presented to three significant figures. EE Recommendation levels also shown. Error shown is SD.

Iceland AE = 84.3 ± 16.1 g g^{-1}) and all treatments other than the PK chemical fertilizer treatment met the recommended AE rating for K (16–20 g g^{-1}) (Figures 2D; Table 3).[65] These results suggest that glacial flour efficiently increased crop yields. The high EE values may be due to be due to factors other than P and K availability, such as micronutrient availability. Soybeans treated with chemical fertilizers may have experienced micronutrient limitations impacting crop yields, and the low EEs may reflect competition between the crops and microbial soil communities for nutrient uptake, or sorption to the artificial soil matrix.[66]

While these results indicate that Himalayan and Icelandic glacial flours have the potential to efficiently release elements required by crops from mineral phases, our experiments were only performed over a single crop cycle. Quantifying the use of each element and the potential long-term weathering effects of glacial flour could not therefore be evaluated. We might expect the release of nutrients from mineral phases to persist over multiple crop seasons, but this should be a topic for further study.[19]

Glacial flour improved N fixing capability and maintained the photosynthetic efficiency of crops

To assess the effect of glacial flour application on biological nitrogen fixation (BNF) and maintenance of photosynthetic efficiency in the soybean plants, root nodule counts and inferred photosynthetic capacity of the soybean plants were measured[67] (Fv/Fm; the ratio between variable fluorescence and maximum fluorescence, representing the maximum potential quantum efficiency of Photosystem II if all capable reaction centers were open). Both BNF and Fv/Fm parameters correlated positively with crop yield in all experimental treatments ($p < 0.05$, $r^2 = 0.85$ and $p < 0.05$, $r^2 = 0.62$, respectively) (Figures 3A and 3B; Table 1; Tables S3 and S4). Over the first 30 days of growth, there were reductions in Fv/Fm across all treatments (Figures 3C; Table S3), which suggests that nutrient limitation constrained photosynthetic efficiency. However, the plants receiving the glacial flour treatments (2 T ha^{-1}) had the smallest reduction in Fv/Fm. Final Fv/Fm ratios for Himalayan flour (0.655 ± 0.003)

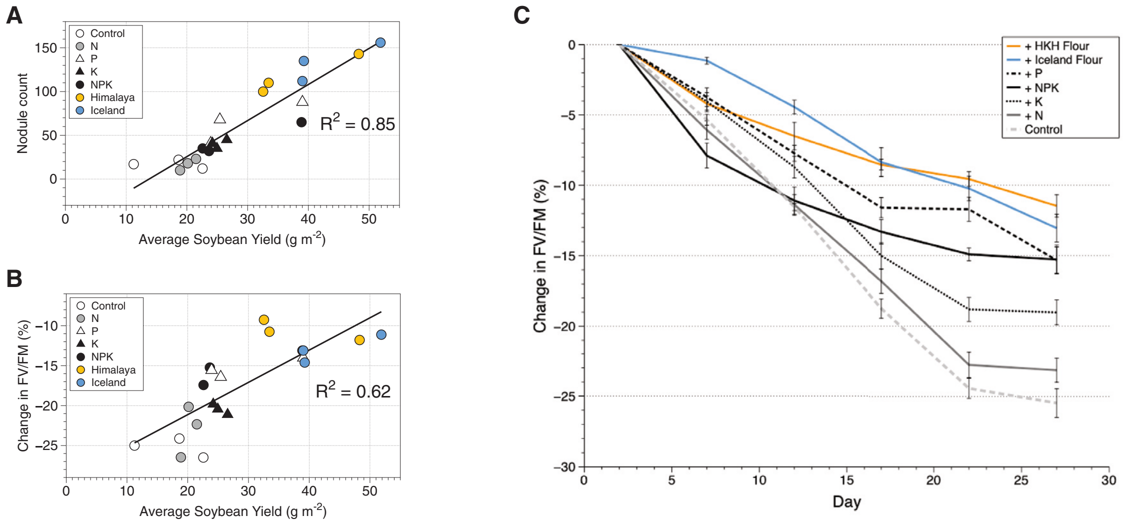


Figure 3. Nodule counts and Fv/Fm for soybean yield experiment

(A) Linear regression of soybean nodule count and average yield across all experiments, $R^2 = 0.85$.

(B) Linear regression of the percentage change in Fv/Fm compared to Day 0 and average soybean yield (g m^{-2}).

(C) Time series of Fv/Fm (%) over the first month of the experiment for all treatments (27 days).

and Icelandic flour (0.662 ± 0.004), were 16.2 ± 0.5% and 17.6 ± 0.8% lower than the start of the experiment, compared to 31.1 ± 1.5% lower Fv/Fm in the control treatment and chemical fertilizer treatments (Fv/Fm results, N treated = 23.4 ± 2.7%, P treated 20.5 ± 1.8%, K treated 24.6 ± 1.2%, and NPK treated 24.6 ± 1.9%, Table 1; Table S3). The glacial flour-treated soybeans also displayed the highest mean nodule counts, with average nodule counts of 105 ± 11 (Himalaya) and 150 ± 19 (Iceland) compared to the control (28 ± 18) and chemical fertilizers (N (31 ± 22), P (87 ± 25), PK (91 ± 23), NPK (52 ± 17)) (Figures 3A; Table 1).

The success of glacial flour in enhancing BNF capacity and supporting plant growth, compared to chemical fertilizers, is likely due to three factors. First, the low-N soil matrix and glacial flour treatments may have up-regulated nodule development, whereas chemical N treated pots likely had nodule development down-regulated, which is commonly observed in chemical N-fertilised cropland.[68] Second, it is likely that soybeans with lower nodule counts remobilized N from their leaves to the grain, diminishing their photosynthetic capacity as indicated by a steep reduction in Fv/Fm, and subsequently limiting crop yield.[69] For example, chemical N-treated pots were likely to have taken up the N rapidly into crop biomass at the start of the experiment, but further N supply later in the experiment was unavailable for growth. Third, prolific nodule growth and biological nitrogen fixation are dependent on the availability of P and micronutrients (Fe, S, Mo, and V), potentially supplied by glacial flour but not by chemical fertilizers,[70] which is a hypothesis explored in more detail later in discussion.

Glacial flour was a source of macro and micronutrients to crops

Our data suggest that glacial flours can act as a source of both plant macro and micronutrients in controlled growth experiments. Principal Component Analysis (PCA) was used to explore associations between the supply of essential plant nutrients (P, K, Fe, Mg, Ca, Si, Mn, Zn, Ni, and S) and the soybean crop yield. The first two components of our PCA accounted for >99% of the total variability in the total metal concentrations in the glacial flours: PC1 77.1%; and PC2 22.0% (Figure S1). Icelandic flour was heavily loaded onto PC1, likely due to the strong enrichment of Icelandic flour with the mafic rock-associated trace elements. This pattern was reversed for PC2, with Himalaya flour more heavily loaded on this component. Elemental loadings on PCs reinforce the likely importance of micronutrients in plant growth. PC1 had high loadings for Zn (0.99), Ni (0.97), Ca (0.95), P (0.93), S (0.92), Mn (0.92) and Mg (0.90) (all high in Icelandic flour), while PC2 had a higher loading for Si (0.97), likely reflecting the higher concentration of aqua regia digestible silicates in Himalayan flour (Total Si 1.02 ± 0.17 mg g^{-1}) (Table 2). Furthermore, although K and Fe had relatively high loadings in PC1 (0.81 and 0.89), they were the only nutrients with strong loadings in PC2 (0.58 and 0.45). We then combined the PCA with a subsequent stepwise regression analysis which showed that 77.1% of the variance in soybean crop yield can be explained by PC1 and 22.0% of the variance by PC2 (Total PC1 + PC2 = 99.9%, $p < 0.0001$, $r^2 = 0.91$), suggesting that glacial flour supplied both essential macro and micronutrients to support crop and plant health in our experiments. While prior research into crushed rock for agriculture has focused on the enhancement of P and K in crop growth experiments, our results suggest that glacial flour improves soil fertility by increasing both the soil macro- and micro-nutrient content.

Glacial flour as a source of beneficial and toxic trace elements

Enhancing the nutritional value of soybeans by boosting micronutrient concentrations (“biofortification”[71]) may have significant

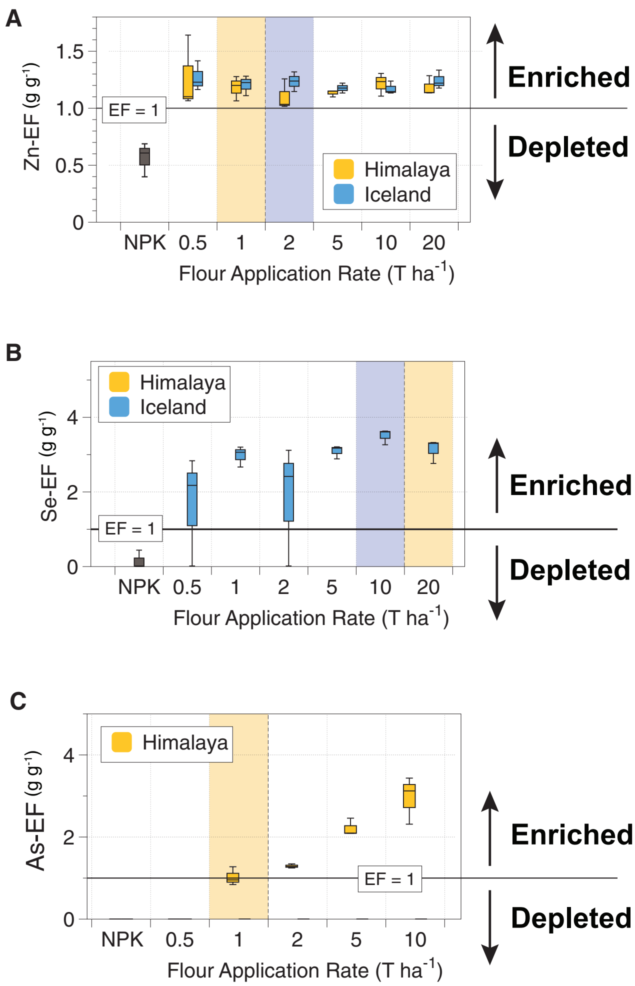


Figure 4. Enrichment factors of trace elements (Zn, Se, and As) within the soybeans from the glacial flour crop yield investigation

