

# 1 **Impacts of enhanced rock weathering on soil sponge function: a** 2 **global synthesis of soil physical and hydrological responses**

3 Behrouz Gholamahmadi <sup>ab</sup>, Lucilla Boito <sup>c</sup>, Laura Steinwider <sup>c</sup>, Sara Vicca <sup>c</sup>

4 <sup>a</sup> Centre for Environmental and Marine Studies (CESAM), Department of Environment and  
5 Planning, University of Aveiro, Aveiro, Portugal

6 <sup>b</sup> Department of Research and Development, Ibero Massa Florestal S.A., Oliveira de Azeméis,  
7 Portugal

8 <sup>c</sup> Biobased Sustainability Engineering (SUSTAIN), Department of Bioscience Engineering,  
9 University of Antwerp, Antwerp, Belgium

10 Correspondence: Behrouz Gholamahmadi (behrouzg@ua.pt); Sara Vicca  
11 (sara.vicca@uantwerpen.be)

## 12 **Abstract**

13 Enhanced rock weathering (ERW) involves the application of finely ground  
14 silicate minerals to soils, where mineral dissolution can alter soil chemistry,  
15 structure, and hydrological functioning. While ERW research has largely focused  
16 on geochemical CO<sub>2</sub> removal, its effects on soil physical and hydrological  
17 properties remain poorly constrained. Here, we present the first structured  
18 evidence synthesis evaluating whether ERW modifies components of the soil  
19 sponge function, defined as the capacity of soils to infiltrate, store, redistribute,  
20 and gradually release water. A systematic literature search identified 17 studies  
21 comprising 261 treatment–control observations. Relative changes were  
22 calculated for key soil physical and hydrological variables and classified as  
23 increase, decrease, or no change using a  $\pm 5\%$  threshold. Given the  
24 heterogeneity of experimental designs and non-independence of observations  
25 within studies, results were interpreted descriptively and primarily at the study  
26 level. ERW effects were variable across soil properties. Bulk density had no  
27 median response (0.0%; n = 72 observations from 10 studies), while aggregate  
28 stability had a weak positive response (+1.9%; n = 35 from 6 studies). Penetration  
29 resistance declined (−18.1%), but this response was based on one study only.  
30 Soil water indicators provided modest evidence for increased storage capacity,  
31 with positive responses in field capacity (+9.4%; n = 23 from 5 studies) and plant  
32 available water (+10.1%; n = 15 from 3 studies), but only a small increase in soil  
33 moisture (+4.4%; n = 21 from 4 studies). Hydraulic responses were mixed:  
34 saturated hydraulic conductivity declined (−27.5%; n = 10 from 2 studies),  
35 porosity declined (−6.3%; n = 34 from 7 studies), and infiltration rate had no  
36 median response (0.0%; n = 13 from 3 studies). Overall, available data suggest  
37 that ERW does not uniformly enhance the soil sponge function; its effects are  
38 context-dependent, and the apparent contrast between increased water-storage  
39 indicators and reduced flow-related properties may reflect differences among  
40 study contexts because these variables were not consistently co-measured within  
41 the same experiments.

42 **Keywords:** enhanced rock weathering (ERW); soil hydrology; water retention;  
43 hydraulic conductivity; soil structure; carbon dioxide removal (CDR)

#### 44 **1. Introduction**

45 Enhanced rock weathering (ERW) is increasingly recognised as a promising soil-  
46 applied carbon dioxide removal (CDR) strategy, but its effectiveness depends on  
47 factors beyond mineral dissolution alone. Although ERW is commonly discussed  
48 through the lens of alkalinity generation and CO<sub>2</sub> removal (Hartmann et al., 2013),  
49 its deployment occurs within structured, biologically active soils rather than inert  
50 reaction vessels. Soil pore architecture, water availability, root activity, microbial  
51 processes, and the spatial distribution of rock particles regulate mineral  
52 weathering, alkalinity generation, porewater transport, and the soil functions that  
53 determine plant growth, carbon cycling, and hydrological resilience (Hartmann et  
54 al., 2013; Taylor et al., 2016; Beerling et al., 2018; Goll et al., 2021; Schiedung et  
55 al., 2026).

56 A useful framework for evaluating these effects is the soil sponge function,  
57 defined as the capacity of soils to infiltrate, store, redistribute, and gradually  
58 release water, thereby buffering hydrological extremes, sustaining plant water  
59 availability, and reducing rapid water losses (Gholamahmadi et al., 2025a). The  
60 soil sponge function emerges from interactions among soil structure, aggregate  
61 stability, pore-size distribution, water retention, hydraulic conductivity, root  
62 activity, and surface protection (Gholamahmadi et al., 2025b). This function is  
63 therefore not captured by a single measurement. Rather, it is reflected in a suite  
64 of physical and hydrological indicators, including bulk density, aggregate stability,  
65 penetration resistance, porosity, soil moisture, field capacity, permanent wilting  
66 point, plant-available water, infiltration rate, and saturated and unsaturated  
67 hydraulic conductivity (Jha et al., 2023).

68 Changes in soil structure and hydrology can generate both soil-fertility co-benefits  
69 and physical trade-offs. Increased aggregate stability, field capacity, or plant  
70 available water could improve soil workability, drought buffering, and crop water  
71 supply, while reduced penetration resistance could facilitate root growth and  
72 access to deeper soil resources. Conversely, reduced porosity, macropore  
73 connectivity, or saturated hydraulic conductivity could restrict drainage, gas  
74 exchange, and root-zone aeration. Physical and hydrological changes may also  
75 affect carbon cycling because soil moisture, aggregation, mineral surfaces, and  
76 pore connectivity regulate microbial activity, root inputs, organic matter  
77 decomposition, and mineral-associated organic carbon formation (Buss et al.,  
78 2024; Boito et al., 2025; Xu et al., 2025). Recent ERW experiments further show  
79 that silicate amendments can shift organic carbon towards more stable  
80 aggregate- and mineral-associated pools, even when inorganic CO<sub>2</sub> removal  
81 remains limited (Steinwider et al., 2025).

82 ERW could influence soil sponge function through direct physical effects of rock  
83 powder addition. Finely ground silicate particles may alter soil particle-size  
84 distribution, packing density, pore-size distribution, and pore connectivity.  
85 Depending on initial soil texture, amendment rate, grain size, incorporation depth,  
86 and management, added particles may increase fine pore fractions and water  
87 retention, or occupy conducting pores and reduce effective macropore continuity  
88 (Zhu et al., 2025; Akortey et al., 2026). This is particularly relevant because  
89 proposed ERW application rates typically exceed conventional liming rates,  
90 raising concerns about compaction, pore clogging, restricted aeration, and  
91 altered water movement (Schiedung et al., 2026).

92 ERW may also affect soil physical functioning through geochemical and  
93 biogeochemical pathways. Weathering releases base cations such as  $\text{Ca}^{2+}$  and  
94  $\text{Mg}^{2+}$ , modifies pH and cation exchange processes, and can influence nutrient  
95 availability, secondary mineral formation, and soil organic matter stabilisation  
96 (Hartmann et al., 2013; Beerling et al., 2018, 2024, 2025; Goll et al., 2021; Xu et  
97 al., 2025). These changes may impact soil structure through cation bridging, clay  
98 formation, flocculation, microbial activity, root growth, and organo-mineral  
99 interactions, thereby affecting aggregation and pore organisation (Angers and  
100 Caron, 1998; Kleber et al., 2021; Slessarev et al., 2022; Buss et al., 2024; Xu et  
101 al., 2025).

102 Biological controls further complicate ERW effects on soil structure and  
103 hydrology. Plants can stimulate weathering through rhizosphere  $\text{CO}_2$ , proton  
104 release, organic ligands, nutrient uptake, and root-driven modification of soil  
105 structure (Hinsinger, 1998; Harley and Gilkes, 2000; Dontsova et al., 2020; Boito  
106 et al., 2025). Effects of ERW on roots, earthworms, and other soil biota can also  
107 alter pore architecture through biopore formation, aggregate stabilisation, particle  
108 redistribution, water uptake, and organic matter dynamics (Angers and Caron,  
109 1998; Blouin et al., 2013; Vicca et al., 2022; Vienne et al., 2024). Hence, ERW  
110 effects may depend strongly on whether experiments include plants, soil fauna,  
111 and realistic wetting–drying cycles. For instance, Boito et al. (2025) indicated that  
112 basalt effects on soil water content and carbon fluxes varied with plant presence,  
113 earthworms, and experimental period, illustrating that ERW responses can be  
114 mediated by biotic context rather than feedstock alone.

115 Hydrology is central to ERW in two directions. First, water is required for mineral  
116 dissolution, porewater transport, and the export or retention of weathering  
117 products. Weathering rates and inorganic  $\text{CO}_2$  removal depend on soil moisture,  
118 vertical water fluxes, flow paths, porewater residence time, leaching, and whether  
119 soil solution remains far from equilibrium (Cipolla et al., 2021a, 2021b; Bertagni  
120 et al., 2025; Beerling et al., 2025). Second, the addition of rock powder may itself  
121 modify the pore system that controls water storage and movement. Recent soil-  
122 physics-based modelling has shown that the wet reactive surface area of rock  
123 powder is not necessarily equal to total applied surface area, but depends non-

124 linearly on soil moisture, pore-size distribution, particle-size distribution, and the  
125 degree of mixing between rock particles and soil pores (Anand et al., 2026).

