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Enhanced rock weathering increases crop yield: a global meta-analysis

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Systematic Review

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Enhanced rock weathering increases crop yield: a global meta-analysis

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Abstract

Enhanced rock weathering (ERW) is increasingly considered for CO_2 removal on agricultural land, yet its effects on crop productivity remain uncertain across crops, soils and amendment practices. This work is the first global meta-analysis of experimental evidence published between 1983 and 2026, comprising 7,236 treatment-control comparisons from 113 publications. Of these, 2,086 comparisons from 52 publications were eligible for multilevel random-effects meta-analysis with publication-clustered robust inference. ERW increased harvested yield by 29.0% (95% CI: 8.7-53.1%; 22 publications, 91 comparisons), shoot dry biomass by 16.1% (95% CI: 8.6-24.2%) and aboveground potassium uptake by 36.5% (95% CI: 26.7-47.0%). However, the publication-balanced median harvested-yield increase was 14.8% across the broader evidence base, and substantial heterogeneity produced a wide prediction interval (-43.4% to +194.0%). Crop-specific responses varied, while exploratory moderator analyses did not establish reliable predictors of agronomic effectiveness across soil conditions, climates, rock materials or application practices. Strictly matched experimental responses revealed a positive association between potassium uptake and harvested yield (Spearman's $\rho = 0.905$; adjusted $q = 0.008$), although the limited evidence and potential mathematical coupling preclude causal interpretation. Overall, ERW can improve agricultural productivity, but the magnitude and consistency of these benefits remain context-dependent. Agronomic performance should therefore be evaluated independently of CO_2 removal, with greater emphasis on replicated field experiments and concurrent measurements of crop productivity, nutrient acquisition and soil conditions.

Keywords: Enhanced rock weathering; Silicate rock amendments; Geochemistry; Crop yield; Soil fertility; Carbon dioxide removal

1. Introduction

Enhanced rock weathering (ERW) is proposed as a land-based carbon dioxide removal (CDR) strategy that seeks to accelerate the natural dissolution of silicate minerals by applying crushed rock to soils. Agricultural land offers a potential setting for ERW deployment because established infrastructure for soil amendments could support large-

scale implementation while providing opportunities for improved soil fertility and crop productivity (Beerling et al., 2020). However, the co-benefits of ERW are not guaranteed and need to be assessed independently of its CO_2 removal potential. Establishing whether silicate rock amendments consistently improve crop performance is therefore important for evaluating their agronomic suitability and wider adoption. The dissolution process can release essential plant nutrients, including calcium, magnesium and potassium, while influencing soil acidity and nutrient availability. Earlier experiments demonstrated the potential of granite powder and other silicate minerals to supply potassium for plant nutrition, although their effectiveness varied with mineral composition and soil conditions (Coroneos et al., 1996; Mohammed et al., 2014; Gunnarsen et al., 2019). Silicate rock powders have also been proposed as multifunctional soil amendments capable of supporting agricultural productivity, soil remineralisation and carbon sequestration (Ramos et al., 2022).

These changes may improve plant growth, particularly in acidic or nutrient-depleted soils. Potassium-bearing agrominerals, including nepheline syenite and phonolite, have also been investigated as alternative nutrient sources for maize (Nogueira et al., 2021). Experimental evidence, such as Kelland et al. (2020), reported a 21% increase in sorghum yield following basalt amendment under controlled conditions, while a four-year field experiment in the United States Corn Belt documented maize and soybean yield increases of approximately 12–16% (Beerling et al., 2024). Nevertheless, positive responses are not universal. In tropical Australian sugarcane fields, repeated basalt application increased soil pH and extractable nutrients without improving crop yield (Holden et al., 2024). Such contrasting findings suggest that crop responses are contingent on interactions among many factors such as rock properties, soil conditions, geographical coverage and experimental setting.

Therefore, yield improvements may not coincide with increases in plant nutrient concentrations, and responses in controlled environments may not translate directly to field conditions. Recent field experiments involving spring oat and permanent hay meadows further illustrate the diversity of crop systems in which agronomic responses to basalt application are being evaluated (Skov et al., 2024; Bell et al., 2026). A recent meta-analysis of silicate agrominerals in Brazil reported increases in crop yield and aboveground biomass, demonstrating the value of quantitative evidence synthesis while highlighting the importance of regional soil and amendment characteristics (Swoboda et al., 2026). However, assessing the broader applicability of these responses requires an integrated evaluation across geographical regions, crop types, soil environments and rock amendment strategies. Particular attention is needed to the non-independence of multiple treatment comparisons within experiments and publications, as well as the uneven availability of sampling variance information.

The present study addresses three central questions: (i) Does enhanced rock weathering consistently improve crop yield and other indicators of plant performance? (ii) Are improvements in yield accompanied by corresponding changes in biomass production, plant growth and nutrient acquisition, or do these responses diverge? (iii) To what extent do soil properties, climate, rock characteristics and application practices explain the magnitude and variability of crop responses? To answer these questions, a global multilevel meta-analysis was conducted encompassing 7,236 treatment–control comparisons from 113 publications, including 2,086 variance-weighted comparisons

from 52 publications. By integrating robust statistical inference, moderator analyses and broader exploratory evidence, this work sought to distinguish generalisable agronomic benefits from responses that depend on specific environmental and management conditions. Ultimately, this synthesis evaluates whether enhanced rock weathering offers consistent agricultural benefits, where those benefits are most likely to occur, and how confidently they can be inferred from the available evidence, independently of its potential for CO_2 removal.

2. Materials and Methods

2.1. Literature identification and study selection

A structured literature search was undertaken to identify primary experimental studies investigating the effects of silicate rock amendments associated with enhanced rock weathering (ERW) on crop performance. Searches were conducted in Scopus using combinations of terms related to enhanced weathering, silicate rock powders, basalt, volcanic rock dust, soil remineralisation and plant or crop responses. Additional records were identified through bibliographic cross-checking, reference screening (Suhrhoff, 2026; Swoboda et al., 2026) and supplementary searches in Web of Science and Google Scholar. The searches were updated throughout 2026 (with temporary cutoffs in June and September 2026), and, with a final cutoff of 10 October 2026, encompassed experimental studies published between 1983 and 2026.

Studies were considered eligible when they reported experimental applications of silicate rock amendments to soils and provided quantitative crop-performance measurements with identifiable untreated or unamended controls. Eligible outcomes included harvested yield, plant biomass, morphological growth traits, nutrient uptake and plant-tissue nutrient concentrations. Non-journal publications, non-English articles and studies without relevant treatment–control comparisons were excluded.

Following literature screening, retrieval and eligibility assessment, 160 articles were retained, of which 113 publications contributed eligible descriptive comparisons and 52 provided sufficient information for the variance-weighted meta-analysis. The identification and selection of studies are summarised in a PRISMA-style flow diagram (Fig. 1), while the detailed search terms and eligibility criteria are provided in the Supplementary Information (Page et al. 2021).