(A) Zn (Zn-EF); (B) Se (Se-EF); and (C) As (As-EF) for glacial flour (0.5–20 T ha^{-1}) and NPK amended experiments. The shaded regions indicate the dose with the highest EF, yellow for Himalayas and purple for Iceland. An EF of 1 is plotted, where points above and below the line are enriched and depleted respectively in the element in question. Data points for Se-EF in Himalayan glacial flour treatments are plotted as single points since undetectable levels were recorded in some pot replicates. As-EF reports only Himalayan data since As in both NPK and Icelandic treatments were below detection.

benefits in addressing micronutrient malnutrition (e.g., Zn),[72] which has particular relevance for rural communities in low and middle-income countries.[73] Conversely, some trace elements may be detrimental to human health when present at high concentrations, with previous research expressing concern related to the potential mobilization of toxic metals (e.g., Cr, Ni, As, and Pb) from crushed rock within the soil matrix.[12] Here, we focus on two beneficial trace elements, zinc (Zn)[74] and selenium (Se),[75] sourced from rock weathering within the soil. We also evaluated concentrations of chromium (Cr), nickel (Ni), lead (Pb), and arsenic (As) in the soybean crop since these have been shown to cause adverse human health impacts in Asia.[76] Potential bioaccumulation of trace elements in our soybean experiments was calculated using enrichment factors (EF), where the concentration of an element in a soy bean (e.g., Zn mg g^{-1}) amended with glacial flour or chemical ferilizer was divided by the concentration in the control experiment (mg g^{-1}) (Equation 3).[77]

Both glacial flours showed the potential to drive the bioaccumulation of beneficial trace elements in soybean crops. The beneficial trace elements Zn and Se had an EF above the chemical fertilizer NPK treatment (Figures 4A and 4B; Table 4, $p < 0.05$). NPK treated soybeans displayed a lower concentration of all trace elements compared to the control and glacial flour treatments. Low EFs may reflect a limited trace element load in the artificial soil matrix. The crop yield of the NPK treatment may also have resulted in a proportional decrease in the concentration of trace elements in the crop. Soybeans had mild Zn enrichment (EF < 1.5) in all glacial flour treatments, which was independent of both the glacial flour application rate, and the total Zn concentration in the flour (Icelandic flour 232 ± 2.2 $\mu g\ g^{-1}$, Himalayan flour 114 ± 3.1 $\mu g\ g^{-1}$) (Figure 4A Table 4). There was significant enrichment of Se in Icelandic flour treated beans with high levels of enrichment (EF > 2) across all doses and was dose dependent. However, no significant enrichment in Se was observed for Himalayan flour treated beans (Figure 4B), which may be due to the lower Se concentrations in Himalayan flour compared to Icelandic flour (3.5 ± 0.5 $\mu g\ g^{-1}$ compared to 6.0 ± 0.2 $\mu g\ g^{-1}$) and slower mineral dissolution rates.

World Health Organization recommended daily allowances (RDA) for Zn are between 6.5 and 9.4 mg day^{-1}, and dietary Se is classed as deficient at < 40 $\mu g\ day^{-1}$ and toxic at > 400 $\mu g\ day^{-1}$.[78] The total theoretical dietary supply (i.e., not the human digestive bioavailable fraction), of Zn and Se for a portion of raw soybeans (35 g) grown in our experiments was calculated using the total element concentration of the soybeans. A portion of soybeans grown in Himalayan flour applied at a low dose of 1 T ha^{-1} (yellow shaded area, Figure 4A) could provide 33.0 ± 2.4% of the recommended Zn daily dietary intake (3.19 ± 0.37 mg of total Zn) but no significant Se intake. However, Icelandic flour applied at the same dose (1 T ha^{-1}) would supply 35.4 ± 2.9% of daily dietary Zn and 952 ± 72.7% of the recommended intake of Se. Consumption of the beans grown in 1 T ha^{-1} Icelandic flour would result in an intake of 1940 ± 450 μg of Se, which is above the daily recommended intake limit of 400 μg.[79] The beans could be regarded but it should be noted there is considerable uncertainty surrounding recommended dietary Se consumption. Moderately high Se diets (>100 μg) have been shown to be anticarcinogenic, highlighting additional work is needed to establish safe dietary Se intake.[75] It is also important to ascertain whether these Se enrichment levels are achieved under real-world conditions. Nevertheless, low doses of glacial flour appear to biofortify crops with beneficial elements.

All glacial flour treated soybeans had undetectable levels of toxic heavy metals Cr, Ni, and Pb (Limit of detection (LODs): Cr 2.75 $\mu g\ g^{-1}$, Ni 6.28 $\mu g\ g^{-1}$, Pb 2.79 $\mu g\ g^{-1}$). Icelandic flour treated soybeans had undetectable As levels (LOD <0.8 $\mu g\ g^{-1}$). However, there was a significant As enrichment (EF = 4.10 ± 0.36 at 20 T ha^{-1}) in Himalayan flour-treated beans with clear dose dependency for application rates above 0.5 T ha^{-1} (Figures 4C; Table 4, $p < 0.05$). High As enrichment in the Himalayan flour treated soybeans is consistent with the

Table 4. Soybean concentrations of chosen metals, uptake, and enrichment factors (EF)

	Zinc			Selenium			Arsenic			
Treatment	Zn Conc (μg g^{-1})	Zn Uptake (μg)	Zn-EF (g g^{-1})	Se Conc (μg g^{-1})	Se Uptake (μg)	Se-EF (g g^{-1})	As Conc (μg g^{-1})	As Uptake (μg)	As-EF (g g^{-1})	n
Control	73.2 ± 5.2	23.8 ± 5.8	N/A	42.1 ± 8.5	13.1 ± 2.3	N/A	< LOD	N/A	N/A	3
NPK	41.2 ± 8.9	42.4 ± 15.9	0.56 ± 0.12	51.4 ± 26.7	33.5 ± 7.2	0.22 ± 0.21	< LOD	N/A	N/A	3
Himalaya (T ha^{-1})										
0.5	95.6 ± 7.7	59.5 ± 6.9	1.31 ± 0.11	< LOD	N/A	N/A	< LOD	N/A	N/A	3
1.0	105 ± 12.0	88.0 ± 12.6	1.43 ± 0.17	< LOD	N/A	N/A	(1.02)	(0.73)	(1.28)	3
2.0	92.7 ± 19.2	92.4 ± 20.4	1.27 ± 0.26	(110)	(107)	(2.63)	(1.03)	(1.02)	(1.28)	3
5.0	86.2 ± 6.4	112 ± 9.1	1.18 ± 0.09	(115)	(144)	(2.74)	1.77 ± 0.14	2.29 ± 0.22	2.21 ± 0.17	3
10.0	80.5 ± 8.0	124 ± 8.7	1.10 ± 0.11	(79.0)	(132)	(1.88)	2.37 ± 0.38	3.67 ± 0.61	2.96 ± 0.47	3
20.0	82.7 ± 1.8	135 ± 15.0	1.13 ± 0.02	(96.5–208)	(137–350)	(2.29–4.94)	3.28 ± 0.29	5.34 ± 0.56	4.10 ± 0.36	3
Iceland (T ha^{-1})										
0.5	88.7 ± 6.0	66.4 ± 10.7	1.21 ± 0.08	105 ± 13.9	49.5 ± 6.3	2.51 ± 0.33	< LOD	N/A	N/A	3
1.0	86.6 ± 5.1	78.0 ± 8.4	1.18 ± 0.07	125 ± 9.5	113 ± 12.2	2.97 ± 0.32	< LOD	N/A	N/A	3
2.0	92.7 ± 7.8	101 ± 20.1	1.27 ± 0.11	116 ± 14.7	77.3 ± 5.6	2.77 ± 0.35	< LOD	N/A	N/A	3
5.0	87.9 ± 5.2	113 ± 5.2	1.21 ± 0.07	130 ± 6.1	167 ± 10.5	3.09 ± 0.14	< LOD	N/A	N/A	3
10.0	90.1 ± 5.1	146 ± 11.6	1.23 ± 0.07	147 ± 7.0	237 ± 15.2	3.50 ± 0.17	< LOD	N/A	N/A	3
20.0	85.9 ± 2.6	168 ± 3.1	1.18 ± 0.04	133 ± 10.9	257 ± 20.0	3.13 ± 0.26	< LOD	N/A	N/A	3

Conc, concentration; EF, enrichment factor; NPK, Nitrogen + Phosphorous + Potassium chemical fertiliser; LOD, limit of detection.
Values from this study are presented in three significant figures. Values in brackets are single replicate results only. Where the control treatment was below the LOD for Total As, the method detection limit was used, shown in italics, for enrichment factor calculations only.

identification of As containing sulfide minerals in the glacial flour identified by SEM/EDS. Additional LA-ICP-MS spot analysis on representative sulfide phases isolated from the flour indicated that the As in Himalayan flour treated beans was sourced from sulfide minerals such as arsenopyrite, pyrite and pyrrhotite (Table 5). The presence of As rich sulfide minerals indicates that these are the likely source of As from the Himalayan glacial flour to the soybean crops.