126 Therefore, ERW-driven changes in soil physical properties may influence CO<sub>2</sub>  
127 removal pathways by modifying water–rock contact, porewater saturation states,  
128 alkalinity transport, and the balance between inorganic and organic carbon  
129 responses. This creates a strong conceptual link between ERW performance and  
130 soil sponge function: the same pore architecture that regulates water–rock  
131 contact also regulates infiltration, storage, drainage, aeration, and plant water  
132 supply.

133 So far, ERW research and synthesis have focused mainly on CO<sub>2</sub> removal,  
134 weathering rates, soil chemistry, nutrient release, crop yield, and carbon pools  
135 (Hartmann et al., 2013; Beerling et al., 2020, 2024, 2025; Clarkson et al., 2024;  
136 Xu et al., 2025; Schiedung et al., 2026). Recent reviews emphasise that ERW  
137 deployment remains uncertain because outcomes depend, among other factors,  
138 on feedstock properties, particle size, soil properties, hydrological conditions,  
139 biological activity, and downstream loss pathways (Beerling et al., 2025; Buma et  
140 al., 2026; Schiedung et al., 2026). Soil physical and hydrological conditions are  
141 especially relevant because they can mediate water–rock contact, leaching,  
142 porewater saturation states, plant water availability, and carbon cycling.

143 However, the evidence remains fragmented: individual studies report variables  
144 such as bulk density, aggregate stability, soil moisture, field capacity, water  
145 retention, infiltration, porosity, or hydraulic conductivity, but these measurements  
146 are rarely combined within the same experiment. This fragmentation hinders a  
147 clear understanding of how ERW affects soil physical and hydrological properties,  
148 and whether observed responses reflect consistent mechanisms or study-specific  
149 outcomes. This is particularly important because individual variables are often  
150 reported across different soils, feedstocks, durations, depths, and experimental  
151 systems, making it difficult to determine whether apparent patterns represent  
152 within-study responses or cross-study contrasts. Therefore, assessing ERW  
153 through soil sponge function provides a structured way to connect soil physics,  
154 hydrology, plant growth, and carbon dynamics while identifying where the  
155 evidence is strongest and where uncertainty remains highest.

156 Here, we provide a first synthesis of experimental studies assessing ERW effects  
157 on soil physical and hydrological properties. We evaluated three hypotheses.  
158 First, we expected ERW effects on soil structure to be more detectable in  
159 functional indicators such as aggregate stability and penetration resistance than  
160 in bulk density, because pore- and aggregate-scale changes may occur without  
161 significant shifts in whole-soil packing. Second, we expected ERW to increase  
162 water-storage indicators, including field capacity and plant available water, if rock  
163 additions increase fine pore fractions, aggregation, or mineral-associated water  
164 retention. Third, we expected ERW to alter flow-related properties such as

165 infiltration rate and hydraulic conductivity, but not necessarily in the same  
166 direction as storage-related variables, because increased storage and reduced  
167 macropore connectivity may occur simultaneously.

168 By synthesising evidence from 17 studies and 261 treatment–control  
169 observations, we assess whether ERW modifies key components of soil sponge  
170 function and identify priorities for future experiments.

## 171 **2. Methods**

### 172 **2.1 Literature search and data collection**

173 A systematic literature search was conducted using the Scopus database,  
174 following the PRISMA guideline (See Supplementary Figure S1), with a cutoff  
175 date of February 2026. The search string combined terms related to enhanced  
176 rock weathering (ERW), including “enhanced rock weathering”, “enhanced  
177 weathering”, “enhanced silicate weathering”, and “enhanced mineral weathering”,  
178 together with terms describing soil physical and hydrological properties:

179 *("enhanced rock weathering" OR "enhanced weathering" OR "enhanced silicate*  
180 *weathering" OR "enhanced mineral weathering" OR "rock dust" OR "rock*  
181 *powder" OR "rock flour" OR "rock amendment" OR basalt OR "basalt dust" OR*  
182 *"basalt powder" OR olivine OR wollastonite OR "silicate rock" OR "ground silicate*  
183 *rock" OR "silicate amendment" OR "mineral amendment" OR "stone meal" OR*  
184 *stonemeal OR remineralization OR remineralisation) AND soil AND ("bulk*  
185 *density" OR porosity OR infiltration OR "hydraulic conductivity" OR "water*  
186 *retention" OR "water holding capacity" OR "water retention curve" OR "soil*  
187 *moisture" OR "aggregate stability" OR "soil structure" OR "penetration*  
188 *resistance")*

189 The initial search returned 519 records. After restricting to peer-reviewed articles,  
190 452 records remained. Filtering to English-language publications resulted in 419  
191 records. Including additional ERW-related search terms did not yield further  
192 studies meeting the inclusion criteria after screening.

### 193 **2.2 Screening and eligibility criteria**

194 A two-stage screening process was applied. First, titles and abstracts were  
195 screened to identify studies reporting soil applications of rock or silicate  
196 amendments, resulting in 389 records considered potentially relevant for full-text  
197 assessment. Studies were retained if they met the following criteria: i. reported  
198 experimental application of rock or silicate materials to soil (field, greenhouse,  
199 pot, or mesocosm), ii. included at least one soil physical or hydrological variable,  
200 iii. provided extractable treatment–control comparisons. Target variables were  
201 grouped into three functional categories: i. Soil structure (e.g., bulk density,  
202 aggregate stability, penetration resistance), ii. Soil water (e.g., soil moisture  
203 including normalised water content, field capacity, permanent wilting point, plant

204 available water), iii. Soil hydraulic behaviour (e.g., infiltration rate, saturated and  
 205 unsaturated hydraulic conductivity). Equivalent measurements were harmonised  
 206 into these categories (e.g., different expressions of aggregate stability or soil  
 207 water content), with full definitions provided in Table 1. Soil texture (sand, silt,  
 208 clay) was retained as contextual information where reported.

### 209 2.3 Study selection and data extraction

210 Following title and abstract screening, 389 records were retained for full-text  
 211 assessment. Of these, 43 studies were initially retained as potentially eligible for  
 212 extraction. One study was excluded because it was a meta-analysis rather than  
 213 an experimental study, resulting in 42 studies eligible for data extraction. Data  
 214 were extracted manually from the main text, tables, figures, and supplementary  
 215 materials, focusing on treatment–control comparisons for the predefined soil  
 216 physical and hydrological variables. A controlled vocabulary was applied to  
 217 harmonise variable names across studies, and functionally equivalent  
 218 measurements were grouped into standardised variable categories (Table 1).  
 219 Observations were excluded when they did not match the predefined variables,  
 220 lacked compatible treatment–control values, or were reported only as relative  
 221 changes, statistical contrasts, or non-comparable formats.

222 Table 1. Definition and harmonisation of soil physical and hydrological variables included in the  
 223 synthesis

Variable	Definition	Unit	Measurement condition	Category
Aggregate stability	Resistance of soil aggregates to disintegration under external forces (e.g. wet sieving)	% or index	Typically measured under wet sieving or rainfall simulation	Soil structure
Bulk density	Mass of dry soil per unit volume, including pore space	g cm <sup>-3</sup>	Oven-dried soil, core method	Soil structure
Penetration resistance	Mechanical resistance of soil to penetration, indicating compaction and strength	MPa or kPa	Field or lab penetrometer, moisture-dependent	Soil structure
Soil moisture	Volumetric water content, including normalised water content, e.g. fraction of water-holding capacity	vol-%	In situ or controlled conditions (e.g. sensors, gravimetric conversion)	Soil water
Field capacity	Water content retained in soil after drainage at approximately -33 kPa matric potential	vol-%	Laboratory water retention curve or field approximation	Soil water
Permanent wilting point	Water content at which plants cannot extract water ( $\approx -1500$ kPa)	vol-%	Laboratory water retention curve	Soil water
Plant available water	Difference between field capacity and permanent wilting point	vol-%	Derived from retention curve measurements	Soil water
Water retention (-100 kPa)	Soil water content at -100 kPa matric potential	vol-%	Laboratory water retention curve	Soil water

Residual water content	Water content remaining in soil at low matric potentials often represents tightly bound water	vol-%	Laboratory retention curve (model-derived or measured)	Soil water
Porosity	Fraction of total soil volume occupied by pores	%	Calculated from bulk density and particle density or measured directly	Soil hydraulics
Infiltration rate	The rate at which water enters the soil surface	mm h <sup>-1</sup> or cm h <sup>-1</sup>	Field infiltration tests (e.g. ring infiltrometer)	Soil hydraulics
Saturated hydraulic conductivity	Water flow capacity of soil under saturated conditions	cm h <sup>-1</sup> or mm h <sup>-1</sup>	Laboratory or field measurements under saturation	Soil hydraulics
Unsaturated hydraulic conductivity	Water flow capacity under unsaturated conditions, dependent on soil water content	cm h <sup>-1</sup> or mm h <sup>-1</sup>	Laboratory or model-derived from retention data	Soil hydraulics

224 After quality control and filtering, the final dataset comprised 17 independent  
225 studies and 261 treatment–control observations. The dataset is organised at the  
226 experiment level rather than publication level, such that multiple observations  
227 (e.g., depths, time points) from the same study are retained but not treated as  
228 independent in the interpretation. Study-by-variable coverage is provided in Table  
229 S1, which shows the number of treatment–control observations extracted for  
230 each variable from each included study. The characteristics of the included  
231 studies are summarised in Table 2, and the global distribution of studies is  
232 provided in Figure 1.