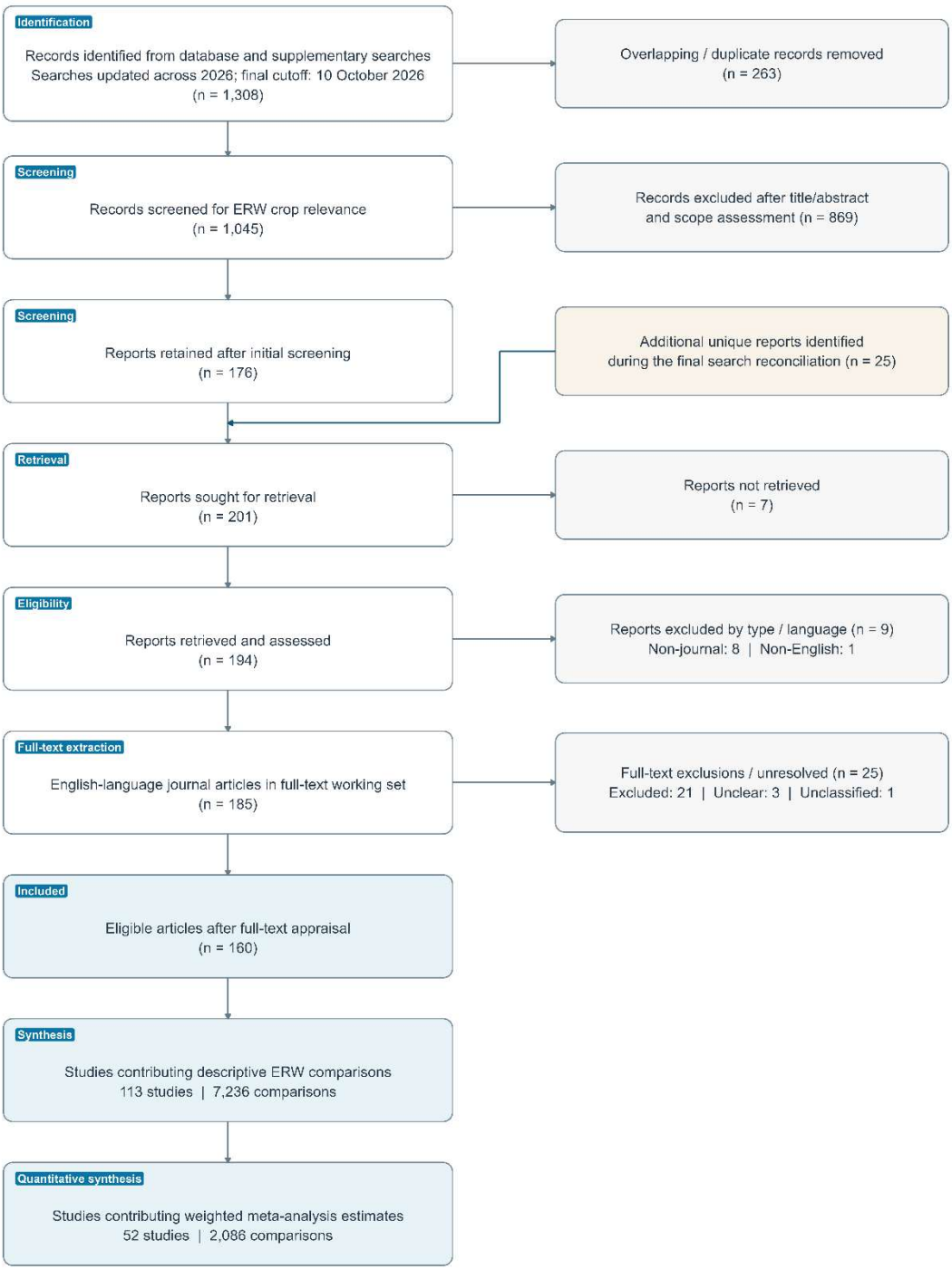


Figure 1. PRISMA-style flow diagram of literature identification and selection.

2.2. Data extraction and harmonisation

Study-level and experimental information was extracted from full texts, tables, figures and supplementary materials. Variables included publication identity, geographical location, crop species, experimental system, soil properties, rock type and lithology, application rate, particle size, incorporation depth, experimental duration and measured plant responses. Treatment and control means, replication and dispersion statistics were recorded where available. Graphically reported values were digitised when necessary.

Outcomes were harmonised into biologically comparable categories covering harvested yield, dry biomass, morphological growth traits, nutrient uptake and plant-tissue nutrient concentrations. Units and endpoint definitions were standardised, and comparisons were linked to their source publications, experiments, treatments, controls and measurement occasions to identify potential dependence. The extraction archive contained 31,782 observations, from which 7,236 eligible treatment–control comparisons were available for descriptive synthesis. Overlapping maize and soybean crop-year observations reported by Kantola et al. (2023) and Beerling et al. (2024) were reconciled to avoid double counting, while the distinct Miscanthus harvest observations were retained.

2.3. Effect-size calculation

Treatment responses were expressed as the natural-log response ratio (lnRR), following Hedges et al. (1999):

$$y_i = \ln(RR_i) = \ln\left(\frac{\bar{X}_{T,i}}{\bar{X}_{C,i}}\right) \quad (1)$$

where $\bar{X}_T$ and $\bar{X}_C$ denote the treatment and control means, respectively. For independent treatment and control arms, sampling variance was approximated as:

$$v_i = \frac{s_{T,i}^2}{n_{T,i}\bar{X}_{T,i}^2} + \frac{s_{C,i}^2}{n_{C,i}\bar{X}_{C,i}^2} \quad (2)$$

where s represents the standard deviation and n the number of replicates. Reported standard errors were converted to standard deviations as $s = SE\sqrt{n}$. Additional variance reconstruction was documented by source and method, and variance provenance was retained for sensitivity analyses. Comparisons lacking sufficient precision information were retained for descriptive analyses but were not automatically assigned inverse-variance weights.

For interpretation, pooled *lnRR* estimates and their confidence limits were back-transformed into percentage changes relative to the control:

$$\Delta(\%) = 100\left(e^{\hat{y}} - 1\right) \quad (3)$$

2.4. Multilevel meta-analysis and heterogeneity

Separate multilevel random-effects meta-analyses were fitted for harmonised crop-performance endpoints using restricted maximum likelihood (REML) (Viechtbauer, 2010). The intercept-only model was specified as:

$$y_{ijk} = \mu + u_j + b_{jk} + \varepsilon_{ijk} \quad (4)$$

where μ represents the pooled lnRR, u_j is the publication-level random effect, b_{jk} is the experiment-level random effect nested within publication, and ε_{ijk} is sampling error with variance v_{ijk}.

The two heterogeneity components were estimated separately, and total heterogeneity was expressed as:

$$\tau^2_{\text{total}} = \tau^2_{\text{publication}} + \tau^2_{\text{experiment}} \quad (5)$$

To account for potentially correlated comparisons within publications, statistical inference was based on cluster-robust variance estimation with the CR2 small-sample correction and Satterthwaite degrees of freedom (Pustejovsky & Tipton, 2018). Two-sided 95% confidence intervals and unadjusted p-values were reported for the main analyses. The working sampling-error covariance matrix was diagonal; publication-level CR2 inference was used to reduce sensitivity to unmodelled within-publication dependence.

2.5. Moderators and sensitivity analyses

Heterogeneity was explored using subgroup analyses and univariable meta-regressions, subject to data availability. Moderators included initial soil pH, soil texture, climate, rock family, experimental system, application rate, incorporation depth and measurement duration. Continuous associations involving soil pH, application rate and measurement time were explored using REML meta-regression with CR2-based uncertainty estimates. Moderator findings were interpreted as associations rather than causal effects.

Robustness was investigated by comparing the broader variance-bearing dataset with a subset excluding reconstructed variances and through leave-one-publication-out assessments. Additional endpoints, heterogeneity components, approximate prediction intervals and exploratory publication-level funnel plots were evaluated in supplementary analyses. To address multiple testing, Benjamini–Hochberg false-discovery-rate (FDR) adjustments were considered for secondary endpoints and exploratory moderator tests, with adjusted results reported in the Supplementary Information (Benjamini & Hochberg, 1995).

2.6. Exploratory descriptive synthesis and reproducibility

The broader descriptive dataset was analysed independently of inverse-variance weighting. Within each endpoint, lnRR values were aggregated sequentially to experiment-level and publication-level medians. Publication-balanced medians, interquartile ranges and proportions of positive or negative responses were then calculated, giving each publication equal descriptive weight. These results were treated as exploratory and were not used for confirmatory inference.

Statistical analyses were conducted in R v4.6.1 (R Core Team, 2026), principally using *metafor* for multilevel REML estimation and *clubSandwich* for CR2 inference. Data processing and visualisation used *dplyr*, *tidyr*, *ggplot2*, patchwork, maps, scales, *ragg* and *systemfonts*.

2.7. Crop-specific responses

Crop-specific responses were evaluated to examine variation in agronomic outcomes among individual crop identities. The descriptive dataset was stratified by harmonised crop identity and crop-performance endpoint, with separate categories retained where different harvested products or crop types could not be reliably combined. Within each crop–endpoint combination, lnRR values were aggregated to experiment-level and subsequently publication-level medians, following the publication-balanced procedure described in Section 2.6. Median percentage changes, interquartile ranges and the proportion of publications showing positive responses were calculated. Crop-specific descriptive estimates were presented for combinations with at least three independent

publications, while less-replicated crop identities were retained in the supplementary evidence inventory.

For harvested yield, exploratory variance-weighted analyses were additionally performed where sufficient eligible comparisons and publication clusters were available. Separate multilevel REML models were fitted for soybean and maize, accounting for publication- and experiment-level heterogeneity, with 95% confidence intervals calculated using publication-clustered CR2 inference. The descriptive and variance-weighted estimates were presented separately because their underlying evidence coverage and statistical interpretation differ. These analyses were considered exploratory, and differences between crop-specific estimates were not interpreted as formal tests of between-crop heterogeneity.

2.8. Experimental evidence networks and paired crop-response associations

To investigate the potential relationships among plant nutritional, physiological and growth responses, an experimental evidence network was constructed from the broader descriptive dataset. Outcomes were grouped into seven families: harvested yield, biomass, plant growth, nutrient uptake, tissue nutrient concentrations, yield components and plant physiology. Connections between outcome families were established when both were measured within at least one common experiment. The number of independent publications reporting each combination was calculated, with each publication counted once per connection to avoid inflating evidence counts through repeated measurements or multiple treatment comparisons. Connections supported by at least three publications were displayed in the evidence network (Fig. S6). This analysis describes the structure of the available experimental evidence rather than biological or causal relationships.

A complementary paired-response analysis examined whether changes in plant nutrition and growth were associated with harvested-yield responses. Treatment–control comparisons were matched within the same publication, experiment, treatment, control, crop identity and reported harvest period or measurement day. Comparisons with ambiguous multi-crop identities or incompatible measurement periods were excluded. Matched lnRR values were subsequently aggregated to publication-level medians, providing one paired observation per publication and endpoint.

For endpoints represented by at least eight independent publications, associations with harvested yield were assessed using Spearman's rank correlation. Uncertainty was estimated using percentile bootstrap 95% intervals based on 2,000 publication-level resamples. Exploratory p-values were adjusted using the Benjamini–Hochberg procedure across the eligible endpoint tests. Paired publications were also classified according to response direction: both outcomes increased, both decreased, or responses were discordant (Fig. 8). These analyses were based on publication-balanced descriptive responses and were interpreted as exploratory associations rather than evidence of causal mediation. Potential mathematical coupling between nutrient uptake and biomass-derived measurements was also considered when interpreting the results.