Toxic levels of As in humans that can cause chronic health impacts (arsenicism) are believed to occur at doses of >100 μg day^{-1}.[80] This value is likely to be a conservative estimate because it is calculated from drinking water concentrations whereas is likely to be highly bioavailable.[81] Soybeans grown in Himalayan flour at a dose required to achieve Zn biofortification (0.5 T ha^{-1}) did not have a measurable total As concentration. However, a portion (35 g dry weight) of soybeans grown in Himalayan flour at a high dose rate (5 T ha^{-1}) would result in an As intake of 44.2 ± 1.8 μg. Although this falls below the daily limit for arsenicism, the cumulative impact of consuming all an individual's dietary needs from crops enriched in As is likely to exceed toxic limits. Although total As levels alone do not indicate high toxicity to humans, As speciation (e.g., organo-As species, As^{3+} and As^{5+}) plays a critical role in potential toxicity, for example, organic arsenicals are much less toxic than inorganic As^{3+} and As^{5+}, and should be investigated in the farm to fork cycle.[82]

The enrichment of As in glacier flour-amended soybeans also highlights the potential of Himalayan glacial flour as an of As contamination to rural communities, either via the cultivation of formerly glaciated soils or the use of glacial flour from such geological provinces in crop fertilization.[80] For smallholder subsistence farmers with a diet mostly sourced from crops, this low level of arsenicism may be of concern. These findings indicate a need to better understand the potential toxicity of soils within deglaciated landscapes and on glacial sediment floodplains. This is of particular importance in regions where glaciers have overly metamorphic/sedimentary bedrocks, for example in the Punjab floodplain and the high Himalayas.[83] Improving the temporal and spatial understanding of glacial flour micronutrient and trace element supply is critical to inform future work.

Table 5. LA-ICP-MS analysis of Fe and As concentrations (mean, (range)) (ppm) measured in sulfides isolated from Himalayan glacial flour

	Element Concentration (ppm)			
Mineral	Fe	S	As	n
Pyrite	500,000 (500,000)	256,000 (195,00–320,000)	1280 (700–1900)	2
Pyrrhotite	660,000 (600,000–700,000)	370,000 (6,500–450,000)	1850 (18–3500)	8
Arsenopyrite	352,000 (350,000–370,000)	276,000 (18,000–350,000)	510,000 (180,000–670,000)	8

Number of samples (n) is shown.

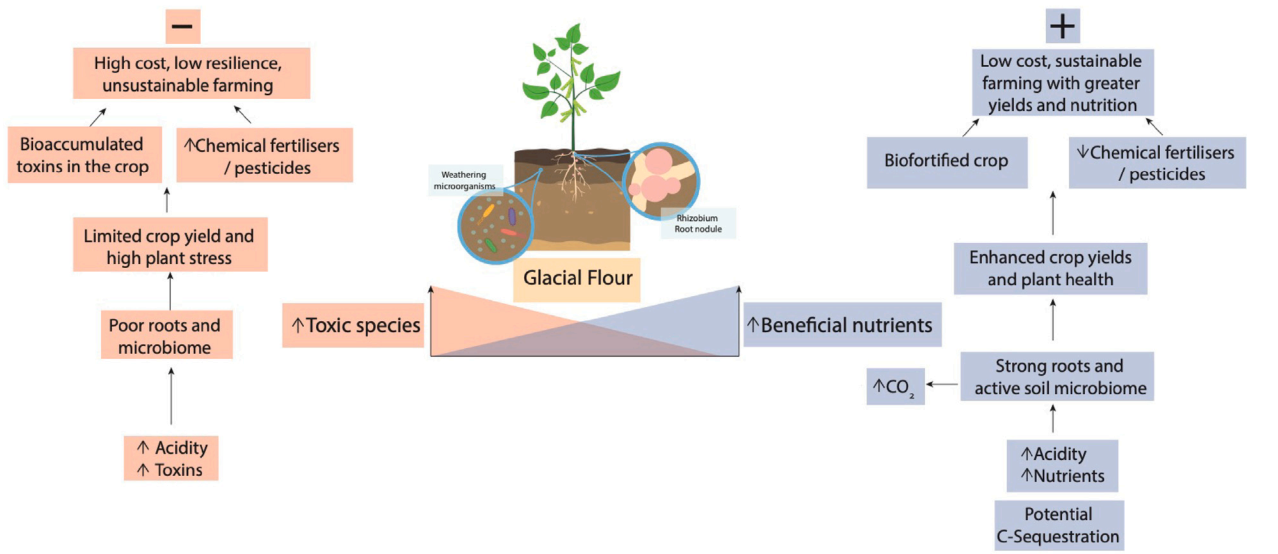


Figure 5. Conceptual diagram of glacial flour as a soil amendment or potential source of toxic elements

As glacial flour weathers two extreme end member scenarios are possible – (i) either glacial flour releases nutrients into the soil which stimulates a cascade of positive impacts upon the soil health and then crop growth and yield, and/or (ii) glacial flour releases toxic elements that negatively impact soil, crop yields, and human health. In practice, a combination of i and ii is possible, as evidenced in our experiments. Hypothetically, the enhanced crop health and yield results in a reduction of intensive farming strategies, shifting toward more sustainable agricultural methods. However, glacial flours that are high in toxic elements may result in farmers looking to amend soils with conventional practices. Greater use of chemical fertilizers and enhanced the bioaccumulation of potentially toxic elements (e.g., As, Se), results in high cost – low resilience unsustainable farming.

Limitations of the study

Limitations of our study include that our investigation only investigates a single plant growth study, in controlled conditions in a greenhouse. Future work should seek to perform field trials within natural agricultural soils to understand the effects of glacial flour within soils.

The future of glacial flour and agriculture

The agricultural application of glacial flour has primarily focused on Greenlandic igneous felsic rocks.[19–21,55,56] However, the impacts of glacial flour from diverse bedrock sources, such as those from the Himalayas (metamorphic/sedimentary) and Iceland (basalts) remain largely unknown. Our research indicates that both Himalayan and Icelandic glacial flour has the potential to increase crop yields (by 85% and 135% respectively at a minimum 2 T ha^{-1} application rate) and enhance plant health acting as a source of nutrients. Our results also indicate glacial flour can act as a source of trace elements, in some cases enhancing nutritional value (e.g., Zn) and in others increasing toxicity (e.g., As). We also found that beneficial micronutrient enrichment in the crop occurred at low glacial flour application rates, <2 T ha^{-1}, suggesting a potential use within small-scale organic farming networks to improve nutritional quality in a sustainable way. This is supported by current research investigating Greenlandic glacial flour within organic agriculture.[19] These findings provide foundational insights for further investigation of glacial flour effectiveness in agriculture across a broader range of lithologies and geographical regions (Figure 5).

However, alongside these benefits, caution is warranted due to the presence of toxic trace elements within glacial flour, notably As, sourced from sulfide minerals. Himalayan flour treated beans were significantly enriched in As, and at high application rates (>5 T ha^{-1}) consumption of the crop would have been above recommended safe As limits.[84] This study highlights the pivotal role of Himalayan glaciers and the delicate relationship between geology and human health. These glaciers are the source of many major Asian rivers that irrigate crop lands that feed up to 38 million people.[85] Himalayan glacier-derived sediment deposited across low-lying pan-Asian flood plains has been inferred as the source of As in groundwater wells, responsible for "the largest poisoning of a population in history,"[86] over 100 million people.[87,88] As climate change continues to transform glaciated regions, glacial flour exports are expected to increase with unknown downstream impacts.[41] To mitigate potential adverse effects on crops and ecosystem health glacial flour requires further study.

Our proof-of-concept findings underscore the dual nature of glacial flour as both a potential soil amendment strategy with beneficial human health impacts within mountain agriculture, but also as a potential source of concern for flours sourced from sulfide-rich deglaciated terrains due to high toxic element concentrations. Our experiments underscore the importance of further research aimed at unraveling the complexities of glacial flour behavior within agriculture. Future research should include analysis of a wider range of lithologically contrasting flours, scrutiny of the biogeochemical mechanisms controlling nutrient release from mineral matrices, trials over single and multiple cropping cycles, and a consideration of both crop yield and trace element bioaccumulation impacts. By leveraging the beneficial aspects of glacial flour application and mitigating potential risks, there is potential in harnessing glacial flour to sustainably bolster food security in the face of climate change.

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Sarah Tingey (sarah.l.tingey@uit.no).

Materials availability

This study did not generate new unique materials.

Data and code availability

- Data: All data reported in this publication will be shared by the lead contact upon request.
- Code: This article does not report any original code.
- Additional resources: Any additional information required to reanalyze the data reported in this article is available from the lead contact upon request.

ACKNOWLEDGMENTS

This research was funded by the Cabot Institute Innovation Fund (University of Bristol), GCRF Pump Priming and Investment grants and UKIERI grant DST-UKIERI-2016-17-0104 to JLW. We acknowledge the Royal Society Wolfson Merit Award (WRM\R1\180015) to JLW and UKRI-BBSRC (Institute Strategic Programmes GEN BB/P013511/1 and BRiC BB/X01102X/1) for support to AND. AH acknowledges support through a Leverhulme Trust Emeritus Fellowship. ST was directly supported by a Leverhulme Trade Trust grant for her PhD. This research was a part of the Center for Arctic Gas Hydrate, Environment, and Climate (CAGE) and the Center for ice Cryosphere, Carbon and Climate (iC3) and was supported by the Research Council of Norway through its Centre of Excellence funding scheme (grants 223259 and 332635 respectively). We would like to thank the GroDome facility, School of Life Sciences, University of Bristol for their support during the crop growth trials. We would also like to thank all the field work support from JNU and their team.