**Global evidence of ERW effects on soil physical and hydrological properties**  
Interactive map of the 17 independent studies included in the synthesis.



233 Source: Gholamzadeh, Bolo, Steinwider & Vicco, "Impacts of enhanced rock weathering on soil sponge function: a global synthesis of soil physical and hydrological responses" - Created with Datawrapper

234 Figure 1. Global distribution of studies included in the synthesis. Pins indicate unique locations  
235 for the 17 independent studies. Yang et al. (2025) and Zhu et al. (2025) conducted their study in  
236 the same location in Japan. The study locations from Obour et al. (2024) and Akortey et al. (2026)  
237 in Ghana were close to each other. An interactive version provides study-level metadata, including  
238 study citation, DOI and geographic coordinates. Link: <https://datawrapper.dwcdn.net/nQY1B/1/>

239 Table 2. Characteristics of the 17 studies included in this synthesis, including geographic location, experimental system, soil texture, rock amendment type, and  
 240 application conditions. Variables are grouped into soil structure (e.g., bulk density, aggregate stability, penetration resistance), soil water status (e.g., soil  
 241 moisture, field capacity, plant available water), and soil hydraulic behaviour (e.g., infiltration rate, hydraulic conductivity). This table provides context for  
 242 interpreting variability in responses across studies. NR = not reported. Variables (last column) indicate whether each study reported measurements related to  
 243 soil structure, soil water, and/or soil hydraulic behaviour. The full dataset is available in the supplementary materials.

Study	Country	Experimental system	Soil texture (USDA)	Rock type	Application rate (t ha <sup>-1</sup> )	Incorporation depth (cm)	Duration (days)	Variables: structure/water/hydraulic	
Akortey et al. (2026)	Ghana	greenhouse	sand/sandy loam/sandy clay loam/clay	glacial flour	rock	50–100	0–15	120	yes/yes/yes
Yang et al. (2025)	Japan	field	loam	basalt		150	0-20	125	no/yes/no
Zhu et al. (2025)	Japan	field	clay loam	basalt		150	0-20	187	yes/yes/yes
Zhou et al. (2025)	China	lab	clay	schist		NR	0–15	240	yes/yes/yes
Pihlap et al. (2025)	USA	field	silt loam	basalt		280	0-20	2190	yes/yes/yes
Boito et al. (2025)	Belgium	mesocosm	sandy loam	basalt		50	0-20	456	no/yes/no
Richardson et al. (2025)	USA	field	silt loam/sandy loam	basalt		6.7	0-25	730 and 2190	yes/no/no
Armah et al. (2025)	Canada	greenhouse	loam	rock dust		NR	NR	730	yes/yes/yes
Costanzo et al. (2025)	USA	field	silt loam	metabasalt		40.3	0-10	1095	yes/yes/yes

Obour et al. (2024)	Ghana	pot/field	sand/sandy loam/sandy clay loam	glacial flour	rock	10–50	0-15	610	yes/no/no
Medeiros et al. (2024)	Brazil	field	sandy loam/clay loam	gneiss		9.5	0-20	730	no/yes/no
Oladele et al. (2024)	Nigeria	field	sandy loam/silt loam	granite		3–10	0-15	120	yes/no/yes
Dupla et al. (2024)	Switzerland	field	loam	basalt		20	0-10	30	yes/no/yes
Chiaravalloti et al. (2023)	USA	mesocosm	sandy loam	basalt		11.2	0-10	24 and 29	no/yes/no
Pavlu et al. (2021)	Czech Republic	field	sandy loam	basalt		NR	NR	1460	yes/yes/yes
Kelland et al. (2020)	UK	mesocosm	clay loam	basalt		100	0-25	120	no/no/yes
Naseri et al. (2019)	Germany	lab	sand/sandy loam	basalt		NR	0-15	NR	yes/no/yes

244 Note: The experimental system follows the terminology and experimental components used in the original studies. Where studies included more than one  
245 experimental component, the system listed reflects the component from which the extracted observations were taken. “Pot” refers to container-based  
246 experiments with individual soil–plant units, whereas “mesocosm” refers to larger controlled experimental units designed to represent more complex soil–  
247 plant–biota interactions or more realistic soil environmental conditions.

## 248 **2.4 Data processing and standardisation**

249 Units were harmonised across studies to ensure comparability of soil physical  
250 and hydrological variables. For each observation, a relative change (RC, %)  
251 between treatment and control was calculated as:

$$252 \quad RC (\%) = \left( \frac{\text{Mean treatment} - \text{Mean control}}{\text{Mean control}} \right) \times 100$$

253 To enable consistent comparison across heterogeneous studies, responses were  
254 classified into three categories using a predefined threshold of  $\pm 5\%$ :

- 255 i. increase: relative change  $> +5\%$
- 256 ii. decrease: relative change  $< -5\%$
- 257 iii. no change:  $-5\% \leq \text{relative change} \leq +5\%$

258 This threshold-based classification provides a consistent and transparent way to  
259 describe response direction across studies, but does not account for variance or  
260 statistical significance and is therefore used for descriptive purposes only. For  
261 each variable, the following summary metrics were calculated:

- 262 i. median relative change (%)
- 263 ii. number of observations (n), and number of studies
- 264 iii. counts and percentages of increase, decrease, and no change

265 These metrics provide complementary descriptions of response magnitude,  
266 through the median relative change, and response direction, through the  
267 categorical distribution.

## 268 **2.5 Variance data**

269 Variance information (standard deviation or standard error) was recorded when  
270 available. When standard error (SE) was reported, it was converted to standard  
271 deviation (SD) using:

$$272 \quad SD = SE \times \sqrt{n}$$

273 Variance data were not consistently reported across studies and were therefore  
274 not used for weighting or statistical inference. Because of the limited number of  
275 studies, all observations were retained in the analysis regardless of variance  
276 availability. This synthesis is therefore based on descriptive metrics (relative  
277 change and categorical classification) rather than variance-weighted effect sizes.  
278 Variance information is reported where available to support transparency and to  
279 facilitate future meta-analytical work. For studies with missing variance  
280 information, corresponding authors were contacted where possible; however, no  
281 additional variance data were received before finalising the synthesis.

## 282 **2.6 Analytical approach**

283 Given the limited number of studies, heterogeneity in experimental designs, and  
284 inconsistent reporting of variance, a quantitative meta-analysis could not be  
285 performed. Instead, a structured evidence synthesis was adopted. This approach  
286 combines: i) median relative change as a measure of central tendency, and ii)  
287 categorical classification of responses (increase, decrease, no change) to  
288 describe response direction. Because multiple observations may originate from  
289 the same study (e.g. different depths or time points), observations are not  
290 statistically independent. Therefore, results are not interpreted at the individual  
291 observation level but rather used to identify general patterns across studies. This  
292 framework provides a transparent and consistent summary of the available but  
293 heterogeneous evidence.

## 294 **3. Results**

### 295 **3.1 Dataset overview**

296 The final dataset comprised 17 independent studies and 261 treatment–control  
297 observations, including repeated measurements across depths, time points,  
298 treatments, and experimental contexts, evaluating the effects of enhanced rock  
299 weathering (ERW) on soil physical and hydrological properties. Study coverage  
300 varied strongly among variables. Bulk density, porosity, and aggregate stability  
301 were the most widely represented variables, each reported in at least six studies.  
302 Soil water variables, including field capacity, permanent wilting point, plant  
303 available water, and soil moisture, were less consistently reported across studies.  
304 Field capacity, permanent wilting point, and plant available water were treated as  
305 water-retention characteristics, whereas soil moisture referred to observed or  
306 normalised water content during the experiment.

307 Hydraulic variables such as infiltration rate and saturated hydraulic conductivity  
308 were also sparsely represented. Some variables, including residual water  
309 content, unsaturated hydraulic conductivity, water retention at  $-100$  kPa,  
310 penetration resistance, and saturated hydraulic conductivity, were available from  
311 only one or two studies (Table 3; Table S1). Because the synthesis is descriptive  
312 and based on uneven study coverage, all responses should be interpreted as  
313 preliminary patterns rather than definitive ERW effects. Variables represented by  
314 only one or two studies identify especially important evidence gaps where further  
315 research is needed.