3. Results

3.1. Study selection and geographical coverage

The literature searches identified 1,308 records, from which 263 overlapping records were removed. Of the 1,045 unique records screened, 869 were excluded during initial relevance assessment. A further 25 unique reports were identified during final search reconciliation, giving 201 reports sought for retrieval. Seven reports could not be obtained, and nine of the 194 retrieved reports were excluded on publication-type or language grounds. Subsequent full-text appraisal of the remaining 185 articles identified 160 eligible articles, including 113 publications contributing 7,236 descriptive treatment–control comparisons (Fig. 1). Sampling variances were available or reconstructed for 2,086 comparisons from 52 publications, representing 80 experiments, which formed the variance-weighted meta-analysis dataset.

Georeferenced study sites were distributed across multiple continents but were unevenly represented geographically (Fig. 2). The mapped evidence included both precisely geolocated experiments and studies for which only country-level locations could be established. Accordingly, the map describes the geographical distribution of the available evidence rather than the global extent of ERW implementation.

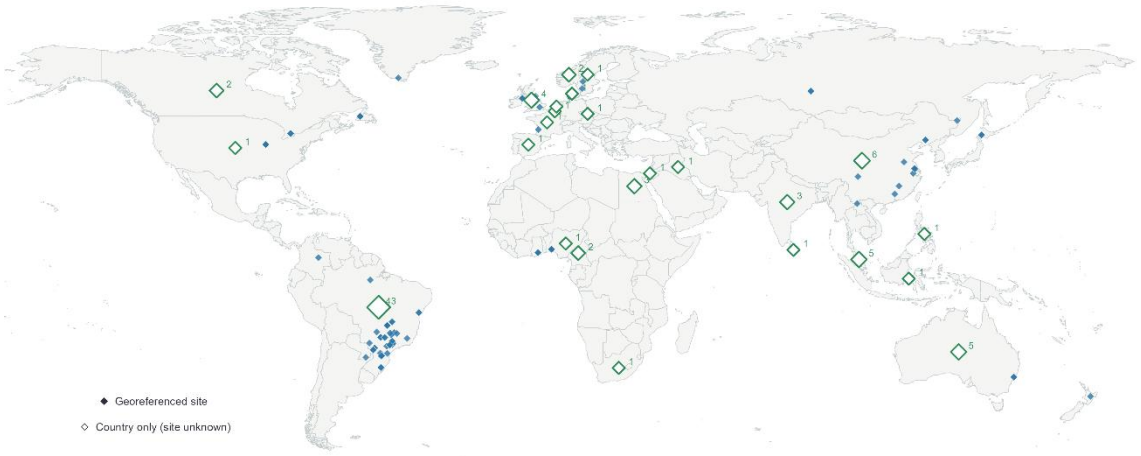


Figure 2. Geographical distribution of experiments evaluating silicate rock amendments and crop performance. Filled symbols identify studies with georeferenced experimental sites; open symbols indicate approximate country-level locations where precise site coordinates were unavailable. Symbols show the locations represented in the extracted literature rather than a spatially representative sample of agricultural ERW deployment.

3.2. Pooled crop-performance responses

Enhanced rock weathering increased harvested yield by 29.00% (95% confidence interval [CI]: 8.68 to 53.10%; p = 0.006; 22 publications and 91 comparisons; Table 1 and Fig. 3a). Shoot dry biomass also increased by 16.10% (95% CI: 8.57 to 24.16%; p < 0.001; 26 publications and 170 comparisons). In contrast, increases estimated for root dry biomass (7.02%; 95% CI: −10.58 to 28.09%) and total dry biomass (19.10%; 95% CI: −10.61 to 58.67%) were statistically uncertain. The yield model exhibited appreciable heterogeneity (total $\tau^2 = 0.149$), whereas the shoot-biomass model had a lower estimated heterogeneity variance (total $\tau^2 = 0.027$).

Table 1. Effects of enhanced rock weathering on crop yield, biomass, growth and nutrient responses.

Crop-performance endpoint	k	n	PC (%)	95% CI (%)	p-value	τ² total
Crop yield						
Harvested yield	22	91	+29.00	+8.68 to +53.10	0.006	0.149
Plant biomass						
Shoot dry biomass	26	170	+16.10	+8.57 to +24.16	<0.001	0.027
Root dry biomass	11	50	+7.02	−10.58 to +28.09	0.418	0.062
Total dry biomass	5	27	+19.10	−10.61 to +58.67	0.166	0.052
Plant growth						
Plant height	14	141	+10.96	−1.65 to +25.18	0.085	0.043
Stem diameter	6	40	+48.63	+12.28 to +96.73	0.016	0.074
Leaf area	5	22	+7.50	−13.18 to +33.11	0.366	0.020
Nutrient uptake						
Aboveground K uptake	9	70	+36.46	+26.68 to +46.99	<0.001	0.019
Nutrient concentrations						
Aboveground P concentration	8	31	−12.35	−22.94 to −0.32	0.046	0.033
Aboveground K concentration	9	48	+15.94	−16.79 to +61.54	0.332	0.192
Aboveground Mg concentration	9	70	+6.66	−0.49 to +14.32	0.064	0.006
Aboveground Ca concentration	8	15	+7.00	+3.69 to +10.42	0.004	0.000
Leaf nutrient concentrations						
Leaf K concentration	7	35	19.07	−3.31 to +46.63	0.084	0.083
Leaf Mg concentration	5	37	19.31	−34.42 to +117.05	0.458	0.226
Leaf Ca concentration	5	37	5.59	−17.88 to +35.77	0.580	0.037

Note: Values represent percentage changes (PC) relative to unamended controls, calculated from natural-log response ratios (lnRR). Pooled estimates were obtained using multilevel restricted maximum-likelihood (REML) models with publication- and experiment-level random effects. Confidence intervals (CI) and p-values were calculated using publication-clustered CR2 robust variance estimation with Satterthwaite degrees of freedom. k denotes independent publications, and n denotes treatment–control comparisons. τ² total is the sum of the publication- and experiment-level heterogeneity variance components on the lnRR scale. P-values are unadjusted; Benjamini–Hochberg false-discovery-rate-adjusted p-values, heterogeneity components and 95% prediction intervals are provided in the Supplementary Information.

Among morphological traits, stem diameter increased by 48.63% (95% CI: 12.28 to 96.73%; p = 0.016; six publications), although the interval was wide. The estimated responses of plant height (10.96%; 95% CI: −1.65 to 25.18%) and leaf area (7.50%; 95% CI: −13.18 to 33.11%) were less precise and their confidence intervals included zero (Fig. 3a).

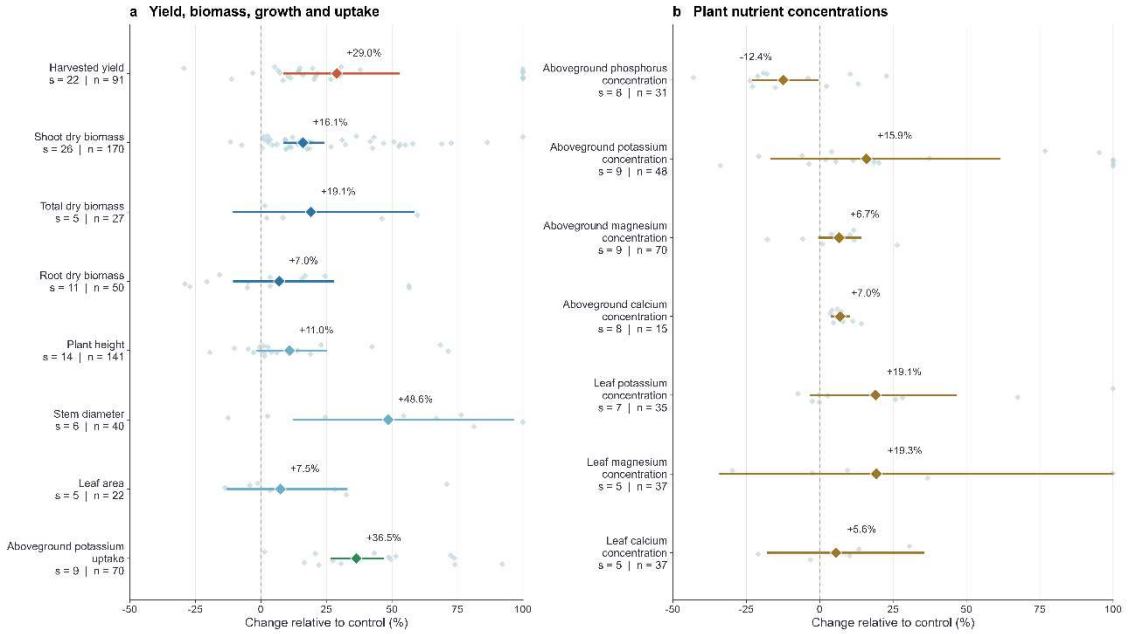


Figure 3. Multilevel REML estimates of crop-performance responses to silicate rock amendments. (a) Yield, biomass, growth and potassium uptake; (b) plant nutrient concentrations. Coloured diamonds show pooled changes relative to controls, horizontal lines show 95% publication-clustered CR2 confidence intervals and pale diamonds show study-level responses. Percentage labels give pooled effects; s and n denote publications and comparisons. The display extends from −50% to +100%, with off-scale values visually capped.