AUTHOR CONTRIBUTIONS

ST, JLW, JRH, and JT conceived the project. ST performed experimentation with support from AH and AND. Lab analysis was performed by ST and SF, with support from JRH, CY, and FS. Mineralogical work was conducted by YM, SSP and. XL ST wrote the article with JLW. Fieldwork was undertaken by ST, GLG in Iceland, and ST, GLG, RB, and ALR in the Himalayas. All authors were participants in reviewing the final article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
  - Glacial flour sites and sampling
- METHOD DETAILS
  - Soil and sediment analytical methods
  - Trace element analysis by LA-SC-ICPMS
  - Nitrogen concentration determination
  - Metal extractions and determination (P, K, Fe, Ca, mg, Mn, S, se, Zn) for sediments and beans
  - Crop yield experiments
  - Growth conditions
  - Soil matrix characteristics
  - Chlorophyll fluorescence imaging
  - Glacial flour application rates to soil
  - Agricultural calculations
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Statistical analysis
  - Principal component regression (PCR)
  - Imaging

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.111476.

Received: June 28, 2024
Revised: October 14, 2024
Accepted: November 22, 2024
Published: November 26, 2024

REFERENCES

1. United Nations, D.o.E.a.S.A. (2017). World Population Prospects: The 2017 Revised, Key Findings and Advanced Tables (United Nations).
2. DeLonge, M.S., Miles, A., and Carlisle, L. (2016). Investing in the transition to sustainable agriculture. Environ. Sci. Pol. *55*, 266–273.
3. Altieri, M., Nicholls, C., and Montalba, R. (2017). Technological approaches to sustainable agriculture at a crossroads: an agroecological perspective. Sustainability *9*, 349.
4. Prosekov, A.Y., and Ivanova, S.A. (2018). Food security: The challenge of the present. Geoforum *91*, 73–77. https://doi.org/10.1016/j.geoforum.2018.02.030.
5. Hensel, J. (1894). Bread from Stones.
6. Liu, R., and Lal, R. (2014). Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max). Sci. Rep. *4*, 5686. https://doi.org/10.1038/srep05686.
7. Coroneos, C., Hinsinger, P., and Gilkes, R.J. (1995). Granite powder as a source of potassium for plants: a glasshouse bioassay comparing two pasture species. Fert. Res. *45*, 143–152.
8. Shivay, Y.S., Krogstad, T., and Singh, B.R. (2009). Mineralization of copper, manganese and zinc from rock mineral flour and city waste compost for efficient use in organic farming. Plant Soil *326*, 425–435. https://doi.org/10.1007/s11104-009-0023-0.
9. Kelland, M.E., Wade, P.W., Lewis, A.L., Taylor, L.L., Sarkar, B., Andrews, M.G., Lomas, M.R., Cotton, T.E.A., Kemp, S.J., James, R.H., et al. (2020). Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. Global Change Biol. *26*, 3658–3676. https://doi.org/10.1111/gcb.15089.
10. Drever, J.I. (1994). The effect of land plants on weathering rates of silicate minerals. Geochem. Cosmochim. Acta *58*, 2325–2332.
11. Gillman, G.P. (1980). The effect of crushed basalt scoria on the cation exchange properties of a highly weathered soil. Soil Sci. Soc. Am. J. *44*, 465–468.
12. 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., et al. (2018). Farming with crops and rocks to address global climate, food and soil security. Nat. Plants *4*, 138–147. https://doi.org/10.1038/s41477-018-0108-y.
13. Priyono, J., and Gilkes, R.J. (2008). High-energy milling improves the effectiveness of silicate rock fertilizers: A glasshouse assessment. Commun. Soil Sci. Plant Anal. *39*, 358–369. https://doi.org/10.1080/00103620701826498.
14. Mohammed, S.M.O., Brandt, K., Gray, N.D., White, M.L., and Manning, D.A.C. (2014). Comparison of silicate minerals as sources of potassium for plant nutrition in sandy soil. Eur. J. Soil Sci. *65*, 653–662. https://doi.org/10.1111/ejss.12172.

15. Bakken, A.K., Gautneb, H., Sveistrup, T., and Myhr, K. (2000). Crushed rocks and mine tailings applied as K fertilisers on grassland. Nutrient Cycl. Agroecosyst. *56*, 53–57.
16. Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Sarkar, B., Andrews, M.G., James, R.H., Pearce, C.R., et al. (2020). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. Nature *583*, 242–248. https://doi.org/10.1038/s41586-020-2448-9.
17. Edwards, D.P., Lim, F., James, R.H., Pearce, C.R., Scholes, J., Freckleton, R.P., and Beerling, D.J. (2017). Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. Biol. Lett. *13*, 20160715. https://doi.org/10.1098/rsbl.2016.0715.
18. Brown, G.H., Tranter, M., and Sharp, M.J. (1996). Experimental investigations of the weathering of suspended sediment by alpine glacial meltwater. Hydrol. Process. *10*, 579–597.
19. Gunnarsen, K.C., Jensen, L.S., Rosing, M.T., and Dietzen, C. (2023). Greenlandic glacial rock flour improves crop yield in organic agricultural production. Nutrient Cycl. Agroecosyst. *126*, 51–66. https://doi.org/10.1007/s10705-023-10274-0.
20. Gunnarsen, K.C., Jensen, L.S., Gómez-Muñoz, B., Rosing, M.T., and de Neergaard, A. (2019). Glacially abraded rock flour from Greenland: Potential for macronutrient supply to plants. J. Plant Nutr. Soil Sci. *182*, 846–856.
21. Weber, P.L., Hermansen, C., Pesch, C., Moldrup, P., Greve, M.H., Blaesbjerg, N.H., Romero, G.M., Arthur, E., and de Jonge, L.W. (2023). Glacial rock flour reduces the hydrophobicity of Greenlandic cultivated soils. Soil Sci. Soc. Am. J. *87*, 439–452.
22. Hinsinger, P., Fernandes Barros, O.N., Benedetti, M.F., Noack, Y., and Callot, G. (2001). Plant-induced weathering of a basaltic rock: experimental evidence. Geochem. Cosmochim. Acta *65*, 137–152.
23. Renforth, P. (2012). The potential of enhanced weathering in the UK. Int. J. Greenh. Gas Control *10*, 229–243.
24. Bousquet, R., Oberhänsli, R., Goffé, B., Wiederkehr, M., Koller, F., Schmid, S.M., Schuster, R., Engi, M., Berger, A., and Martinotti, G. (2008). Metamorphism of Metasediments at the Scale of an Orogen: A Key to the Tertiary Geodynamic Evolution of the Alps (London: The Geological Society of London).
25. Tranter, M., Sharp, M.J., Lamb, H.R., Brown, G.H., Hubbard, B.P., and Willis, I.C. (2002). Geochemical weathering at the bed of Haut Glacier d'Arolla, Switzerland—a new model. Hydrol. Process. *16*, 959–993.
26. Chira, J., Vargas, L., and Castañeda, D. (2022). Surface water quality and geogenic process in the quillcayhuanca and shallap streams, Huaraz-Peru. Int. J. Hydro. *6*, 119–125.
27. Egenhoff, S., and Lucassen, F. (2003). Chemical and isotopic composition of Lower to Upper Ordovician sedimentary rocks (Central Andes/South Bolivia): implications for their source. J. Geol. *111*, 487–497.
28. Dahlstrom, C.D. (1970). Structural geology in the eastern margin of the Canadian Rocky Mountains. Bull. Can. Petrol. Geol. *18*, 332–406.
29. Vasey, D.A., Cowgill, E., Roeske, S.M., Niemi, N.A., Godoladze, T., Skhirtladze, I., and Gogoladze, S. (2020). Evolution of the Greater Caucasus Basement and Formation of the Main Caucasus Thrust, Georgia. Tectonics *39*, e2019TC005828. https://doi.org/10.1029/2019TC005828.
30. Najman, Y. (2006). The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins. Earth Sci. Rev. *74*, 1–72.
31. Ahmad, S., Ansari, Z., and Mulhim, M. (2022). Sedimentological and mineralogical characteristics of active glacial sediments in the Indian Himalaya regions. Geol. Ecol. Landsc. *6*, 265–276.
32. Searle, M.P., Khan, M.A., Fraser, J.E., Gough, S.J., and Jan, M.Q. (1999). The tectonic evolution of the Kohistan-Karakoram collision belt along the Karakoram Highway transect, north Pakistan. Tectonics *18*, 929–949.
33. Bauer, F., Glasmacher, U., Malikwisha, M., Mambo, V., and Mutete, B. (2010). The Eastern Congo—a beauty spot, rediscovered from a geological point of view. Geol. Today *26*, 55–64.
34. Hjelle, A. (1993). Geology of Svalbard.
35. Manning, D.A. (2010). Mineral sources of potassium for plant nutrition. Agron. Sustain. Dev. *30*, 281–294. https://doi.org/10.1051/agro/2009023.
36. Yin, A., and Harrison, T.M. (2000). Geologic Evolution of the Himalayan-Tibetan Orogen. Annu. Rev. Earth Planet Sci. *28*, 211–280. https://doi.org/10.1146/annurev.earth.28.1.211.
37. Gaetani, M., Jadoul, F., Erba, E., and Garzanti, E. (1993). Jurassic and Cretaceous Orogenic Events in the North Karakoram: Age Constraints from Sedimentary Rocks. Geol. Soc. Spec. Publ. *74*, 39–52.
38. Houlton, B.Z., Morford, S.L., and Dahlgren, R.A. (2018). Convergent evidence for widespread rock nitrogen sources in Earth's surface environment. Science *360*, 58–62.
39. Bolch, T., Shea, J.M., Liu, S., Azam, F.M., Gao, Y., Gruber, S., Immerzeel, W.W., Kulkarni, A., Li, H., and Tahir, A.A. (2019). Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People, pp. 209–255.
40. Singh, V.B., Ramanathan, A.L., and Pottakkal, J.G. (2016). Glacial runoff and transport of suspended sediment from the Chhota Shigri glacier, Western Himalaya, India. Environ. Earth Sci. *75*, 695. https://doi.org/10.1007/s12665-016-5271-8.
41. Immerzeel, W.W., van Beek, L.P.H., and Bierkens, M.F.P. (2010). Climate Change Will Affect the Asian Water Towers. Science *328*, 1382–1385. https://doi.org/10.1126/science.1183188.
42. Zhang, T., Li, D., East, A.E., Kettner, A.J., Best, J., Ni, J., and Lu, X. (2023). Shifted sediment-transport regimes by climate change and amplified hydrological variability in cryosphere-fed rivers. Sci. Adv. *9*, eadi5019. https://doi.org/10.1126/sciadv.adi5019.
43. Heckmann, T., McColl, S., and Morche, D. (2016). Retreating ice: Research in pro-glacial areas matters. Earth Surf. Process. Landforms *41*, 271–276.
44. Hawkings, J.R., Wadham, J.L., Tranter, M., Lawson, E., Sole, A., Cowton, T., Tedstone, A.J., Bartholomew, I., Nienow, P., Chandler, D., and Telling, J. (2015). The effect of warming climate on nutrient and solute export from the Greenland Ice Sheet. Geochem. Perspect. Lett. *1*, 94–104. https://doi.org/10.7185/geochemlet.1510.
45. Wadham, J.L., Hawkings, J., Telling, J., Chandler, D., Alcock, J., Lawson, E., Kaur, P., Bagshaw, E.A., Tranter, M., Tedstone, A., and Nienow, P. (2016). Sources, cycling and export of nitrogen on the Greenland Ice Sheet. Biogeosci. Discuss. *13*, 6339–6352. https://doi.org/10.5194/bg-2015-484.
46. Lawson, E.C., Wadham, J.L., Tranter, M., Stibal, M., Lis, G.P., Butler, C.E.H., Laybourn-Parry, J., Nienow, P., Chandler, D., and Dewsbury, P. (2014). Greenland Ice Sheet exports labile organic carbon to the Arctic oceans. Biogeosciences *11*, 4015–4028.
47. Hawkings, J.R., Wadham, J.L., Tranter, M., Raiswell, R., Benning, L.G., Statham, P.J., Tedstone, A., Nienow, P., Lee, K., and Telling, J. (2014). Ice sheets as a significant source of highly reactive nanoparticulate iron to the oceans. Nat. Commun. *5*, 3929. https://doi.org/10.1038/ncomms4929.
48. Hawkings, J.R., Skidmore, M.L., Wadham, J.L., Priscu, J.C., Morton, P.L., Hatton, J.E., Gardner, C.B., Kohler, T.J., Stibal, M., Bagshaw, E.A., et al. (2020). Enhanced trace element mobilization by Earth's ice sheets. Proc. Natl. Acad. Sci. USA *117*, 31648–31659. https://doi.org/10.1073/pnas.2014378117.
49. Saltzman, A., Birol, E., Bouis, H.E., Boy, E., De Moura, F.F., Islam, Y., and Pfeiffer, W.H. (2013). Biofortification: progress toward a more nourishing future. Global Food Secur. *2*, 9–17.
50. Galán, E., Fernández-Caliani, J.C., González, I., Aparicio, P., and Romero, A. (2008). Influence of geological setting on geochemical baselines