316 Table 3. Summary of ERW effects on soil physical and hydrological variables. Median change (%)  
317 indicates the median relative change in each variable under ERW compared with the control.  
318 Observations (n) indicate the number of extracted treatment–control comparisons, while studies  
319 indicate the number of independent studies contributing to each variable. The increase, decrease,  
320 and no change columns describe the directional distribution of observations, calculated using the  
321  $\pm 5\%$  threshold. For example, aggregate stability had a median relative change of  $+1.9\%$ , while  
322  $37\%$  of observations were classified as increases,  $26\%$  as decreases, and  $37\%$  as no change.  
323 Variables represented by one or two studies should be interpreted as evidence gaps rather than

324 general ERW responses. Unsaturated hydraulic conductivity is reported for transparency but was  
 325 not interpreted further because comparison depends strongly on the measurement water content  
 326 and matric potential.

Variable	Category	Median change (%)	Studies	Observations (n)	Increase (%)	Decrease (%)	No change (%)
Aggregate stability	Soil structure	+1.9	6	35	37	26	37
Bulk density	Soil structure	0.0	10	72	22	26	51
Penetration resistance	Soil structure	-18.1	1	10	0	90	10
Soil moisture	Soil water	+4.4	4	21	48	24	29
Field capacity	Soil water	+9.4	5	23	57	13	30
Plant available water	Soil water	+10.1	3	15	67	0	33
Permanent wilting point	Soil water	+2.6	3	15	40	20	40
Water retention	Soil water	-4.0	1	5	0	40	60
Residual water content	Soil water	+12.5	2	3	100	0	0
Porosity	Soil hydraulics	-6.3	7	34	12	53	35
Infiltration rate	Soil hydraulics	0.0	3	13	31	46	23
Saturated hydraulic conductivity	Soil hydraulics	-27.5	2	10	10	90	0
Unsaturated hydraulic conductivity	Soil hydraulics	+125	1	5	100	0	0

### 327 **3.2 Soil structure**

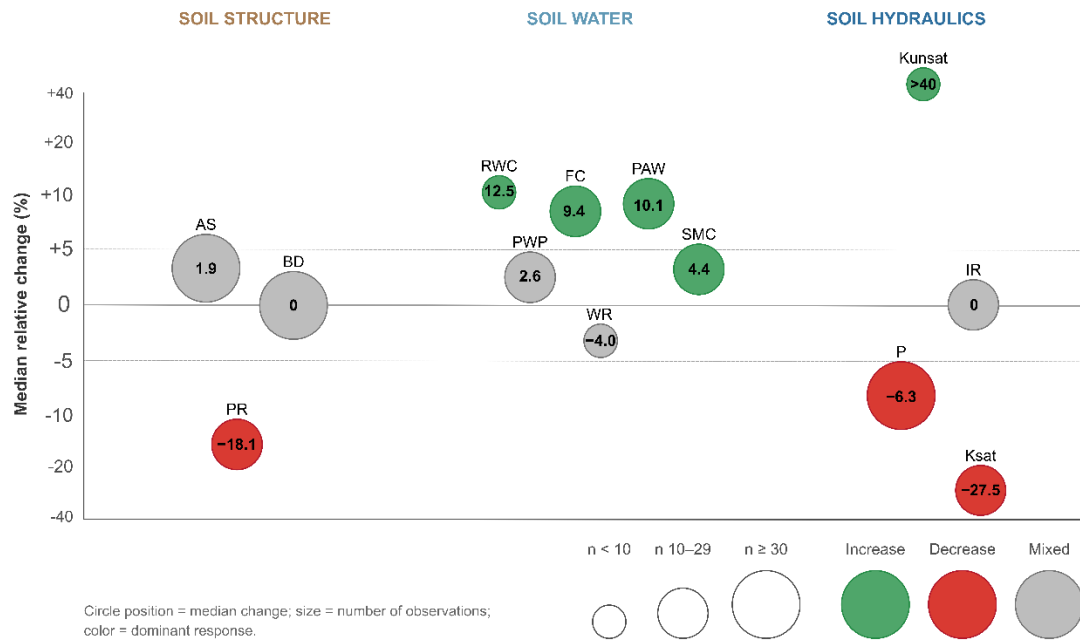
328 Soil structural indicators were associated with contrasting responses to ERW.  
 329 Bulk density exhibited no overall response (median: 0.0%), with 22% of  
 330 observations classified as increases, 26% as decreases, and 51% as no change.  
 331 Aggregate stability showed a small positive median response (+1.9%), with 37%  
 332 of observations classified as increases, 26% as decreases, and 37% as no  
 333 change. Penetration resistance had a negative median response (-18.1%), but  
 334 this variable was available for only one experiment (Figure 2).

### 335 **3.3 Soil water properties**

336 Water-related variables were associated with variable responses across studies.  
337 Soil moisture was enhanced by a median of +4.4%, with 48% of observations  
338 classified as increases, 24% as decreases, and 29% as no change across four  
339 experiments. Field capacity increased by a median of +9.4%, with 57% of  
340 observations classified as increases, 13% as decreases, and 30% as no change.  
341 Plant available water had a median increase of +10.1%, with 67% of observations  
342 classified as increases and 33% as no change. Permanent wilting point indicated  
343 a median increase of +2.6%, with 40% of observations classified as increases,  
344 20% as decreases, and 40% as no change. Water retention at -100 kPa was  
345 measured in only one experiment, with a median response of -4.0%, with 40%  
346 of observations classified as decreases and 60% as no change. Residual water  
347 content exhibited a median increase of +12.5%, based on three observations  
348 across two experiments, all classified as increases.

### 349 **3.4 Soil hydraulic behaviour**

350 Hydraulic variables were characterised by variable responses across studies.  
351 Infiltration rate had no median response (0.0%), with 31% of observations  
352 classified as increases, 46% as decreases, and 23% as no change. Saturated  
353 hydraulic conductivity had a negative median response (-27.5%), with 10% of  
354 observations classified as increases and 90% as decreases. Porosity also had a  
355 negative median response (-6.3%), with 12% of observations classified as  
356 increases, 53% as decreases, and 35% as no change. Unsaturated hydraulic  
357 conductivity had a positive median response (+125.0%), with all observations  
358 classified as increases, but it was extracted from one field study only and is  
359 reported mainly for transparency. Because comparison of unsaturated hydraulic  
360 conductivity depends strongly on measurement water content and matric  
361 potential, this variable was not interpreted further.



362

363 Figure 2. Evidence map of enhanced rock weathering (ERW) effects on soil physical and  
 364 hydrological properties. Each circle represents a soil variable and is positioned according to its  
 365 median relative change (%). Circle size reflects the number of observations (n), while colour  
 366 indicates the dominant response direction (increase, decrease, or mixed). Variables are grouped  
 367 into soil structure, soil water status, and soil hydraulic behaviour. Abbreviations: AS, aggregate  
 368 stability; BD, bulk density; PR, penetration resistance; SMC, soil moisture content; FC, field  
 369 capacity; PAW, plant available water; PWP, permanent wilting point; WR, water retention (–100  
 370 kPa); RWC, residual water content; P, porosity; IR, infiltration rate; K<sub>sat</sub>, saturated hydraulic  
 371 conductivity. Unsaturated hydraulic conductivity (K<sub>unsat</sub>) is shown for transparency but was not  
 372 interpreted further because it was available from one study only and depends strongly on  
 373 measurement water content and matric potential.

374 Variable-level distributions of relative changes are provided in Figures S3.1–S3.3  
 375 for soil structural variables, Figures S4.1–S4.6 for soil water variables, and  
 376 Figures S5.1–S5.4 for soil hydraulic variables.

## 377 4. Discussion

### 378 4.1 ERW effects on soil sponge function are variable, context-dependent, 379 and not uniformly positive

380 As expected, this synthesis shows that ERW does not produce uniform  
 381 responses across soil physical and hydrological properties. Instead, the available  
 382 evidence points to variable, process-specific responses, with modest changes in  
 383 water-storage indicators, mixed structural responses, and contrasting effects on  
 384 flow-related properties. This finding aligns with recent assessments suggesting  
 385 that ERW outcomes are strongly site-specific and depend on soil type, feedstock  
 386 properties, climate, water fluxes, biological activity, application rate, and  
 387 experimental duration rather than on rock addition alone (Beerling et al., 2025;  
 388 Buma et al., 2026; Schiedung et al., 2026). This variability is not surprising given  
 389 the structure of the dataset.

390 The 17 included studies ranged from laboratory and pot experiments to  
391 greenhouse, mesocosm, and field systems; soil textures ranging from sand and  
392 sandy loam to clay loam and clay; and amendments including basalt, glacial rock  
393 flour, gneiss, granite, metabasalt, schist, and mixed rock dusts. Application rates  
394 also varied widely, from low rates such as 3–10 t ha<sup>-1</sup> (Oladele et al., 2024;  
395 Richardson, 2025) to moderate and high rates of 40–100 t ha<sup>-1</sup> (Akortey et al.,  
396 2026; Boito et al., 2025; Costanzo et al., 2025; Kelland et al., 2020), and up to  
397 150–280 t ha<sup>-1</sup> in intensive field studies (Pihlap et al., 2025; Yang et al., 2025;  
398 Zhu et al., 2025). Such differences make a uniform “ERW effect” highly unlikely.