Nutrient responses were not uniform (Fig. 3b). Aboveground potassium uptake increased by 36.46% (95% CI: 26.68 to 46.99%; $p < 0.001$), whereas aboveground phosphorus concentration decreased by 12.35% (95% CI: −22.94 to −0.32%; $p = 0.046$). Aboveground calcium concentration increased by 7.00% (95% CI: 3.69 to 10.42%; $p = 0.004$). Estimates for aboveground potassium and magnesium concentrations and for leaf potassium, magnesium and calcium concentrations were positive, but their 95% confidence intervals crossed zero. These comparisons are based on unadjusted p-values, with interpretation also informed by the breadth of the outcome family.

3.3. Responses across environmental and amendment categories

Subgroup estimates showed variation across soil texture, climatic setting, rock family, experimental system and rock application rate for harvested yield and shoot dry biomass (Fig. 4). Harvested-yield responses were generally positive across the represented categories, although several subgroup estimates had wide confidence intervals, particularly where few publications contributed. Shoot-biomass responses likewise differed across the available soil-pH, climate, rock-family, experimental-system and application-rate categories. The uncertainty around individual subgroup estimates and the unequal representation of categories limit conclusions about differences between moderators; separate subgroup confidence intervals should not be interpreted as formal tests of interaction.

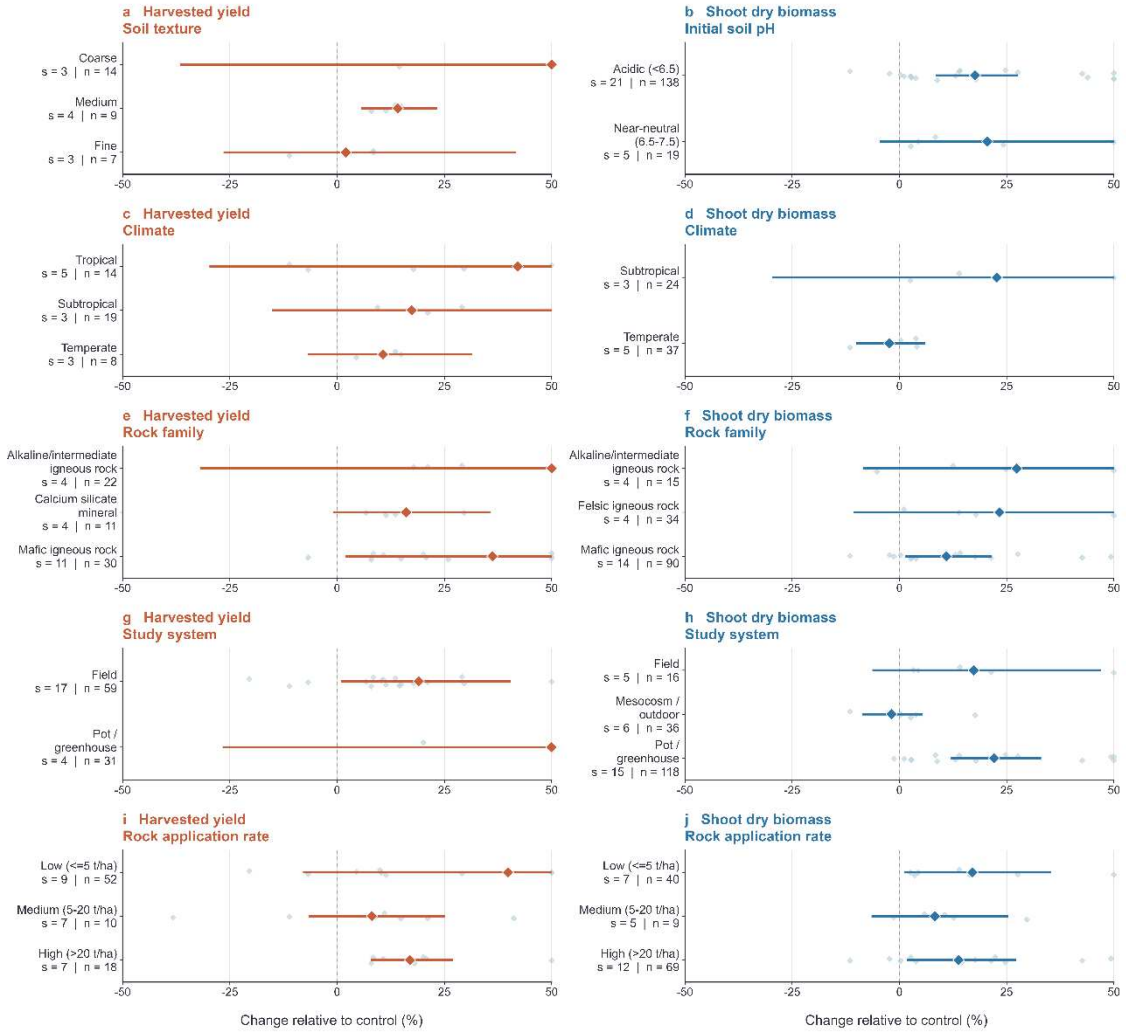


Figure 4. Subgroup responses of (left) harvested yield and (right) shoot dry biomass across soil and amendment characteristics. Panels show (a, b) soil texture or initial soil pH, (c, d) climate, (e, f) rock family, (g, h) experimental system and (i, j) rock application rate. Coloured diamonds and horizontal lines represent subgroup-specific multilevel REML percentage estimates and 95% CR2 confidence intervals; pale diamonds show publication-level responses. The category labels include the number of publications (s) and comparisons (n). The x-axis is visually restricted to −50% to +50%, with off-scale values capped at the corresponding boundary. Harvested-yield incorporation-depth results are presented separately in Fig. S5.

For other endpoints, subgroup estimates were available for plant height, aboveground potassium uptake and aboveground phosphorus and magnesium concentrations (Fig. 5).

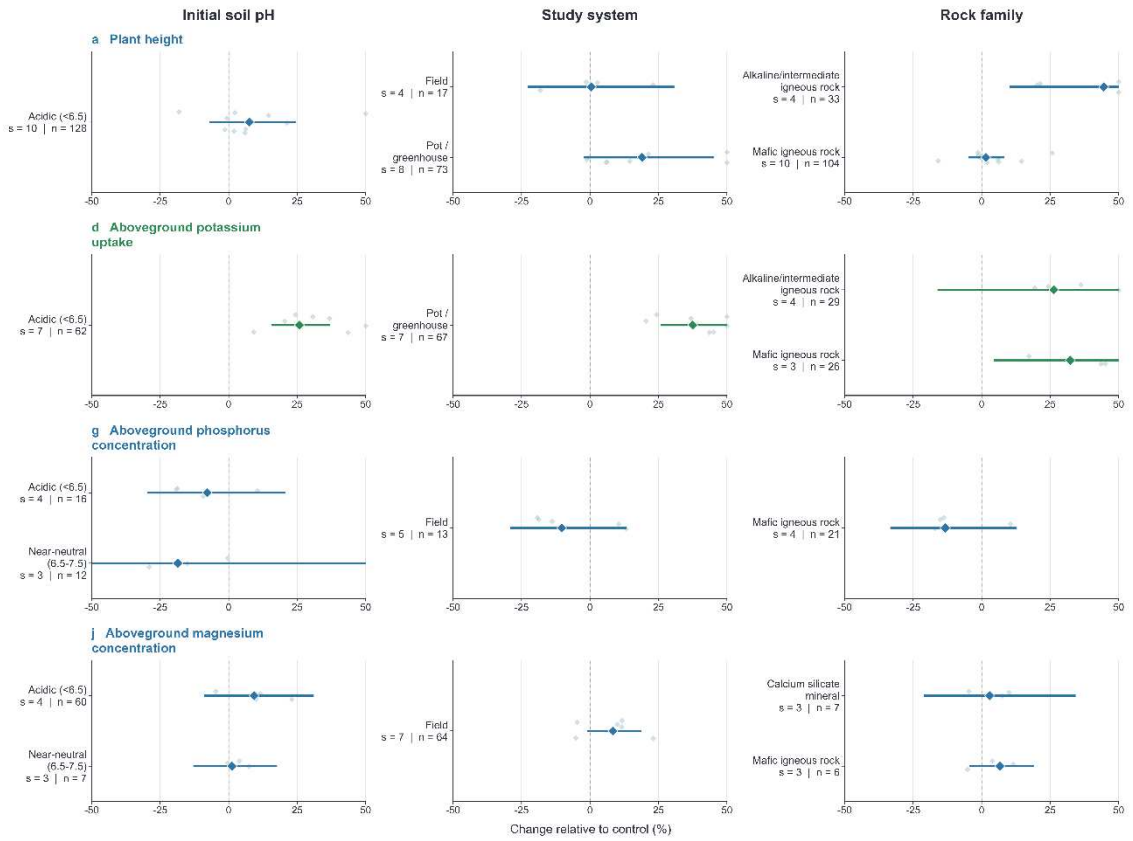


Figure 5. Secondary crop-performance subgroup estimates by initial soil pH (left column), study system (middle column) and rock family (right column). Rows represent (a–c) plant height, (d–f) aboveground potassium uptake, (g–i) aboveground phosphorus concentration and (j–l) aboveground magnesium concentration. Diamonds indicate multilevel REML estimates and horizontal lines their 95% CR2 confidence intervals; pale diamonds show publication-level responses where plotted. The category labels report publication (s) and comparison (n) counts. The plotted x-axis is restricted to −50% to +50%, with boundary capping of off-scale values.