of trace elements in soils. Application to soils of South–West Spain. J. Geochem. Explor. 98, 89–106. https://doi.org/10.1016/j.gexplo.2008.01.001.

51. Holloway, J.M., and Dahlgren, R.A. (2002). Nitrogen in rock: occurrences and biogeochemical implications. Global Biogeochem. Cycles 16, 65–71.
52. Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., and Eriksson, M. (2019). Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: a review. Reg. Environ. Change 19, 1311–1326. https://doi.org/10.1007/s10113-019-01484-w.
53. Rasul, G., Saboor, A., Tiwari, P.C., Hussain, A., Ghosh, N., and Chettri, G.B. (2019). Food and Nutrition Security in the Hindu Kush Himalaya: Unique Challenges and Niche Opportunities. In The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People, P. Wester, A. Mishra, A. Mukherji, and A.B. Shrestha, eds. (Springer International Publishing), pp. 301–338. https://doi.org/10.1007/978-3-319-92288-1_9.
54. Wester, P., Mishra, A., Mukherji, A., and Shrestha, A.B. (2019). The Hindu Kush Himalaya Assessment (Basel, Switzerland: Cham: Springer International Publishing).
55. Dietzen, C., and Rosing, M.T. (2023). Quantification of CO2 uptake by enhanced weathering of silicate minerals applied to acidic soils. Int. J. Greenh. Gas Control 125, 103872. https://doi.org/10.1016/j.ijggc.2023.103872.
56. Sukstorf, F.N., Bennike, O., and Elberling, B. (2020). Glacial Rock Flour as Soil Amendment in Subarctic Farming in South Greenland. Land 9, 198. https://doi.org/10.3390/land9060198.
57. Sigmarsson, O., and Steinthórsson, S. (2007). Origin of Icelandic basalts: A review of their petrology and geochemistry. J. Geodyn. 43, 87–100.
58. Kumar, S., and Dobhal, D. (1997). Climatic effects and bedrock control on rapid fluctuations of Chhota Shigri glacier, northwest Himalaya, India. J. Glaciol. 43, 467–472.
59. Maibam, B., Singh, Y.R., Shukla, A., and Ramanathan, A. (2016). Geochemical Study of The Granitoids Around Chhota Shigri Area, Himachal Pradesh, India. J. Appl. Geochem. 18, 408–413.
60. Chatterjee, S., Dutta, A., Gupta, R.K., and Sinha, U. (2022). Genesis, evolution, speciation and fluid-mineral equilibrium study of an unexplored geothermal area in Northeast Himalaya, India. Geothermics 105, 102483.
61. Robson, T.C., Braungardt, C.B., Keith-Roach, M.J., Rieuwerts, J.S., and Worsfold, P.J. (2013). Impact of arsenopyrite contamination on agricultural soils and crops. J. Geochem. Explor. 125, 102–109.
62. Goldich, S.S. (1938). A Study in Rock-Weathering. J. Geol. 46, 17–58. https://doi.org/10.1086/624619.
63. Tessier, A., Campbell, P.G.C., and Bisson, M. (1979). Sequential extraction procedure for the speciation of particulate trace metals. Anal. Chem. 51, 844–851.
64. Roy, R.N., Finck, A., Blair, G.J., and Tandon, H.L.S. (2006). In Plant nutrition for food security: A guide for integrated nutrient management, U.N. Food and A. Organization, eds. (FAO Publishing).
65. Fixen, P., Brentrup, F., Bruulsema, T., Garcia, F., Norton, R., and Zingore, S. (2015). Nutrient/fertilizer use efficiency: measurement, current situation and trends. In Managing water and fertilizer for sustainable agricultural intensification, 270, pp. 2–7.
66. Sager, M., Park, J.H., and Chon, H.T. (2007). The Effect of Soil Bacteria and Perlite on Plant Growth and Soil Properties in Metal Contaminated Samples. Water Air Soil Pollut. 179, 265–281. https://doi.org/10.1007/s11270-006-9230-y.
67. Maxwell, K., and Johnson, G.N. (2000). Chlorophyll fluorescence–a practical guide. J. Exp. Bot. 51, 659–668. https://doi.org/10.1093/jxb/51.345.659.
68. Ferguson, B.J., Indrasumunar, A., Hayashi, S., Lin, M.H., Lin, Y.H., Reid, D.E., and Gresshoff, P.M. (2010). Molecular analysis of legume nodule development and autoregulation. J. Integr. Plant Biol. 52, 61–76. https://doi.org/10.1111/j.1744-7909.2010.00899.x.
69. Mengel, K. (1994). Symbiotic dinitrogen fixation-its dependence on plant nutrition and its ecophysiological impact. J. Plant. Nutrition. Soil. 157, 233–241.
70. Smith, V.H. (1992). Effects of nitrogen: phosphorus supply ratios on nitrogen fixation in agricultural and pastoral ecosystems. Biogeochemistry 18, 19–35.
71. White, P.J., and Broadley, M.R. (2009). Biofortification of crops with seven mineral elements often lacking in human diets–iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytol. 182, 49–84.
72. Cakmak, I. (2008). Enrichment of cereal grains with zinc: agronomic or genetic biofortification? Plant Soil 302, 1–17.
73. Asia, F. (2018). The Pacific Regional Overview of Food Security and Nutrition 2018–Accelerating progress towards the SDGs. Bangkok: License: CC BY-NC-SA 3.
74. Roohani, N., Hurrell, R., Kelishadi, R., and Schulin, R. (2013). Zinc and its importance for human health: An integrative review. J. Res. Med. Sci. 18, 144–157.
75. Li, D., Graef, G.L., Yee, J.A., and Yan, L. (2004). Dietary Supplementation with High-Selenium Soy Protein Reduces Pulmonary Metastasis of Melanoma Cells in Mice. J. Nutr. 134, 1536–1540. https://doi.org/10.1093/jn/134.6.1536.
76. Kaur, S., Mehra, R., and Kumar, M.R. (2022). Quantification of health risks and spatial distribution of heavy metals in groundwater of Lower Himalayas, India. Int. J. Environ. Sci. Technol. 19, 3201–3218. https://doi.org/10.1007/s13762-021-03258-6.
77. Kisku, G.C., Barman, S.C., and Bhargava, S.K. (2000). Contamination of Soil and Plants with Potentially Toxic Elements Irrigated with Mixed Industrial Effluent and its Impact on the Environment. Water Air Soil Pollut. 120, 121–137. https://doi.org/10.1023/A:1005202304584.
78. Organization, W.H. (2004). Vitamin and Mineral Requirements in Human Nutrition (World Health Organization).
79. Organization, F.W.H. (2011). Evaluation of Certain Food Additives and Contaminants: Seventy-Third [73rd] Report of the Joint FAO/WHO Expert Committee on Food Additives (World Health Organization), pp. 9241209607.
80. van Geen, A., Farooqi, A., Kumar, A., Khattak, J.A., Mushtaq, N., Hussain, I., Ellis, T., and Singh, C.K. (2019). Field testing of over 30,000 wells for arsenic across 400 villages of the Punjab plains of Pakistan and India: Implications for prioritizing mitigation. Sci. Total Environ. 654, 1358–1363. https://doi.org/10.1016/j.scitotenv.2018.11.201.
81. World Health Organization (2017). Evaluation of certain contaminants in food. In World Health Organ. Tech. Rep. Ser., pp. 1–166.
82. Koch, I., Wang, L., Ollson, C.A., Cullen, W.R., and Reimer, K.J. (2000). The predominance of inorganic arsenic species in plants from Yellowknife, Northwest Territories, Canada. Environ. Sci. Technol. 34, 22–26.
83. Kumar, A., Singh, C.K., Bostick, B., Nghiem, A., Mailloux, B., and van Geen, A. (2020). Regulation of groundwater arsenic concentrations in the Ravi, Beas, and Sutlej floodplains of Punjab, India. Geochem. Cosmochim. Acta 276, 384–403. https://doi.org/10.1016/j.gca.2020.03.003.
84. Organization, W.H. (2022). Evaluation of Certain Food Additives and Contaminants (WHO technical report series).
85. Biemans, H., Siderius, C., Lutz, A.F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R.R., Wester, P., Shrestha, A.B., and Immerzeel, W.W. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nat. Sustain. 2, 594–601. https://doi.org/10.1038/s41893-019-0305-3.
86. Smith, A.H., Lingas, E.O., and Rahman, M. (2000). Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bull. World Health Organ. 78, 1093–1103.