399 The limited number of independent studies remains a central constraint. Although  
400 the dataset contains 261 treatment–control observations, these are distributed  
401 across only 17 studies and often include repeated depths, time points, or  
402 experimental contexts. In addition, the limited number of studies reporting specific  
403 variables precluded more in-depth analyses of how soil texture, feedstock type,  
404 application rate, depth, duration, and experimental system mediate ERW  
405 responses. Therefore, the results should be interpreted as a structured synthesis  
406 of evidence rather than a formal meta-analysis. The value of the dataset lies in  
407 revealing where ERW responses appear directionally consistent, where they  
408 remain mixed, and where standardised measurements are urgently needed.

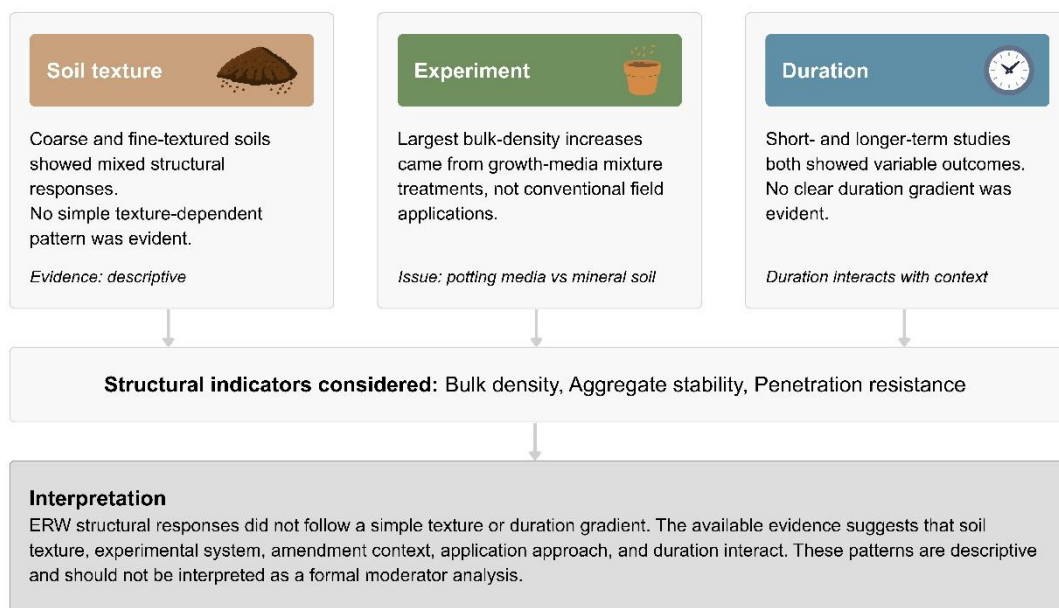
#### 409 **4.2 Structural responses: neutral bulk density, weak aggregate response,** 410 **and reduced penetration resistance**

411 The results partly support the expectation that ERW effects on soil structure may  
412 be more detectable in functional indicators than in bulk whole-soil metrics,  
413 although evidence remains uneven among variables. Bulk density had no median  
414 response (0.0%), while aggregate stability showed only a small positive median  
415 response (+1.9%). The neutral bulk-density response is not surprising given the  
416 diversity of soil textures, application rates, amendment contexts, and  
417 experimental systems covered by the synthesis. This neutral bulk-density  
418 response is broadly consistent with Xu et al. (2025), who reported a negligible,  
419 non-significant bulk-density response for crushed rock and lime amendments  
420 (+0.3%; n = 20). However, their synthesis focused on soil carbon responses and  
421 included a broader set of amendment types than the present study.

422 Although soil texture is likely to mediate ERW effects on bulk density, the  
423 available evidence did not indicate a simple texture-dependent pattern (Figure 3).  
424 Bulk-density responses appeared more strongly influenced by study design and  
425 amendment context. In particular, the largest increases came from a  
426 greenhouse/growth-chamber study in which rock dust was used as a volumetric  
427 component of potting media mixtures rather than as a conventional field  
428 application to mineral soil. Therefore, the neutral median response in bulk density  
429 likely reflects a combination of experimental system, amendment rate or  
430 proportion, mixing approach, and sampling depth, rather than texture alone.

431 This also highlights the need to distinguish conventional soil amendment studies  
 432 from pot-media formulation experiments when interpreting ERW effects on bulk  
 433 physical properties. Therefore, the absence of a consistent bulk-density response  
 434 should not be interpreted as evidence that ERW did not affect soil structure. Bulk  
 435 density is a coarse indicator and may not detect changes in pore-size distribution,  
 436 aggregate arrangement, or mechanical strength. Schiedung et al. (2026)  
 437 highlighted that high rock powder additions could affect soil structure through  
 438 compaction or temporary macropore clogging, particularly when application rates  
 439 exceed conventional liming rates. Aggregate stability was associated with a small  
 440 and mixed median increase. This weak signal is notable because several  
 441 mechanisms would predict stronger aggregation responses: ERW can release  
 442  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , modify pH, stimulate microbial activity, and create new mineral  
 443 surfaces for organo-mineral associations (Kleber et al., 2021; Rowley et al., 2018;  
 444 Slessarev et al., 2022; Xu et al., 2025). However, these processes require time  
 445 for roots, microbial residues, and mineral weathering products to interact.

446 Yet, the available data do not indicate a simple duration gradient in structural  
 447 responses (Figure 3). Short-term studies showed mixed outcomes: aggregate  
 448 stability was near neutral or slightly negative in Akortey et al. (2026) and Dupla et  
 449 al. (2024), but increased in Oladele et al. (2024), while bulk-density responses  
 450 ranged from slight increases to decreases. Longer-term field studies were also  
 451 variable, with near-neutral bulk-density responses in Pihlap et al. (2025) and  
 452 Pavlů et al. (2021), reduced aggregate stability but lower penetration resistance  
 453 in Costanzo et al. (2025), and positive aggregate-stability responses in Pavlů et  
 454 al. (2021). Thus, duration may interact with soil texture, amendment type,  
 455 application rate, and biological feedbacks, but the current dataset is insufficient  
 456 to fully unravel these effects and potential interactions.



457

458 Figure 3. Context-dependence of ERW effects on soil structural responses. The figure  
459 summarises qualitative study-level patterns for bulk density, aggregate stability, and penetration  
460 resistance. The available evidence did not indicate a simple texture-dependent response or a  
461 clear short-term versus long-term gradient. Instead, structural responses appeared to vary with  
462 experimental system, amendment context, application approach, and study duration. The largest  
463 positive bulk-density responses were associated with a greenhouse/growth-chamber study in  
464 which rock dust was used as a volumetric component of growth media rather than as a  
465 conventional field application to mineral soil. This figure is descriptive and should not be  
466 interpreted as a formal moderator analysis.

467 Penetration resistance showed a strong negative median response, but this  
468 pattern was based on one study only and should be treated as a preliminary  
469 indication rather than a general structural response. Nevertheless, it is a  
470 potentially important variable for future ERW studies because it directly relates to  
471 root-relevant soil mechanical resistance and may change even when bulk density  
472 remains near neutral. Because penetration resistance is highly moisture-  
473 sensitive, future studies should report soil water content at the time of  
474 measurement alongside bulk density and porosity.

#### 475 **4.3 Soil water responses: water retention characteristics increased more** 476 **consistently than dynamic soil moisture**

477 The evidence provides modest support for improved water storage, but not a  
478 universal increase in dynamic soil water content. Field capacity (+9.4%) and plant  
479 available water (+10.1%) had positive median responses, whereas soil moisture  
480 increased only modestly (+4.4%). Permanent wilting point and water retention at  
481 -100 kPa were hardly affected, although the latter was available from one study  
482 only. While soil moisture is a dynamic state variable controlled by rainfall or  
483 irrigation, drainage, evapotranspiration and plant uptake, field capacity,  
484 permanent wilting point, water retention and plant available water describe  
485 intrinsic soil hydraulic properties. Consequently, changes in water-retention  
486 properties do not necessarily translate into higher measured soil moisture during  
487 an experiment.

488 Water-storage responses were also highly context-dependent. Akortey et al.  
489 (2026) showed consistent increases in field capacity and plant available water  
490 across several soil textures under glacial rock flour addition, whereas Pihlap et  
491 al. (2025) observed small negative responses in both variables in a long-term  
492 basalt-amended field trial. Similarly, Costanzo et al. (2025) showed mixed water-  
493 retention responses, with increases in plant available water occurring mainly  
494 where metabasalt was combined with additional amendments, including olivine,  
495 biochar, compost, or biochar plus compost, rather than uniformly across  
496 metabasalt-only treatments. Dynamic soil moisture was also study-specific:  
497 Medeiros et al. (2024), using gneiss in a field system, showed consistently  
498 positive soil moisture responses across sandy-loam and clay soils, whereas Boito  
499 et al. (2025) and Yang et al. (2025) showed neutral to negative responses under  
500 basalt addition.