Potassium-uptake estimates were positive across the represented soil-pH, study-system and rock-family categories, whereas phosphorus and magnesium concentration responses were less consistent. Several endpoint–moderator combinations were supported by only one reported category or a small number of publications. Thus, these analyses describe the observed conditional responses rather than establishing a comprehensive ranking of soil or amendment conditions.

3.4. Continuous moderator associations

Exploratory univariable meta-regressions examined the relationships between plant responses and initial soil pH, rock application rate and measurement time (Fig. 6). Fitted harvested-yield responses increased with initial pH in the displayed data range, while the association with rock application rate was comparatively shallow. For shoot dry biomass, the fitted association with initial pH was slightly negative, whereas application rate and measurement time showed weak positive slopes. Confidence bands, particularly towards the limits of the observed moderator ranges, were broad. These patterns therefore indicate exploratory associations, not established dose–response relationships.

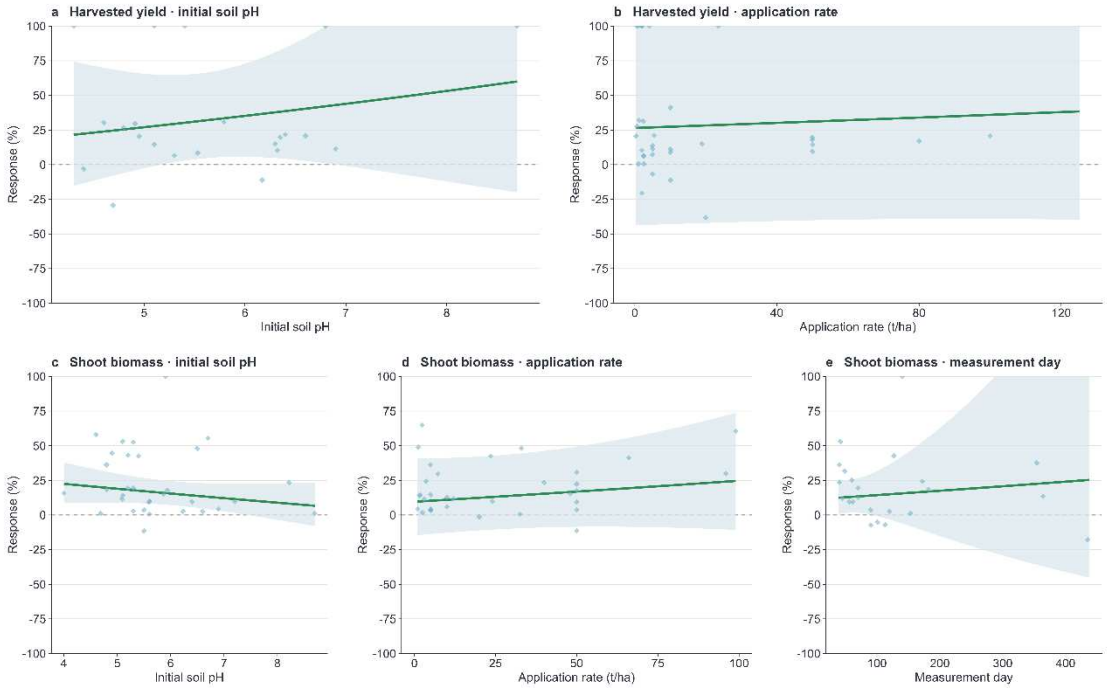


Figure 6. Exploratory continuous moderator associations for (a, b) harvested yield and (c–e) shoot dry biomass. The panels show relationships with initial soil pH, rock application rate and, for shoot biomass, measurement time. Solid curves are fitted values from univariable multilevel REML meta-regressions; shaded bands represent 95% uncertainty intervals calculated using publication-clustered CR2 covariance estimates. Pale symbols show publication-level observations. The fitted associations are descriptive and should not be interpreted as causal dose–response functions.

3.5. Sensitivity and broader descriptive evidence

The direct-variance sensitivity analyses retained the direction of the main pooled responses for harvested yield, shoot dry biomass, plant height and aboveground potassium uptake (Fig. S3). Publication-level funnel visualisations for yield and shoot dry biomass are provided in Fig. S4; these exploratory plots were not treated as formal tests of small-study effects. The additional incorporation-depth subgroups for harvested yield are shown in Fig. S5.

The broader descriptive synthesis provided an independent view of outcomes beyond the variance-weighted evidence (Figs. S1 and S2; Tables S1 and S2). Among the 55 publications reporting harvested yield, the publication-balanced median change was 14.84% (interquartile range [IQR]: 7.44 to 34.97%), compared with 14.62% (IQR: 8.90 to 25.90%) among the 22 publications represented in the weighted subset. Corresponding descriptive medians were 13.82% for shoot dry biomass (49 publications), 15.67% for root dry biomass (20 publications) and 38.47% for aboveground potassium uptake (34 publications). Aboveground phosphorus concentration showed a negative median response (−10.72%; 18 publications). These descriptive medians and IQRs are not inverse-variance-weighted estimates or inferential confidence intervals, and they were not used to modify the primary REML–CR2 results.

3.6. Crop-specific responses

Crop-specific descriptive analyses revealed variation in harvested-yield responses among the represented crop identities (Fig. 7a; Table S11). Rice showed a publication-balanced median yield increase of 18.4% (interquartile range [IQR]: 10.9 to 45.3%; 13 publications and 37 comparisons), with positive responses in 12 of 13 publications. Corresponding median increases were 16.2% for soybean (IQR: 13.7 to 33.6%; ten publications and 59 comparisons) and 16.3% for maize (IQR: 7.9 to 51.9%; seven publications and 51 comparisons). All seven maize publications showed positive median responses. Italian ryegrass exhibited a larger median increase of 37.4% (IQR: 27.9 to 78.8%), although this estimate was based on only three publications. In contrast, bread wheat showed a slightly negative median response of −5.7% (IQR: −10.8 to 2.4%; four publications), with positive responses in only one publication. Additional crop identities were represented by fewer independent publications, limiting the reliability of crop-specific generalisations (Table S11).

Exploratory variance-weighted analyses were feasible for soybean and maize (Fig. 7b; Table S12). The multilevel REML estimate for soybean indicated a 48.4% yield increase (95% CI: −16.9 to 165.0%; p = 0.141; six publications and 29 comparisons), while the corresponding estimate for maize was 66.1% (95% CI: −44.0 to 392.6%; p = 0.227; four publications and 16 comparisons). Both estimates were positive but statistically uncertain, with wide confidence intervals encompassing zero. The differences between descriptive medians and variance-weighted estimates reflect differences in evidence coverage and statistical aggregation. These findings therefore suggest variation in observed crop responses but do not establish statistically supported differences in ERW effectiveness among crop species.

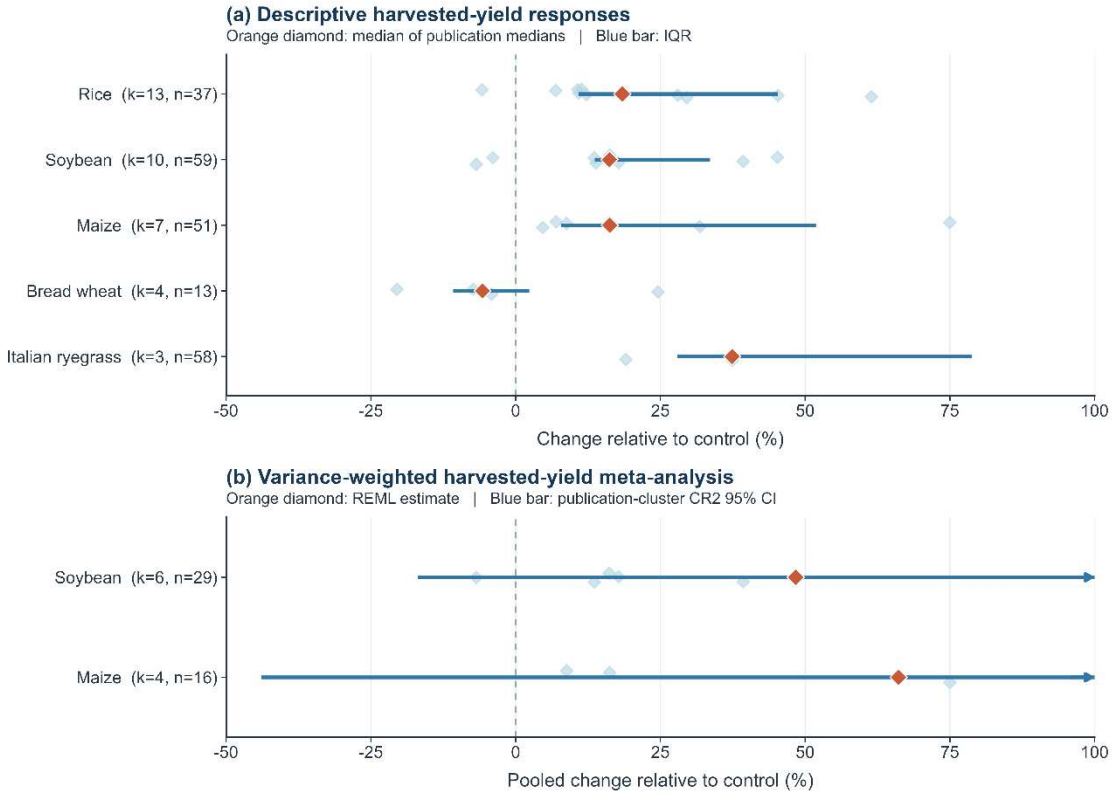


Figure 7. Crop-specific harvested-yield responses to enhanced rock weathering. (a) Publication-balanced descriptive median percentage changes and interquartile ranges (IQRs) for five crop identities. Orange