87. Ravenscroft, P., Brammer, H., and Richards, K. (2009). Arsenic Pollution: A Global Synthesis (John Wiley & Sons).
88. Fendorf, S., Michael, H.A., and van Geen, A. (2010). Spatial and Temporal Variations of Groundwater Arsenic in South and Southeast Asia. Science *328*, 1123–1127. https://doi.org/10.1126/science.1172974.
89. Wood, D.A. (1978). Major and trace element variations in the Tertiary lavas of eastern Iceland and their significance with respect to the Iceland geochemical anomaly. J. Petrol. *19*, 393–436.
90. Larsen, G., Dugmore, A., and Newton, A. (1999). Geochemistry of historical-age silicic tephras in Iceland. Holocene *9*, 463–471.
91. Azam, M.F., Wagnon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A., Pottakkal, J.G., Chevallier, P., Singh, V.B., and Berthier, E. (2012). From balance to imbalance: a shift in the dynamic behaviour of Chhota Shigri glacier, western Himalaya, India. J. Glaciol. *58*, 315–324. https://doi.org/10.3189/2012JoG11J123.
92. Van Actherbergh, E. (2001). Data reduction software for LA-ICP-MS. In Laser Ablation-ICP-Mass Spectrometry in the Earth Sciences: Principles and Applications, pp. 239–243.
93. Maynard, D., Kalra, Y., and Crumbaugh, J. (1993). Nitrate and exchangeable ammonium nitrogen. In Soil sampling and methods of analysis, *1*, pp. 25–38.
94. Stibal, M., Tranter, M., Telling, J., and Benning, L.G. (2008). Speciation, phase association and potential bioavailability of phosphorus on a Svalbard glacier. Biogeochemistry *90*, 1–13. https://doi.org/10.1007/s10533-008-9226-3.
95. Hawkings, J., Wadham, J., Tranter, M., Telling, J., Bagshaw, E., Beaton, A., Simmons, S.-L., Chandler, D., Tedstone, A., and Nienow, P. (2016). The Greenland Ice Sheet as a hot spot of phosphorus weathering and export in the Arctic. Global Biogeochem. Cycles *30*, 191–210. https://doi.org/10.1002/2015gb005237.
96. ten Berge, H.F.M., van der Meer, H.G., Steenhuizen, J.W., Goedhart, P.W., Knops, P., and 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*, e42098. https://doi.org/10.1371/journal.pone.0042098.
97. Silber, A., Bar-Yosef, B., Levkovitch, I., and Soryano, S. (2010). pH-Dependent surface properties of perlite: Effects of plant growth. Geoderma *158*, 275–281. https://doi.org/10.1016/j.geoderma.2010.05.006.
98. Pedersen, P., and Lauer, J.G. (2004). Response of soybean yield components to management system and planting date. Agron. J. *96*, 1372–1381.
99. Devasenapathy, P. (2008). Efficiency Indices for Agriculture Management Research (New India Publishing).
100. Dobermann, A. (2007). Nutrient use efficiency–measurement and management.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental models: Organisms/strains		
Soybean (Glycine max) ‘Black jet’ seeds	LegumeFix, UK	N/A
Bacteria and virus strains		
Bradyhizobium japonicum inoculum	LegumeFix, UK	N/A (microbial inoculum used for root nodule formation)
Chemicals, peptides, and recombinant proteins		
Ammonium Nitrate (NHNO)	Analytical grade	Used for chemical nitrogen fertilizer
Phosphorus Pentoxide (PO)	Analytical grade	Used for chemical phosphorus fertilizer
Potassium Oxide (KO)	Analytical grade	Used for chemical potassium fertilizer
Sodium Acetate (NaOAc)	Analytical grade	Used in metal extractions as per Tessier et al. method
Magnesium Chloride (MgCl)	Analytical grade	Used in phosphorus and potassium extraction
HCl, HNO, HO (Trace Metal Grade)	Trace Metal Grade Chemicals	Used for aqua regia and extractions
Software and algorithms		
GLITTER Software	Australian National University	Software for data processing in LA-ICP-MS
DataGraph Software	Visual Data Tools	Used for generating graphical figures
R Statistical Software	R Foundation	http://www.R-project.org
BioRender Software	BioRender	License number: FS26X5S5BD for Figure 5 images
Other		
Vermiculite	Local supplier	Used for initial germination
Perlite (Silvaperl P35 Grade)	Hoben International, UK	Expanded, inorganic, amorphous volcanic glass
Reverse Osmosis (RO) Water	In-house supply	N/A
Malvern Mastersizer 3000	University of Bristol	Used for particle size analysis
Nu AttoM SC-ICP-MS	Nu Instruments Ltd., UK	Used for trace element analysis
Excite 193 ArF laser-ablation system	Photon Machines, San Diego, USA	For LA-ICP-MS analysis
Imaging-PAM M-Series Mini fluorimeter	Walz	For chlorophyll fluorescence imaging
LaChat QuikChem 8500 FIA system	LaChat Instruments, Loveland, CO	Used for nitrogen and phosphorus colorimetric analysis
Agilent 710 ICP-OES	Agilent Technologies	Used for exchangeable K and trace element concentration
Agilent 7500 ICP-MS	Agilent Technologies	Used after microwave digestion for trace element analysis
Mars 6 Microwave Digestion System	CEM Corporation	Used for microwave digestion of sediment samples
Whatman® GD/XP PES filters	Whatman	0.45 μm 25 mm filters used for extraction solution
Hach Pocket Pro pH meter	Hach	Used for measuring pH in artificial soil matrix
Commercial Seedling Compost	Melcourt and Levingtons, UK	Low-nutrient compost for experimental soil matrix

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Glacial flour sites and sampling

All sediment samples were collected from the banks of meltwater streams as close to the glacial portal as possible using sterilized trowels. Sediment was immediately transferred into Whirl-Pak bags and stored in a refrigerator (~2°C–4°C) until further analysis and crop growth experiments. Glacial flour was collected from two glacier field sites.

(1) Icelandic Flour: This sample was collected from Sólheimajökull, Iceland (63.4 °N, 19.4 °W) during October 2016, near the end of the ablation season. Sólheimajökull is a land-terminating outlet glacier of the Mýrdalsjökull ice cap, which lies above the Katla volcanic system. The bedrock at this site comprises relatively young (<0.7 million years) basalts known to contain elevated concentrations of elements such as Mg, Fe, Ca, Mn, Ni, Co, Zn, P, and S.[57,89,90]

(2) Himalayan Flour: Collected from Chhota Shigri (32.3 °N, 77.7 °E), a typical low-latitude Himalayan glacier located in the Chandra Bhaga river basin of the Lahaul and Spiti Valley, Pir Panjal range, Hindu Kush Himalayas, NW India. Samples were obtained at the end of the ablation season in September 2017. The geology of Chhota Shigri is complex, comprising migmatites and gneisses with granitic intrusions, overlain by metasediments including black slates, phyllites, and fine-grained biotite-schists.[91]

METHOD DETAILS

Soil and sediment analytical methods

- Particle Size Analysis
  - Particle size was determined from five replicates of each sample using a Malvern Mastersizer 3000 at the School of Geographical Sciences, University of Bristol. Prior to analysis, a sonication probe was used to aid in sediment disaggregation. The sediment was dispersed in ultra-pure water before being introduced into the Mastersizer. Particle size distribution was then determined using laser diffraction, and results were tabulated (see Table S1 for full data).
- Mineralogical Composition
  - All glacial flour samples were air-dried before analysis. Heavy minerals were separated from the dried samples using a 50% v/v lithium tetraborate solution, followed by manual handpicking of minerals under a binocular microscope at the Department of Geosciences, UiT – The Arctic University of Norway. Handpicked grains were further analyzed under a reflected light microscope (Leica DM LM equipped with 2.5x, 5x, 10x, and 63x objectives) and a Hitachi Tabletop SEM. Detailed elemental mapping of mineral grains was conducted, and individual mineral grains were selected for LA-ICP-MS spot analysis, performed at the Geological Survey of Finland (GTK).