501 Taken together, these findings indicate that ERW may increase potential water-  
502 storage capacity under some conditions, but this does not consistently translate  
503 into higher observed soil moisture during experiments. The positive median  
504 responses in field capacity and plant available water are consistent with the  
505 hypothesis that fine mineral additions may shift pore-size distribution towards  
506 greater capillary water retention. However, this mechanism cannot be  
507 generalised across studies because soil texture, feedstock type, application rate,  
508 biological context, and measurement conditions varied substantially among  
509 experiments. This context dependence is also consistent with Boito et al. (2025),  
510 where soil water responses varied across experimental conditions rather than  
511 following a uniform direction. In some studies, interpretation was further  
512 complicated by treatments that combined rock powders with other amendments,  
513 including biochar, compost, or manure.

514 Future experiments should prioritise complete water-retention curves, repeated  
515 soil moisture measurements, and paired reporting of plant uptake, drainage, and  
516 hydraulic properties within the same experimental systems. Such integrated  
517 datasets would help clarify whether observed changes in soil water retention  
518 translate into meaningful improvements in water availability under field  
519 conditions.

#### 520 **4.4 Hydraulic behaviour: preliminary evidence for reduced saturated flow**

521 Hydraulic variables were sparsely represented and showed variable responses.  
522 Saturated hydraulic conductivity ( $K_{\text{sat}}$ ) had a negative median response, porosity  
523 declined moderately, and infiltration rate had no median response. The negative  
524 response in  $K_{\text{sat}}$  is mechanistically plausible because fine rock particles may  
525 occupy larger conducting pores, reduce macropore continuity, and increase  
526 tortuosity (Schiedung et al., 2026). This interpretation is also consistent with pore-  
527 scale modelling showing that the spatial arrangement of rock particles in soil  
528 pores can influence both water–rock contact and water movement (Anand et al.,  
529 2026). However, the available evidence is not sufficient to conclude that ERW  
530 generally reduces hydraulic flow, because  $K_{\text{sat}}$  was available from only two  
531 studies, and infiltration rate showed no median response.

532 Unsaturated hydraulic conductivity was extracted from one study and is reported  
533 for transparency, but it was not used to infer a general hydraulic mechanism  
534 because it depends strongly on soil water content and matric potential.

#### 535 **4.5 Apparent storage–flow trade-off and limits of cross-variable** 536 **interpretation**

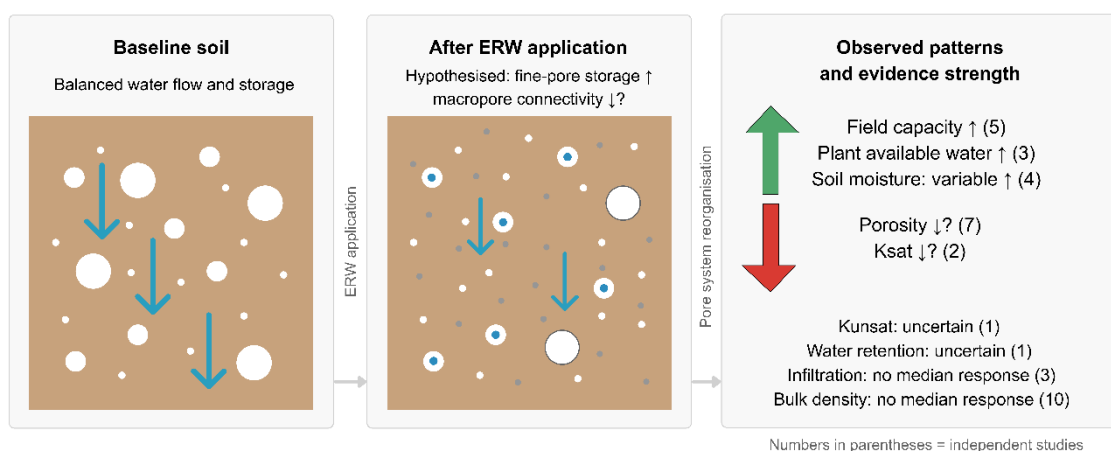
537 When variables were summarised across the full synthesis, field capacity and  
538 plant available water tended to increase, whereas saturated hydraulic  
539 conductivity and porosity tended to decline. However, these variables were not  
540 consistently measured within the same experiments. Therefore, this pattern

541 should be interpreted as an apparent synthesis-level trend rather than direct  
 542 evidence that ERW caused a storage–flow trade-off within individual studies. The  
 543 hypothesis is mechanistically plausible because pore-size distribution and pore  
 544 connectivity jointly regulate water retention, saturated flow, and unsaturated  
 545 redistribution (Nimmo, 2004; Dexter et al., 2008; Ding et al., 2016; Brutsaert,  
 546 2023).

547 However, the study-by-variable coverage matrix (Table S1) shows that only a  
 548 subset of studies measured multiple components of soil water storage, structure,  
 549 and hydraulic behaviour together. Studies such as Akortey et al. (2026), Costanzo  
 550 et al. (2025), Pavlů et al. (2021), and Oladele et al. (2024) are therefore  
 551 particularly useful for within-study interpretation, but even these studies  
 552 measured different combinations of variables. As a result, the proposed storage–  
 553 flow trade-off remains a hypothesis requiring targeted experiments that co-  
 554 measure water retention, pore structure, infiltration, and hydraulic conductivity  
 555 under comparable conditions.

556 Temporal mismatch and experimental duration add further uncertainty. In the  
 557 present dataset, soil moisture observations often represented dynamic  
 558 measurements over experimental periods or specific crop stages, whereas  
 559 variables such as aggregate stability, bulk density, porosity, water-retention  
 560 characteristics, infiltration rate, and hydraulic conductivity were usually measured  
 561 at discrete sampling dates. Experimental duration also varied widely, from short-  
 562 term laboratory, pot, greenhouse, and mesocosm studies to multi-year field trials.

563 Therefore, apparent contrasts among soil moisture, water retention, and  
 564 hydraulic variables may partly reflect differences in measurement timing and  
 565 experimental duration rather than direct functional decoupling within the same  
 566 soil system. Early physical effects of rock-powder addition may differ from longer-  
 567 term responses involving mineral weathering, aggregation, root activity, and  
 568 biological feedback (Figure 4).



569

570 Figure 4. Conceptual representation of hypothesised ERW effects on soil pore structure and  
 571 hydrological functioning. ERW may alter soil sponge function by changing pore-size distribution,

572 pore connectivity, and water–rock contact. The hypothesised mechanism is that fine rock particles  
573 may increase capillary water storage while reducing effective macropore connectivity, depending  
574 on soil texture, feedstock properties, particle size, application rate, incorporation depth, and  
575 biological activity. Evidence from the present synthesis provides descriptive support for increased  
576 field capacity and plant available water, more variable support for changes in dynamic soil  
577 moisture, and preliminary evidence for reduced saturated hydraulic conductivity and porosity.  
578 Numbers in parentheses indicate the number of independent studies contributing to each  
579 variable. Responses in water retention at –100 kPa and unsaturated hydraulic conductivity were  
580 each based on one study and are therefore treated as uncertain. The figure is conceptual and  
581 should be interpreted as a hypothesis-generating framework rather than a mechanism confirmed  
582 across all included studies.

#### 583 **4.6 Key drivers of variability: application rate, texture, feedstock, and** 584 **mixing**

585 Application rate, soil type and texture, climate, feedstock identity, particle size,  
586 and incorporation depth likely explain much of the observed heterogeneity in  
587 ERW effects on soil sponge function (Beerling et al., 2025; Schiedung et al.,  
588 2026). Low application rates, such as 3–10 t ha<sup>-1</sup>, may have limited physical  
589 effects, whereas higher rates increase the likelihood of interactions between rock  
590 particles and the pore network (Oladele et al., 2024; Richardson, 2025; Pihlap et  
591 al., 2025; Yang et al., 2025; Zhu et al., 2025). Finer particles can increase reactive  
592 surface area but may also modify pore connectivity and water movement (Anand  
593 et al., 2026; Schiedung et al., 2026).

594 Soil texture likely controls whether these changes improve storage or restrict flow.  
595 In sandy and sandy-loam soils, fine mineral additions may increase water  
596 retention and plant-available water (Naseri et al., 2019; Obour et al., 2024;  
597 Medeiros et al., 2024; Boito et al., 2025; Richardson, 2025). In finer-textured soils,  
598 effects may instead be more related to pore connectivity, aeration, and saturated  
599 flow (Kelland et al., 2020; Pihlap et al., 2025; Yang et al., 2025; Zhou et al., 2025;  
600 Zhu et al., 2025).

601 Feedstock differences add further variability. The included studies used basalt,  
602 glacial rock flour, gneiss, metabasalt, schist, mixed rock dusts, and, in one case,  
603 granite dust. These materials differ strongly in mineralogy, dissolution rate,  
604 particle-size distribution, nutrient release, and secondary mineral formation  
605 potential (Akortey et al., 2026; Armah et al., 2025; Costanzo et al., 2025;  
606 Medeiros et al., 2024; Obour et al., 2024; Zhou et al., 2025). Granite dust should  
607 be interpreted cautiously in an ERW context because it is generally less reactive  
608 and poorer in Ca and Mg than typical ERW feedstocks such as basalt or  
609 wollastonite; in the present synthesis, it was retained because the study reported  
610 soil physical responses to a silicate dust amendment (Oladele et al., 2024).