diamonds indicate cross-publication medians, blue horizontal lines represent IQRs, and pale diamonds show individual publication medians. (b) Exploratory variance-weighted multilevel REML estimates for soybean and maize, with 95% publication-clustered CR2 confidence intervals. Labels report independent publications (k) and treatment–control comparisons (n). Maize refers to grain or unspecified harvested yield, excluding silage maize. Both panels use a common −50% to +100% display range; arrows indicate confidence intervals extending beyond the plotted limits. Descriptive IQRs and inferential confidence intervals represent different measures of uncertainty.

3.7. Associations between harvested yield and other crop-performance responses

Experimental co-measurement analysis showed that harvested yield was frequently evaluated alongside plant nutritional and growth responses, although the extent of evidence varied among outcome families (Fig. S6). Of the 55 publications reporting harvested yield, 29 also measured tissue nutrient concentrations, 18 measured nutrient uptake, 18 measured plant growth, 16 measured biomass and 16 measured yield components within at least one common experiment. In contrast, only five publications included physiological measurements alongside harvested yield. These differences indicate uneven coverage of potential agronomic pathways, particularly those involving plant physiological processes.

Strictly matched treatment–control comparisons provided sufficient publication-level evidence for exploratory associations between harvested yield and four additional endpoints (Fig. 8a). Aboveground potassium uptake showed a strong positive association with harvested yield (Spearman's $\rho = 0.905$; bootstrap 95% CI: 0.392 to 1.000; BH-adjusted $q = 0.008$; eight publications). Positive but statistically uncertain associations were observed for shoot dry biomass ($\rho = 0.491$; 95% CI: −0.400 to 0.827; $q = 0.299$; ten publications) and plant height ($\rho = 0.383$; 95% CI: −0.421 to 1.000; $q = 0.411$; nine publications). Aboveground potassium concentration showed little association with harvested yield ($\rho = 0.050$; 95% CI: −0.688 to 0.741; $q = 0.898$; nine publications). Other measured endpoints did not meet the minimum threshold of eight independent publications for correlation analysis.

Directional concordance provided complementary evidence (Fig. 8b). Increases in both harvested yield and aboveground potassium uptake occurred in seven of eight matched publications, while all ten publications with matched shoot dry biomass measurements showed increases in both outcomes. For plant height, six of nine publications showed concurrent increases, two showed decreases in both responses and one showed discordant responses. Concurrent increases in harvested yield and aboveground potassium concentration occurred in six of nine publications, with discordant responses in the remaining three. These findings indicate that improvements in harvested yield frequently accompanied greater potassium uptake and biomass accumulation, although the magnitude of these relationships differed across endpoints. The exploratory associations do not establish causal mediation, particularly because nutrient uptake may be partly dependent on biomass accumulation and the available matched evidence was limited to relatively few independent publications.

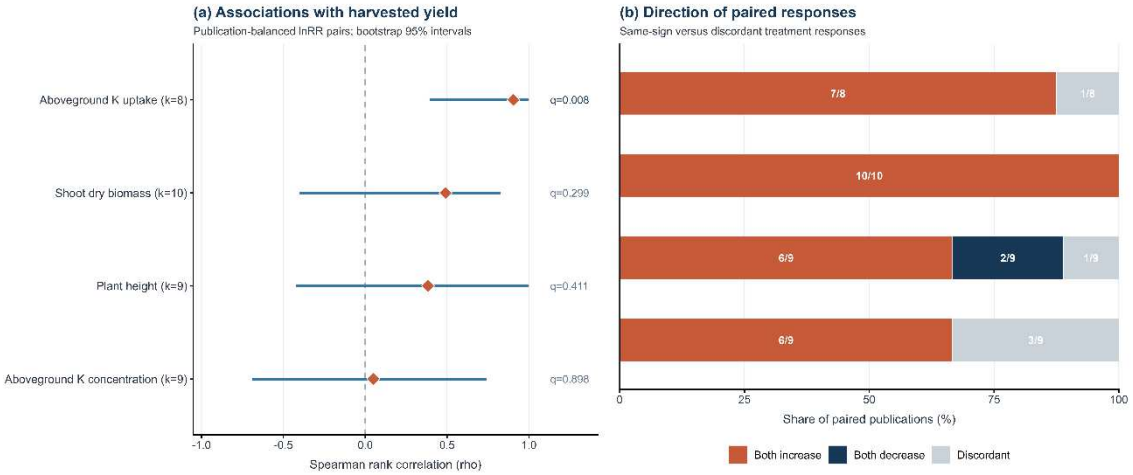


Figure 8. Exploratory associations and directional concordance between harvested yield and selected crop-performance responses under enhanced rock weathering. (a) Spearman rank correlations (ρ) between publication-balanced paired lnRR responses for harvested yield and aboveground potassium uptake, shoot dry biomass, plant height and aboveground potassium concentration. Orange diamonds represent correlation coefficients, and blue horizontal lines indicate bootstrap 95% confidence intervals based on publication-level resampling. Benjamini–Hochberg-adjusted q-values are displayed alongside the estimates. (b) Proportions of matched publications showing increases in both responses, decreases in both responses or discordant response directions. Numbers within bars indicate the corresponding publication counts. The number of independent publications (k) is given for each endpoint in panel (a). Only endpoints supported by at least eight independent publications were included. All associations are exploratory and should not be interpreted as evidence of causal mediation.

4. Discussion

4.1. Overall agronomic responses to enhanced rock weathering

The overall increase in harvested yield (+29.0%) and shoot dry biomass (+16.1%) provides evidence that silicate rock amendments can enhance agricultural productivity. However, the magnitude of the response warrants careful interpretation. The publication-balanced median yield increase was 14.8% across the broader descriptive evidence base and 14.6% among publications contributing to the variance-weighted analysis. The similarity between these descriptive estimates suggests that the availability of sampling variances did not substantially shift the central tendency of the represented publications. In contrast, the higher REML pooled estimate reflects a different statistical summary, influenced by the distribution and precision of treatment responses. Consequently, the estimated 29.0% increase should not be interpreted as the yield improvement expected from a typical field application.

Despite this distinction, the positive average effect was not limited to comparisons with reconstructed sampling variances. The positive effect persisted when the analysis was restricted to directly reported variances (+23.5%, 95% CI: +4.0% to +46.7%). Nevertheless, the substantial between-study heterogeneity (total $\tau^2 = 0.149$) and broad approximate 95% prediction interval (−43.4% to +194.0%) indicate considerable variability in potential outcomes. Thus, the evidence supports an overall agronomic benefit without establishing that ERW will improve productivity under all agricultural conditions. This distinction between a robust average response and uncertain local performance is particularly important when considering the application of rock amendments across heterogeneous agricultural landscapes.

The findings are broadly consistent with the regional meta-analysis of Swoboda et al. (2026), which reported increases of 33% in crop yield and 42% in aboveground biomass following silicate agromineral application in Brazil. Although the yield estimates are comparable, the larger biomass response in the Brazilian synthesis contrasts with the present global estimate. This discrepancy cannot be attributed to geographical conditions alone, because the analyses differ in experimental coverage, amendment classification and statistical structure, and their underlying studies may overlap. Moreover, the present evidence base contains a substantial concentration of Brazilian experiments, limiting the independence of any regional comparison. The agreement between the two yield estimates therefore supports the existence of positive agronomic responses across the represented studies, rather than demonstrating that a particular climate or soil environment consistently produces larger benefits.

An additional consideration is the distinction between harvested yield and vegetative growth. Their positive pooled responses indicate improvements in both agricultural production and biomass accumulation, but the larger numerical estimate for yield does not necessarily imply greater allocation of assimilates to harvestable organs. The two endpoints were not evaluated using identical sets of experiments, and their pooled effects should not be treated as a direct comparison of biomass partitioning. Importantly, changes in plant height, root biomass and leaf area were less consistent than those in harvested yield and shoot biomass. This suggests that agronomic improvements need not be accompanied by uniform morphological responses and reinforces the importance of evaluating harvested production separately from general plant growth.