Trace element analysis by LA-SC-ICPMS

- Laser Ablation-ICP-MS Analysis
  - Trace element analysis of sulfide minerals was performed using a Nu AttoM SC-ICP-MS (Nu Instruments Ltd., Wrexham, UK) and an Excite 193 ArF laser-ablation system (Photon Machines, San Diego, USA) at Geological Survey of Finland (GTK).
  - The laser operated at a pulse frequency of 5 Hz and a pulse energy of 5 mJ with 40% attenuation, producing an energy flux of 2.9 J cm^{-2} on the sample surface with a 40 μm spot size.
  - Each analysis began with 5 shots of pre-ablation followed by a 20-s baseline measurement. This was followed by laser ablation for 40 s for signal acquisition. Analyses were made using time-resolved analysis (TRA) with continuous acquisition of data for each set of points (typically following the scheme of primary standard, quality control standard, and 10–20 unknowns).
  - For sulfides, the synthetic pressed nanopellet sulfide standard UQAC FeS-1 was used for external standardization, [https://sulfideslasericpms.wordpress.com/rm-available/] with FeS-5 and FeS-6 nanopellet standards used as quality controls. Measurements covered 65 isotopes across 38 elements at low resolution (ΔM/M = 300) using the Fastscan mode. For Fe and Fe-Ti oxides, GSE glass was used as the primary external standard, with BHVO-2G, BCR-2G, and GSD as reference materials for quality control.
  - Data reduction was performed using GLITTER™[92] software, allowing baseline subtraction, integration of the signal over a selected time-resolved area, and quantification using known concentrations of the external and internal standards. Both sulfide and oxide data were calibrated with[57] Fe as an internal standard, assuming stoichiometric composition. Data was then presented as the total element concentration of the minerals.

Nitrogen concentration determination

- Method: Exchangeable total nitrogen (Ex-N), including nitrate (NO_3^--N) and ammonia (NH_4^+-N), was determined using a 2M KCl solution as described by Maynard et al.[93] The extraction solutions were filtered through 0.45 μm 25 mm Whatman GD/XP PES filters. NO_3^--N and NH_4^+-N concentrations in the extraction solution were determined colorimetrically using a LaChat QuikChem 8500 Series 2 FIA system with QuikChem methods 31-107-06-1-I for NH_4^+-N and 31-107-05-1-K for NO_3^--N.
- Precision and Accuracy: Precision for NO_3^--N was ±1.8% (n = 12) with an accuracy of +1.1%, based on six replicate matrix-matched standards across concentrations of 1, 5, 10, 25, 50, 100, 250, and 500 μg L^{-1} NO_3^--N. For NH_4^+-N, precision was ±3.2% (n = 12) and accuracy ±0.9%, based on matrix-matched standards across the same concentration range. Detection limits for NH_4^+-N and NO_3^--N were 0.12 and 0.09 μg g^{-1} for dry sediment, respectively.

Metal extractions and determination (P, K, Fe, Ca, mg, Mn, S, se, Zn) for sediments and beans

- Phosphorous Extraction: Method: Sequential extraction for P was conducted using methods adapted from Stibal et al.[94] and Hawkings et al..[95] Four extractions were performed:
  - Extraction 1: Loosely sorbed P was removed using 1M $MgCl_2$.
  - Extraction 2: Fe– and Al–bound P, potentially biolabile, was removed with 0.1M NaOH.
  - Extraction 3: Ca- and Mg-bound P was removed with HCl, often associated with apatite.
  - Extraction 4: Residual and organic-bound P was extracted using potassium persulfate/sulfuric acid digestion.
  - Sediments (50 mg) were suspended in 1.5 mL extraction solution, filtered through 0.45 μm Whatman GD/XP PES filters, washed ×6 with ultrapure water, and centrifuged at 3000 rpm for 5 min to a pellet and then supernatant filtered as above and added to the extract filtrate.
  - Soluble reactive phosphorus in extracts was measured colorimetrically on a LaChat QuikChem 8500 analyzer. (QuikChem method 31-115-01-1-I).

- Solutions were diluted prior to analysis, with dilution factors as follows, extraction 1 d.f. x2, extraction 2 d.f. x5, extraction 3 d.f. x50.
- Precision was ±0.5%, ±0.4%, ±0.2% and accuracy was −0.5%, +0.3%, +1.4% based on six replicate standards for extractions 1, 2, 3. Standards used were matrix matched and concentrations spanned 1, 5, 10, 25, 50, and 100 $\mu g\ L^{-1}$ PO_4-P^-. Standards were checked by independent reference check standards and monitored for drift throughout analytical runs (50 and 100 $\mu g\ L^{-1}$ PO_4-P^-).

- Exchangeable Potassium: Method: Following the method by Tessier et al.,[63] exchangeable K was determined using a sequential method.
  - Extraction 1: 0.5M $MgCl_2$loosely sorbed trace elements
  - Extraction 2 1M sodium acetate (NaOAc) metals bound to carbonates
  - Approximately 100 mg of sediment was used, with supernatants filtered (0.45 μm 25 mm Whatman GD/XP PES filters) and then the sediment was washed with 2 mL of MQ which was filtered as above and added to the extract filtrate (dilution factor (d.f) x2).
  - Syringe filters (Whatman GD/XP 25 0.45 μm) were acid washed using 20 mL 0.01M HCl followed by 30 mL MQ before flushing with air and leaving for 12 h to ensure drying in a trace element clean laminar flow (Class 100).
  - The combination of both extraction 1 (e.g., MgCl-K) and extraction 2 (e.g., NaOAc-K) are termed ‘exchangeable K′
  - Trace element concentrations in the extracts were determined on an Agilent 710 ICP-OES. All extraction solutions were diluted by a d.f. ×100 in 0.1M HNO_3 before running on the ICP-OES.
  - Standards covered concentrations from 0 to 500 $\mu g\ L^{-1}$, with results recorded in Table S2.
  - Precision was ±0.8%, ±0.5%, ±1.3%, ±3.2 and accuracy was +2.2%, +1.6%, +2.8%, −2.4 based on six replicate matrix matched standards for extractions 1, 2. Matrix matched standards for all element concentrations ranged from the 0.1 M HNO_3 blank (0), 1 5, 10, 25, 50, 100, 250 $\mu g\ L^{-1}$.
- Total element (P, K, Fe, Ca, Mg, Mn, S, Se, Zn): Method: Microwave Digestion and ICP-MS determination
  - 0.1–0.5 g of sediments were digested in modified aqua regia (2 mL of 30% w/v H_2O_2, 2.5 mL 37% w/v HCl, and 10 mL 67% w/v HNO_3)
  - Digestions were carried out in pressurized Teflon vessels using a Mars 6 microwave.
  - For each digestion, the temperature was ramped for 20 min to 210°C, where it was held for 15 min.
  - Samples digests were filtered through Whatman grade 41 filter papers and diluted to 50 mL before analysis.
  - Filtered samples were diluted to 50 mL before analysis with an Agilent 7500 ICP-MS
  - The ICP-MS was configured with a micromist nebulizer, a cooled double concentric spray chamber and nickel cones. Drift was monitored and corrected for using a 50 ppb In internal standard added in line to each sample using a T-junction inline mixing kit. Polyatomic interferences were removed using kinetic energy discrimination in a collision-reaction cell with He gas.
  - Precision for each element was P ±2.6%, K ±2.9%, Fe ± 0.8%, Ca ±5.9%, Mg ±2.6%, Mn ± 2.2%, S ±9.1%, Se ±1.9%, Zn ±1.9%, As ±2.2%. Accuracy for each element was as follows P +0.2%, K +2.5%, Fe +1.1%, Ca +0.4%, Mg +3.8%, Mn + 0.7%, S +4.1%, Se +11.1%, Zn +6.6%, As +6.7%, based on 6 replicate matrix matched standards covering the range of concentrations. Certified reference materials (JCR) were also run to ensure standards were correct.
- Bean trace element concentrations

Following crop growth experiments the soybean plant material was extracted and analyzed as per the sediment extraction methods outlined above using microwave digestion and ICP-MS (Newcastle University).