611 Incorporation depth and mixing also matter because most studies focused on the  
612 upper 0–25 cm, where rock particles interact most strongly with roots, pores,  
613 water, and organic matter (Boito et al., 2025; Costanzo et al., 2025; Dupla et al.,  
614 2024; Medeiros et al., 2024; Pihlap et al., 2025). Effects on deeper hydraulic

615 properties and downward transport of weathering products remain poorly  
616 constrained (Buma et al., 2026; Schiedung et al., 2026).

#### 617 **4.7 Implications for plant growth and soil carbon**

618 The physical and hydrological responses to ERW have direct implications for  
619 agronomy and CO<sub>2</sub> removal. Increased field capacity and plant available water,  
620 coupled with reduced penetration resistance, can directly support crop water  
621 supply and root elongation. Conversely, restricted saturated flow could limit root-  
622 zone oxygen in poorly drained systems. While large-scale trials (e.g., Beerling et  
623 al., 2024; Kelland et al., 2020) have demonstrated agronomic benefits, these are  
624 traditionally interpreted through geochemical and nutritional pathways; the  
625 mediating role of soil physics is rarely tested directly.

626 Soil sponge function is inextricably linked to soil carbon stabilisation. Moisture,  
627 aggregation, porosity, and newly available mineral surfaces regulate microbial  
628 activity and the formation of mineral-associated organic carbon (MAOC) (Angers  
629 and Caron, 1998; Rowley et al., 2018; Kleber et al., 2021; Slessarev et al., 2022;  
630 Xu et al., 2025). However, recent evidence also indicates mixed effects of ERW  
631 on mineral-associated organic matter over short timescales. Sokol et al. (2024)  
632 reported reduced mineral-associated organic matter after two years of crushed  
633 rock application, whereas Steinwider et al. (2025) found no clear ERW effect on  
634 MAOC. In contrast, Xu et al. (2025) reported an overall positive MAOC response  
635 in a global meta-analysis, with an average increase of 6.1%, although responses  
636 differed among rock types.

637 These contrasting results highlight that soil carbon responses may depend on  
638 site conditions, amendment type, mineral reactivity, experimental duration, and  
639 biological feedbacks. As demonstrated by Xu et al. (2025) and Boito et al. (2025),  
640 ERW effects on carbon cannot be evaluated solely through inorganic weathering  
641 pathways. This is further supported by recent evidence showing that active  
642 weathering does not necessarily translate into high inorganic CO<sub>2</sub> removal,  
643 because released base cations may be immobilised in exchangeable pools,  
644 secondary minerals, or soil organic matter rather than exported as alkalinity or  
645 stored as carbonates (Steinwider et al., 2026). These carbon-related outcomes  
646 are therefore partly dependent on how rock amendments restructure the physical  
647 environment in which water, roots, microbes, organic matter, and minerals  
648 interact.

#### 649 **4.8 Research priorities and outlook**

650 To improve our insights into the effects of ERW on soil physical and hydrological  
651 properties, more studies are required that measure soil structure, water retention,  
652 and hydraulic behaviour within the same experiments. Future ERW studies  
653 should prioritise a tiered set of soil physical and hydrological measurements. At  
654 a minimum, studies should report bulk density, soil texture, aggregate stability,

655 repeated soil moisture, and a water-retention curve from which field capacity,  
656 permanent wilting point, and plant available water can be derived (Hillel, 1998).  
657 These variables are essential because they describe the basic soil physical  
658 context, water-storage capacity, and the dynamic soil water status that controls  
659 plant water availability and weathering conditions (Cousin et al., 2022). Where  
660 resources allow, infiltration rate and saturated hydraulic conductivity should be  
661 added to assess whether increased water storage is accompanied by changes in  
662 water-entry and drainage pathways, because infiltration is jointly controlled by  
663 soil hydraulic conductivity, sorptivity, and hydraulic gradients (Vereecken et al.,  
664 2019).

665 Penetration resistance is recommended when plant-root constraints are relevant,  
666 but it should always be measured together with soil moisture because soil  
667 strength and penetrometer resistance vary strongly with soil water status  
668 (Bengough and Mullins, 1991; Yapa et al., 1988). Unsaturated hydraulic  
669 conductivity is valuable for mechanistic interpretation but should be treated as an  
670 advanced measurement because it requires standardised matric-potential or  
671 water-content conditions for comparison across studies (van Genuchten, 1980).  
672 These measurements should be reported with treatment and control means,  
673 variance, replication, soil depth, sampling time, soil moisture at measurement,  
674 feedstock mineralogy, particle-size distribution, application rate, incorporation  
675 depth, and experiment duration. This information is essential for meaningful  
676 comparison across sites and for distinguishing whether ERW responses are  
677 driven mainly by soil texture, amendment properties, application intensity,  
678 biological context, or time since application (Beerling et al., 2025).

679 Treatment and control means with variance, and replication would enable future  
680 formal meta-analysis (Gerstner et al., 2017), while soil depth, sampling time, and  
681 incorporation depth would help determine whether responses occur within the  
682 amended layer or reflect deeper soil conditions. Reporting soil moisture at the  
683 time of measurement is particularly important for interpreting penetration  
684 resistance and hydraulic conductivity (Bengough & Mullins, 1991; Vereecken et  
685 al., 2008). Feedstock mineralogy and particle-size distribution are needed to link  
686 physical responses to rock reactivity, pore filling, and water–rock contact  
687 (Beerling et al., 2025; Anand et al., 2026).

688 Together, these data would allow future studies to move beyond descriptive  
689 comparisons and test the mechanisms underlying ERW effects on soil sponge  
690 function. This need for integrated measurement aligns with recent ERW reviews  
691 (Beerling et al., 2025; Schiedung et al., 2026) and expert assessments (Buma et  
692 al., 2026), highlighting persistent uncertainties around feedstock performance,  
693 soil–plant responses, water-mediated weathering, and long-term CO<sub>2</sub> removal  
694 efficiency. It is also supported by pore-scale modelling showing that water–rock  
695 contact depends on soil moisture, pore structure, particle size, and mixing degree  
696 (Anand et al., 2026), and by recent carbon-focused studies showing that ERW

697 effects on soil carbon depend on climate, soil properties, application amount,  
698 duration, and biological processes (Boito et al., 2025; Xu et al., 2025).

699 Overall, ERW does not uniformly enhance soil sponge function. Its effects appear  
700 variable and context-dependent, with modest changes in water-storage  
701 indicators, limited evidence for bulk structural change, reduced saturated flow-  
702 related properties, and possible pore-scale reorganisation. Future field studies  
703 should therefore test soil sponge function, plant performance, carbon cycling,  
704 runoff, and soil erosion together under realistic management conditions  
705 (Gholamahmadi et al., 2023).

## 706 **5. Conclusion**

707 This synthesis shows that enhanced rock weathering (ERW) does not produce a  
708 uniform improvement in soil sponge function. Across 17 studies and 261  
709 treatment–control observations, ERW effects were variable and depended  
710 strongly on the soil property considered. Bulk density had no median response,  
711 aggregate stability changed only weakly, and penetration resistance declined in  
712 the only study reporting this variable. Soil water responses provided modest  
713 evidence for increased water-storage capacity, particularly through positive  
714 median responses in field capacity and plant available water. However, dynamic  
715 soil moisture increased only slightly, indicating that ERW does not consistently  
716 increase observed soil water content across experimental conditions. Hydraulic  
717 responses were also mixed: saturated hydraulic conductivity and porosity tended  
718 to decline, while infiltration rate had no median response.

719 Because these variables were not consistently measured within the same  
720 experiments, the apparent contrast between increased water-storage indicators  
721 and reduced flow-related properties should be interpreted as a hypothesis-  
722 generating pattern rather than definitive evidence of a storage–flow trade-off.  
723 Overall, ERW effects on soil physical and hydrological properties appear process-  
724 specific, context-dependent, and not uniformly positive. The available evidence  
725 supports the need to evaluate ERW not only as a geochemical carbon dioxide  
726 removal strategy, but also as a soil physical intervention with potential co-benefits  
727 and trade-offs. Future studies should co-measure soil structure, water-retention  
728 curves, repeated soil moisture, hydraulic behaviour, plant responses, and carbon  
729 dynamics within the same experiments to determine when, where, and how ERW  
730 can enhance soil sponge function.

## 731 **Data availability**

732 The dataset supporting this synthesis is provided as an associated file with the  
733 preprint.

## 734 **Author contributions**

735 B.G. conceptualised the study, conducted the literature search, extracted and  
736 harmonised the data, analysed the dataset, prepared the figures and tables, and  
737 wrote the first draft. L.B., L.S., and S.V. contributed to interpretation, conceptual  
738 framing, and manuscript review and editing. All authors reviewed and approved  
739 the final version of the manuscript.