4.2. Crop-specific variability in agronomic responses

The differences observed among crop species raise an important question: whether some crops are intrinsically more responsive to silicate rock amendments, or whether their apparent responses reflect the environments in which they have been studied. Rice, soybean and maize generally showed positive harvested-yield responses, whereas bread wheat exhibited a slightly negative median response. However, crop identity is closely associated with differences in soil fertility, climate, amendment mineralogy and experimental design. The available evidence therefore does not support a simple ranking of crops according to their responsiveness to ERW.

The relatively consistent positive response of rice is particularly interesting because the contributing experiments represent different agronomic conditions and silicate materials. In Malaysian acid sulphate soils, Panhwar et al. (2016) demonstrated that ground basalt could improve soil chemical conditions and rice production, with benefits developing over successive growing seasons. By contrast, Wang et al. (2024) reported a 12% increase in rice yield following wollastonite application to paddy fields in Northeast China, accompanied by increased soil pH, available silicon and plant silicon uptake. These studies suggest that improved rice productivity may arise through different processes, including alleviation of soil acidity, improved nutrient availability and silicon nutrition. Nevertheless, their relative contributions cannot be distinguished from crop identity alone. The broader rice response may therefore reflect the successful correction of specific soil constraints rather than a universally greater sensitivity of rice to silicate amendments. Other rice experiments have examined the effects of basalt on acid sulphate soils and plant nutrient acquisition, as well as the influence of different

wollastonite application doses on harvested production (Panhwar et al., 2014; Uchibayashi et al., 2025; Wang et al., 2027).

Maize and soybean also showed predominantly positive responses, but evidence from individual field trials illustrates the importance of site conditions and amendment persistence. Beerling et al. (2024) reported yield improvements in both crops following repeated basalt applications under a maize–soybean rotation in the United States Corn Belt. More substantial maize responses were documented by Oppong Danso et al. (2025) in Ghana, where a single application of 50 t ha^{-1} Greenlandic glacial rock flour increased grain yield across five successive growing seasons. In comparison, Gunnarsen et al. (2023) found that the same type of material improved crop production during the year of application in Denmark, but yield benefits did not persist in subsequent seasons. Although differences in experimental design prevent direct attribution, the contrast suggests that the duration and magnitude of crop responses may depend on initial nutrient limitations and subsequent nutrient supply. Consequently, positive responses in maize and soybean should not be assumed to be independent of soil fertility or amendment management. Additional experiments in Brazil have examined basalt-derived nutrient supply and the use of rock remineralisers in soybean, maize and sorghum production (Luchese et al., 2023; Rodrigues et al., 2024). Wollastonite application has also been evaluated for soybean productivity and potential trace-element accumulation (Wang et al., 2025).

The comparatively weak response of bread wheat provides a useful counterpoint. Bolland and Baker (2000) found that powdered granite was not an effective fertiliser for wheat in sandy soils of Western Australia, while Ramezanian et al. (2013) reported no observable benefit of volcanic rock dust for wheat growth or nutrient composition across three soil types. Similarly, Gunnarsen et al. (2023) found no residual yield improvement in spring wheat following earlier applications of glacial rock flour. These observations are consistent with the limited positive responses represented in the wheat evidence, but they do not demonstrate that wheat is inherently unresponsive to ERW. Rather, they indicate that the agronomic effectiveness of a silicate amendment depends on whether its mineral constituents become available in sufficient quantities and at appropriate times to address crop nutrient requirements. The small wheat evidence base and differences among the materials tested prevent stronger conclusions.

Italian ryegrass exhibited the largest descriptive median response among the five crop identities, although its evidence was limited to three publications involving controlled growing conditions. Priyono and Gilkes (2008) demonstrated that intensively milled gneiss improved ryegrass biomass production and potassium uptake, whereas milled K-feldspar was considerably less effective. More recently, Desmalles et al. (2025) found that basalt increased ryegrass production on potassium-deficient sandy soil but produced no significant biomass response on a contrasting loamy soil. These findings illustrate how mineral dissolution and initial soil nutrient status can determine the effectiveness of the same broad amendment strategy. Furthermore, forage production measured through repeated biomass harvests is not directly equivalent to grain yield, limiting the interpretation of ryegrass responses alongside cereal and legume crops. Earlier pasture and grass–clover experiments also demonstrated that changes in plant nutrient composition and dry-matter production do not necessarily occur in parallel following mineral amendment (Hanly et al., 2005; Dahlin et al., 2015).

Finally, the exploratory variance-weighted crop-specific estimates were higher than their corresponding descriptive medians for soybean and maize, but both had wide confidence intervals encompassing zero. This uncertainty reflects the limited number of independent publications available for crop-specific inference and reinforces the distinction between a consistent direction of response and a precisely estimated response magnitude.

4.3. Environmental and amendment-related variability

The considerable heterogeneity in crop responses suggests that the agronomic effectiveness of ERW depends on interactions between soil conditions, amendment characteristics and crop nutrient requirements. Although subgroup estimates varied across soil texture, initial pH, climate, rock family and experimental system, candidate moderator relationships remained uncertain at the level of independent publications (Table S7). Thus, the apparent differences between categories should not be interpreted as evidence that a particular environment or amendment consistently produces greater yield benefits. The weak association between harvested-yield response and application rate further indicates that increasing the quantity of rock applied does not necessarily result in proportional productivity gains. These findings point towards the importance of identifying the conditions under which mineral amendments alleviate specific agronomic constraints, rather than assuming a general response based on application rate or rock classification alone.

Initial soil pH is frequently considered a major determinant of silicate amendment effectiveness because mineral dissolution can neutralise acidity and modify nutrient availability. However, the exploratory positive association between initial pH and harvested-yield response in the dataset of the current study does not support the simple expectation that more acidic soils necessarily produce larger yield gains. This distinction is illustrated by contrasting field evidence. Beerling et al. (2024) reported improvements in soil fertility and crop productivity following basalt application in the United States Corn Belt, whereas Holden et al. (2024) observed increased soil pH and extractable magnesium and silicon without a corresponding sugarcane yield response in acidic tropical soil. Similarly, Desmalles et al. (2025) found that basalt improved ryegrass biomass production in potassium-deficient sandy soil but not in a contrasting loamy soil, despite measurable changes in soil chemistry. Collectively, these observations suggest that soil chemical improvement and crop response are not interchangeable outcomes. Initial soil pH alone is unlikely to capture the combined influences of nutrient limitation, mineral dissolution and crop demand. Recent evidence from highly weathered tropical soils also indicates that rock type and soil texture can shape microbial community responses and plant biomass production (Oliveira et al., 2025).

Rock mineralogy and particle characteristics provide another possible explanation for variable responses. Although silicate materials are commonly grouped into broad lithological categories, their nutrient composition and dissolution behaviour can differ considerably. Experiments with potassium-bearing silicate minerals have also demonstrated that mineral identity and processing conditions can substantially affect potassium availability and plant responses (Madaras et al., 2013; Ciceri et al., 2019). Priyono and Gilkes (2008), for example, found that intensively milled gneiss was substantially more effective than milled K-feldspar in supplying potassium to ryegrass, demonstrating that greater particle fineness does not necessarily compensate for

differences in mineral reactivity. Application rate may also interact with soil fertility and time since amendment. Oppong Danso et al. (2025) reported sustained maize yield improvements over five growing seasons following application of 50 t ha^{-1} glacial rock flour in Ghana, whereas the benefits of 10 t ha^{-1} diminished over time. By contrast, Gunnarsen et al. (2023) observed first-year yield improvements without persistent residual effects in subsequent seasons in Denmark. These examples indicate that amendment performance depends on the relationship between mineral nutrient release and crop requirements, rather than application rate alone. However, the limited reporting of particle-size distributions in the current dataset prevented a robust quantitative assessment of this potentially important factor. Multi-season experiments with alternative potassium sources in grain-crop systems have similarly demonstrated the importance of residual amendment effects (Soratto et al., 2021).

The interpretation of environmental moderators is further constrained by the uneven distribution of experimental evidence. Brazil accounted for 52 of the 113 publications in the descriptive dataset and 18 of the 52 publications contributing to variance-weighted analyses, while other agricultural regions were represented by substantially fewer studies (Table S8). Furthermore, experimental systems were not evenly distributed, and controlled-environment studies cannot necessarily reproduce the soil–plant interactions, weathering processes and management conditions encountered in agricultural fields. Even when initial soil properties were reported, information on particle size, amendment incorporation and changes in soil chemical conditions was less consistently available. Consequently, the present moderator results identify plausible sources of agronomic variability but do not provide a reliable basis for predicting yield responses across untested combinations of soil, climate, crop and rock characteristics. More informative comparisons would require coordinated experiments that vary amendment mineralogy and application rate across contrasting soils while maintaining consistent measurements of crop productivity and nutrient availability.