Crop yield experiments

Soybean plant material and growth preparations

- Soybean Germination and Inoculation
  - Soybean *(Glycine max)* ‘Black jet’ seeds were stratified at 4°C for 3 days to break dormancy, then sown into vermiculite bags and propagated in a growth chamber at 25°C with 100% humidity until germination (visible chitting, typically 5–8 days). Each germinated seed was then coated with a microbial inoculum of *Bradyhizobium japonicum* carried by peat (LegumeFix, UK) to encourage root nodule formation, simulating a natural soil microbial ecosystem.
- Soil Preparation and Treatment
  - Artificial soil was prepared using a 9:1 volume-to-volume ratio of perlite to commercial seedling compost (Silver Sand, Melcourt and Levingtons Seedling Compost) to create a low-nutrient matrix.[14] Expanded perlite (Silvaperl P35 Grade, Hoben International, UK) was chosen due to its high water-holding capacity and sufficient pore space for root growth. This combination of low-nutrient compost and perlite provided a chemically inert matrix with minimal external nutrient interference.[96]
  - Preliminary trials using quartz sand as an inert medium (9:1 with compost), resulted in root rot, waterlogging and soybean death. Although perlite is not truly chemically inert,[97] we performed sequential and total extractions on both the compost

and perlite (Table S4). The artificial soil matrix had low nutrient concentrations comparative to agricultural soils, supporting our experimental use.

- All materials were chosen for their low nutrient content comparable with most other plant growth matrixes to minimise external variables.
- Prior to planting, artificial soils were mixed in sterile ziplock bags to ensure a homogeneous matrix and then added to each pot 48 h prior to planting, where they were watered with reverse osmosis (RO) water to saturation point.
- When soils were mixed, treatment components were applied and left to equilibriate, briefly, these were as follows; both glacial flours were applied at 0.5, 1.0, 2.0, 5.0, 10.0 and 20.0 T ha^{-1} equivalents which have been determined as the most widely used crushed rock application rates.[15]
- Fertilisers were applied at the follow rates; Chemical N at 10 kg ha^{-1}, Chemical P at 10 kg ha^{-1} and Chemical K at 10 kg ha^{-1}. Treatments are outlined via Table S5. Chemical N fertiliser addition was achieved through the application of solutions of Ammonium nitrate, NH_4NO_3, chemical P through P_2O_5 and chemical K through K_2O, all reagents were analytical grade with <0.5ppm heavy metals, dilute solutions were made using RO water. To ensure accurate treatment, solutions were added to each individual pot using a syringe.

- Experimental Design
  - Treatments were applied to individual pots, which were then left to equilibrate for 7 days in a growth chamber before transplanting seedlings. The experiment was conducted three times with four replicates for growth comparison between 2 T ha^{-1} glacial flour, control, and chemical fertilizer treatments. A separate dose-response experiment was conducted for glacial flour application rates from 0.5 to 20.0 T ha^{-1}.

Growth conditions

- Controlled Environment Setup
  - Plants were grown in controlled GroDome chambers (Unigro) with a 12:12 h light photoperiod, 50% humidity, and 20°C ambient temperature. Supplemental lighting was provided by Attis7 LED grow lamps (<206 W, photon flux density of 100 μmol m^{-2} s^{-1}). All soybean experiments were conducted from November to March 2018 to ensure consistent light levels.
  - Plants were hand-watered daily with RO water to maintain optimal moisture levels while minimizing nutrient addition. Pots were placed in individual trays to collect water runoff and reduce nutrient leaching. Once weekly, 100 mL of RO water was applied directly to the base of each plant as per Mohammed et al.[14] At the end of the experiment post-harvest, all plants were recovered from the soils and root nodules were counted as an indicator of microbial soil health and nutrient availability.[14]

Soil matrix characteristics

Physical and chemical properties of soil

- Soil Composition and Preparation
  - The artificial soil matrix used in the crop experiment consisted of a 9:1 perlite to compost ratio. The characteristics of both components are presented in Table S4.
- Soil pH Measurement
  - pH of perlite and compost was determined by adding 30 g of each component to a 100 mL flask, saturating with RO water (pH neutral), and measuring with a Hach Pocket Pro pH meter.
- Moisture Content Determination
  - Soil moisture was assessed by weighing ~5 g of soil into a ceramic container, drying at 105°C for 24 h, and weighing immediately upon removal. The soil moisture (%) was calculated based on the mass difference between the wet and dry samples.
- Loss on Ignition (LOI)
  - LOI was determined by weighing out 1 g of dried soil and heating it in a furnace at 550°C for 1 h to remove all organic matter. The difference in mass before and after heating was used to calculate LOI (%).

Chlorophyll fluorescence imaging

Measurement of photosynthetic Activity

- Methodology
  - Chlorophyll fluorescence imaging was used to assess photosynthetic efficiency in the soybean plants. The first fully expanded leaf from the top of each plant was measured to evaluate the photosynthetic efficiency of Photosystem II (PSII) at multiple intervals (2, 7, 12, 17, 22, and 27 days from the start of the experiment). Leaves were not detached, ensuring non-destructive measurement.
- Equipment and Setup
  - Measurements were conducted at a leaf temperature of 20°C after plants were dark-adapted in a fully dark chamber for 30 min. Chlorophyll fluorescence was then measured using anpulse modulated fluorimeter, Imaging-PAM M-Series Mini fluorimeter (Walz).
- Data Analysis

- Fv/Fm provides information about the relative capacity of photosystem II, which is the first protein complex in the light-dependent reactions of photosynthesis.[67] Fv/Fm test compares the minimum fluorescence (Fo) to maximum fluorescence (Fm). The fewer reaction centers available, the lower the photosynthetic efficiency. The difference between Fo and Fm is Fv, variable fluorescence. Fv/Fm is a normalised ratio that reports the maximum potential quantum efficiency of photosystem II if all available photosynthetic reaction centers were open. Fv/Fm was measured from four separate regions of interest on the lead that was selected for measurement. The % change in Fv/Fm was calculated compared to the day 0 score for that plant, the day the seedling was transplanted into the soils.

Glacial flour application rates to soil

Calculation of application thickness

- Method
  - We calculated the potential thickness of glacial flour when applied at a 2 T ha-1 application rate to demonstrate the addition as follows:
  - 2 T ha^{-1} = 0.0002 T m^{-2}
  - 0.0002 T m^{-2} = 200 g m^{-2} = 0.2 kg m^{-2}
  - Using the standard silt density = 1.366 *g per cubic centimeter* = 1366 kg m^{-3} and standard sand density = 1602 kg m^{-3} the thickness of the flour layer was estimated:
  - e.g., if we use 2 T ha^{-1} as an example: 2 T ha^{-1} = 0.2 kg m^{-2}
  - If using the density of sand = 1602 kg m^{-3}, Thickness = 0.125 mm.
  - If using the density of silt = 1366 kg m^{-3}, Thickness = 0.146 mm

Agricultural calculations

Crop yield and elemental efficiency

- Crop yield calculation
  - At the end of the experiment (50 days), plants were harvested, dried for 7 days at 65°C and separated to record biomass. Crop yield (g m^2) was calculated using the agricultural standard yield estimation (Equation 1).[98] Soybean yields were calculated for each separate experiment run.

$$\frac{100 \times seed\ weight\ (g)}{seed\ yield\ (m^2)} \quad \text{(Equation 1)}$$

- Uncertainty in the crop yield
  - Variation in the experiment was likely to be driven by random inter-plant variability in response to the growth environment and application treatment response. The larger variation in uncertainty in the control and chemical N treatment was driven by a random individual plants generating significantly low yields in each experimental run (Table 1).
- Elemental efficiency (EE)
  - EE was calculated using crop yield to assess efficacy of treatments (Equation 2). We used these theoretical calculations to determine element availability and efficiency in generating observed crop yields in our experiments.

$$EE = (Y - Y_0) / F \quad \text{(Equation 2)}$$

  - Where, Y is the yield of the crop with additional nutrient applied (in units of g m^{-2}), Y_0 is the yield with no nutrient applied in control experiments (in units of g m^{-2}), and F is the mass of nutrient applied (in units of kg m^{-2}).[99,100]

- Enrichment factors (EF)
  - Enrichment factors (EF) for treatments were determined following the analysis of the trace element content of plant material, where enrichment factors >1 indicate the transfer of metals from treatment to the crop.[77]

$$EF = M_0 / M_x \quad \text{(Equation 3)}$$

  - Where, M_0 is the metal concentration in the no treatment control experiment. M_x is the metal concentration experiments treated with glacial flour or chemical fertiliser. Where the no treatment control was below the limit of detection of the ICP-MS extraction method, the calculation was determined using the method limit of detection.

QUANTIFICATION AND STATISTICAL ANALYSIS

Statistical analysis

- Software and Approach

   - Statistical analysis was performed using R (R Core Team, 2013) R: A language and environment for statistical computing. R foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.)
   - Tests for significance set at $p < 0.05$. Patterns of yield, nodules, Fv/Fm parameters were tested using a combination of the coefficient of determination (r^2) values, further supported using a test for significance, a p value <0.05 is determined significant. This combination approach was used to increase confidence and to avoid inclusions of correlations that are weak due to low sample numbers.
- Statistical Method
   - Significance was evaluated using the combination of correlation coefficients and significance tests, enhancing confidence and minimizing weak correlations due to low sample sizes.

Principal component regression (PCR)

- Methodology
   - Principal component regression (PCR) was applied using the pls package in R to identify relationships among complex datasets.
   - PCR is a data transformation technique used to determine underlying relationships in complex datasets. PCR achieves this by reducing data dimensionality, forming new principal components (PCs), which are then used as predictors to fit a linear regression (stepwise) model
- PCR Application
   - Predictors were normalized by dividing each by its standard deviation. PCs were calculated on the normalized total concentration of elements detected. If elements were below detection limits, method detection limit concentrations were used.
   - The PC were not rotated due to high correlation between variables.

Imaging

Graphical figures were generated using Datagraph software and R studio. Figure 5 images were created using BioRender license number: FS26 × 5S5BD. Graphical abstract also created in BioRender. Tingey, S. (2024) https://BioRender.com/f17t106.