4.4. Nutrient acquisition and potential mechanisms underlying crop responses

The strong increase in aboveground potassium uptake (+36.5%) provides one of the clearest indications of a nutritional pathway potentially contributing to ERW-associated yield improvements. This interpretation is strengthened by the positive association between potassium uptake and harvested yield in the matched-response analysis (ρ = 0.905; q = 0.008), with both responses increasing in seven of eight publications. However, the corresponding relationship between yield and potassium concentration was negligible, despite a positive pooled concentration estimate. This distinction suggests that total nutrient acquisition may be more closely associated with productivity than nutrient concentration alone. Nevertheless, potassium uptake is commonly calculated as the product of tissue concentration and biomass, creating a mathematical dependence on plant growth. Greater uptake may therefore represent increased nutrient supply, increased biomass production or their combined effects. Experiments combining silicate rock powder with humic-like substances have likewise investigated nutrient uptake and plant growth in highly weathered tropical soils, highlighting the difficulty of separating individual amendment effects from broader changes in nutrient availability (Busato et al., 2022). The observed association supports potassium acquisition as a plausible component of the agronomic response but cannot establish it as an independent causal mechanism.

The primary experimental evidence suggests that nutrient supply and changes in soil chemical conditions may contribute through complementary pathways. The use of organically altered dacite rock powder in black oat and maize provides further experimental evidence that mineral processing and amendment composition influence nutrient release to crops (Ramos et al., 2021). Beerling et al. (2024) demonstrated that basalt weathering increased phosphorus and potassium release, improved soil pH and altered root nutrient-transport gene expression in maize and soybean. Importantly, increased potassium accumulation in soybean was associated with mineral nutrient release, whereas greater potassium content in maize grain was partly attributed to redistribution from vegetative tissues. This distinction illustrates that similar yield responses may arise through different nutrient-acquisition and allocation processes. Moreover, the absence of a comparable maize yield response to conventional liming in part of their experiment suggests that correcting soil acidity alone may not explain the benefits of basalt application. Similarly, Desmalles et al. (2025) attributed improved ryegrass production on potassium-deficient sandy soil to potassium supplied by basalt, while the response was absent on a contrasting soil. These findings favour a mechanism in which mineral dissolution alleviates specific nutritional constraints, potentially reinforced by changes in soil acidity and root nutrient acquisition, rather than a uniform fertilising or liming effect across agricultural systems.

The contrasting phosphorus response introduces an important qualification to this interpretation. Aboveground phosphorus concentration decreased by 12.4%, although this effect did not remain significant after correction for multiple testing ($q = 0.116$). A reduction in tissue concentration does not necessarily indicate a reduction in total phosphorus uptake or the development of phosphorus deficiency. Increased biomass production may dilute phosphorus concentrations, while changes in soil pH and mineral surfaces may simultaneously influence phosphorus solubility, sorption and plant availability. Desmalles et al. (2025) observed reduced ryegrass phosphorus concentrations and soil-extractable phosphorus following basalt application, without a corresponding significant reduction in total phosphorus uptake. Conversely, Beerling et al. (2024) reported increased phosphorus accumulation in harvested grain following basalt weathering. These contrasting observations suggest that phosphorus responses are sensitive to soil conditions and nutrient allocation, and that concentration-based measurements alone may obscure changes in nutrient acquisition. The positive response of aboveground calcium concentration (+7.0%) and less certain magnesium response (+6.7%) further indicate that ERW does not produce a uniform nutritional response across elements. Rather, the balance between nutrient supply, availability, uptake and plant demand is likely to determine whether changes in soil chemistry translate into improved crop production.

The relationship between vegetative growth and harvested yield provides complementary, although less conclusive, mechanistic evidence. All ten publications with strictly matched measurements of shoot dry biomass and harvested yield showed increases in both outcomes, but the correlation between their response magnitudes was statistically uncertain ($\rho = 0.491$; $q = 0.299$). Thus, greater biomass accumulation frequently accompanied improved harvested production without a consistent proportional relationship. Differences in biomass partitioning, reproductive development and nutrient allocation may contribute to this variability, but these processes could not

be isolated using the available evidence. Furthermore, although numerous experiments measured plant nutrients alongside yield, only five publications jointly reported physiological outcomes, and the curated data did not support direct matching of soil chemical changes with subsequent plant responses. Niron et al. (2026) also investigated the combined effects of basalt, microbial inoculation and soil moisture on maize physiology and nutrient uptake, illustrating the importance of evaluating environmental interactions alongside nutritional responses. The combined evidence therefore supports a plausible sequence in which mineral dissolution modifies soil chemical conditions and nutrient availability, potentially enhancing nutrient acquisition, vegetative growth and harvested production, but does not establish the causal links between these stages. Resolving these pathways will require experiments that simultaneously quantify mineral dissolution, soil nutrient availability, plant nutrient concentrations and total uptake, biomass allocation and harvested yield under matched treatments, including appropriate liming and nutrient-fertilisation controls.

4.5. Evidence representativeness, uncertainty and implications for ERW deployment

A central limitation of the available evidence is the difference between the number of reported experimental observations and the number of independent publications supporting statistical inference. Although 113 publications contributed to the broader descriptive synthesis, only 52 provided eligible comparisons for variance-weighted analyses. Among Brazilian experiments, 18 independent publications contributed to the weighted synthesis across all endpoints, of which only six contributed to the harvested-yield model, although these six publications accounted for 47 treatment–control comparisons. This illustrates why the apparent abundance of experimental comparisons should not be equated with independent replication. Multiple amendment rates, crop varieties and repeated measurements can provide valuable information, but they may share controls or experimental conditions and therefore cannot be treated as statistically independent observations. Accounting for this dependence is essential for avoiding overstated precision when assessing agronomic benefits.

The geographical scope of the synthesis also requires careful interpretation. Although the included publications originated from several continents, their distribution across agricultural environments was uneven, and field experiments were frequently combined with controlled-environment studies. This distinction matters because mineral dissolution, root development, nutrient transport and crop growth are influenced by environmental conditions that may differ substantially between experimental systems. The absence of consistently significant moderator relationships does not imply that these environmental factors are unimportant. Rather, the limited number of independent publications within some categories, together with correlated soil, crop and amendment characteristics, restricts the ability to distinguish their individual contributions. Consequently, the pooled estimates cannot be directly extrapolated to agricultural regions or management systems that remain poorly represented in the experimental literature.

Incomplete reporting of experimental characteristics and precision estimates represents a further limitation. Although baseline soil pH and broad rock classifications were frequently available, quantitative particle-size information was reported in only ten of the

113 descriptive publications, and several potentially important soil and amendment properties could not be evaluated consistently. Similarly, the absence of usable measures of dispersion prevented some otherwise relevant treatment responses from contributing to inverse-variance-weighted inference. This difficulty is particularly important for comparisons with other quantitative syntheses, because differences in study eligibility, variance reconstruction, treatment–control matching and statistical dependence can influence pooled estimates even when the underlying literature overlaps. The separation of descriptive and variance-weighted evidence in the present analysis therefore provides a transparent account of both the available observations and the more restricted evidence supporting statistical inference, rather than assuming that all reported comparisons carry equivalent precision.

For practical deployment, improved crop productivity should be considered a potential co-benefit of ERW rather than an assured outcome of rock application. Agronomic benefits and verified CO_2 removal represent distinct outcomes that require separate assessment, particularly because measurable mineral weathering does not necessarily translate into additional harvested production. Their joint evaluation should account for soil and crop suitability, mineral reactivity, amendment costs, nutrient balance, potential environmental consequences and uncertainty in carbon-removal quantification (Levy et al., 2024; Gholamahmadi, 2026). Experimental comparisons of basalt, concrete fines and steel slag have also examined potential trace-element accumulation in maize, reinforcing the need to assess amendment safety alongside agronomic performance (Rijnders et al., 2025). Future research should therefore prioritise coordinated multi-site field experiments that compare rock materials across contrasting soils and crops, incorporate appropriate fertilisation and liming controls, and monitor agronomic and geochemical responses over successive growing seasons. Standardised reporting of experimental replication, dispersion statistics, amendment mineralogy and particle-size distributions would further improve the reliability and transferability of future syntheses. Such evidence is essential for identifying the conditions under which ERW can deliver reproducible agricultural benefits alongside independently verified CO_2 removal.

5. Conclusions

This global meta-analysis demonstrates that silicate rock amendments associated with enhanced rock weathering can improve crop productivity, with a pooled harvested-yield increase of 29.0% alongside positive responses in shoot dry biomass and aboveground potassium uptake. However, the lower publication-balanced median yield response and substantial between-study heterogeneity indicate that the pooled effect should not be interpreted as the expected benefit under typical agricultural conditions. Crop-specific responses were variable, and the available evidence did not establish consistent environmental or amendment-related predictors of yield improvement.

The association between potassium uptake and harvested yield suggests that improved nutrient acquisition may contribute to agronomic responses, although the available paired observations cannot establish a causal mechanism. Differences between nutrient uptake and tissue nutrient concentrations further indicate that changes in plant nutrition do not necessarily translate proportionally into harvested production. More broadly, the limited number of independent publications supporting individual crop and moderator estimates constrains the transferability of these findings across agricultural systems.

Future research should prioritise coordinated, multi-season field experiments across contrasting soil and climatic conditions, with explicit comparisons of amendment mineralogy, application rates and appropriate fertilisation and liming controls. Concurrent measurements of mineral dissolution, soil nutrient availability, plant nutrient acquisition and harvested yield are essential for identifying the processes responsible for productivity gains. Ultimately, ERW offers a promising potential agronomic co-benefit, but its practical value depends on demonstrating reproducible improvements under specific agricultural conditions, independently of verified CO_2 removal.

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