#### 740 **Funding**

741 This research was supported by the Research Foundation Flanders (FWO), grant  
742 number 1174925N.

#### 743 **Competing interests**

744 The authors declare no competing interests.

#### 745 **References**

746 Akortey, W., Oppong Danso, E., Dietzen, C., Amponsah, W., Arthur, E., Mensah,  
747 B. K. B., Obour, P. B., Nyasapoh, J. B. A., Darko, D. A., Dorvlo, S. Y., Sabi, E. B.,  
748 Abenney-Mickson, S., & Rosing, M. T. (2026). Short-term effects of Greenlandic  
749 glacial rock flour on soil physical properties and maize yield. *Nutrient Cycling in*  
750 *Agroecosystems*, 132, Article 13. <https://doi.org/10.1007/s10705-025-10452-2>

751 Anand, S. K., Duffy, K. A., & Cardenas, M. B. (2026). Soil structure and mixing  
752 controls on water–rock contact: Implications for enhanced weathering. *Water*  
753 *Resources Research*. <https://doi.org/10.1029/2025WR041479>

754 Angers, D. A., & Caron, J. (1998). Plant-induced changes in soil structure:  
755 Processes and feedbacks. *Biogeochemistry*, 42, 55–72.  
756 <https://doi.org/10.1023/A:1005944025343>

757 Armah, A., Alrayes, L., Pham, T. H., Nadeem, M., Bartlett, O., Fordjour, E.,  
758 Cheema, M., Galagedara, L., Abbey, L., & Thomas, R. (2025). Integrating rock  
759 dust and organic amendments to enhance soil quality and microbial activity for  
760 sustainable crop production. *Plants*, 14(8), Article 1163.  
761 <https://doi.org/10.3390/plants14081163>

762 Beerling, D. J., Epihov, D. Z., Kantola, I. B., Masters, M. D., Reershemius, T.,  
763 Planavsky, N. J., Reinhard, C. T., Jordan, J. S., Thorne, S. J., Weber, J., Martin,  
764 M. V., Freckleton, R. P., Hartley, S. E., James, R. H., Pearce, C. R., DeLucia, E.  
765 H., & Banwart, S. A. (2024). Enhanced weathering in the US Corn Belt delivers  
766 carbon removal with agronomic benefits. *Proceedings of the National Academy*  
767 *of Sciences*, 121(9), e2319436121. <https://doi.org/10.1073/pnas.2319436121>

768 Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrazio, R. M., Renforth,  
769 P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt,  
770 H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.  
771 F., Janssens, I. A., ... Banwart, S. A. (2020). Potential for large-scale CO<sub>2</sub> removal

772 via enhanced rock weathering with croplands. *Nature*, 583, 242–248.  
773 <https://doi.org/10.1038/s41586-020-2448-9>

774 Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N.,  
775 Bird, M., Kantzas, E., Taylor, L. L., Sarkar, B., Kelland, M., DeLucia, E., Kantola,  
776 I., Müller, C., Rau, G., & Hansen, J. (2018). Farming with crops and rocks to  
777 address global climate, food and soil security. *Nature Plants*, 4(3), 138–147.  
778 <https://doi.org/10.1038/s41477-018-0108-y>

779 Beerling, D. J., Reinhard, C. T., James, R. H., Khan, A., Pidgeon, N., & Planavsky,  
780 N. J. (2025). Challenges and opportunities in scaling enhanced weathering for  
781 carbon dioxide removal. *Nature Reviews Earth & Environment*, 6, 672–686.  
782 <https://doi.org/10.1038/s43017-025-00713-7>

783 Bengough, A. G., & Mullins, C. E. (1991). Penetrometer resistance, root  
784 penetration resistance and root elongation rate in two sandy loam soils. *Plant and*  
785 *Soil*, 131, 59–66. <https://doi.org/10.1007/BF00010420>

786 Bertagni, M. B., Calabrese, S., Cipolla, G., Noto, L. V., & Porporato, A. (2025).  
787 Advancing enhanced weathering modeling in soils: Critical comparison with  
788 experimental data. *Journal of Advances in Modeling Earth Systems*, 17,  
789 e2024MS004224. <https://doi.org/10.1029/2024MS004224>

790 Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R.,  
791 Dai, J., Dendooven, L., Peres, G., Tondoh, J. E., Cluzeau, D., & Brun, J.-J. (2013).  
792 A review of earthworm impact on soil function and ecosystem services. *European*  
793 *Journal of Soil Science*, 64(2), 161–182. <https://doi.org/10.1111/ejss.12025>

794 Boito, L., Steinwigger, L., Rijnders, J., Berwouts, J., Janse, S., Niron, H.,  
795 Roussard, J., Vienne, A., & Vicca, S. (2025). Enhanced rock weathering altered  
796 soil organic carbon fluxes in a plant trial. *Global Change Biology*, 31(8), Article  
797 e70373. <https://doi.org/10.1111/gcb.70373>

798 Brutsaert, W. (2023). *Hydrology: An introduction* (2nd ed.). Cambridge University  
799 Press. <https://doi.org/10.1017/9781316471562>

800 Buma, B., Dietzen, C., Gordon, D. R., Maher, K., Neumann, R. B., Planavsky, N.  
801 J., Reershemius, T., Suhrhoff, T. J., Vicca, S., Waring, B. G., Almaraz, M.,  
802 Calabrese, S., Derry, L. A., Morgan, M. G., Higgins, J., Houlton, B. Z., Kanzaki,  
803 Y., Klemme, A., Kukla, T., ... Zhang, S. (2026). Expert elicitation on agricultural  
804 enhanced weathering reveals carbon dioxide removal potential and uncertainties  
805 in loss pathways. *Communications Earth & Environment*, 7, 376.  
806 <https://doi.org/10.1038/s43247-026-03375-5>

807 Buss, W., Hasemer, H., Ferguson, S., & Borevitz, J. (2024). Stabilisation of soil  
808 organic matter with rock dust partially counteracted by plants. *Global Change*  
809 *Biology*, 30(1), e17052. <https://doi.org/10.1111/gcb.17052>

810 Chiaravalloti, I., Theunissen, N., Zhang, S., Wang Sun, F., Ahmed, A. A., Pihlap,  
811 E., Reinhard, C. T., & Planavsky, N. J. (2023). Mitigation of soil nitrous oxide  
812 emissions during maize production with basalt amendments. *Frontiers in Climate*,  
813 5, Article 1203043. <https://doi.org/10.3389/fclim.2023.1203043>

814 Cipolla, G., Calabrese, S., Noto, L. V., & Porporato, A. (2021a). The role of  
815 hydrology on enhanced weathering for carbon sequestration I: Modeling rock-  
816 dissolution reactions coupled to plant, soil moisture, and carbon dynamics.  
817 *Advances in Water Resources*, 154, 103934.  
818 <https://doi.org/10.1016/j.advwatres.2021.103934>

819 Cipolla, G., Calabrese, S., Noto, L. V., & Porporato, A. (2021b). The role of  
820 hydrology on enhanced weathering for carbon sequestration II: From  
821 hydroclimatic scenarios to carbon-sequestration efficiencies. *Advances in Water*  
822 *Resources*, 154, 103949. <https://doi.org/10.1016/j.advwatres.2021.103949>

823 Clarkson, M. O., Larkin, C. S., Swoboda, P., Reershemius, T., Suhrhoff, T. J.,  
824 Maesano, C. N., & Campbell, J. S. (2024). A review of measurement for  
825 quantification of carbon dioxide removal by enhanced weathering in soil.  
826 *Frontiers in Climate*, 6, 1345224. <https://doi.org/10.3389/fclim.2024.1345224>

827 Costanzo, S. A., Holzer, I. O., Moonilall, N. I., Davenport, A., Houlton, B. Z., &  
828 Nocco, M. A. (2025). Preliminary assessment of crushed rock, compost, and  
829 biochar amendments on soil physical properties. *Agricultural & Environmental*  
830 *Letters*, 10(2), Article e70028. <https://doi.org/10.1002/ael2.70028>

831 Cousin, I., Buis, S., Lagacherie, P., Doussan, C., Le Bas, C., & Guérif, M. (2022).  
832 Available water capacity from a multidisciplinary and multiscale viewpoint: A  
833 review. *Agronomy for Sustainable Development*, 42, 46.  
834 <https://doi.org/10.1007/s13593-022-00774-8>

835 Dexter, A. R., Czyż, E. A., Richard, G., & Reszkowska, A. (2008). A user-friendly  
836 water retention function that takes account of the textural and structural pore  
837 spaces in soil. *Geoderma*, 143(3–4), 243–253.  
838 <https://doi.org/10.1016/j.geoderma.2007.11.010>

839 Ding, D., Zhao, Y., Feng, H., Peng, X., & Si, B. (2016). Using the double-  
840 exponential water retention equation to determine how soil pore-size distribution  
841 is linked to soil texture. *Soil and Tillage Research*, 156, 119–130.  
842 <https://doi.org/10.1016/j.still.2015.10.007>

843 Dontsova, K., Balogh-Brunstad, Z., & Chorover, J. (2020). Plants as drivers of  
844 rock weathering. In S. Brantley, K. Dontsova, & Z. Balogh-Brunstad (Eds.),  
845 *Biogeochemical cycles: Ecological drivers and environmental impact* (pp. 33–58).  
846 American Geophysical Union. <https://doi.org/10.1002/9781119413332.ch2>

847 Dupla, X., Claustre, R., Bonvin, E., Graf, I., Le Bayon, R.-C., & Grand, S. (2024).  
848 Let the dust settle: Impact of enhanced rock weathering on soil biological,

849 physical, and geochemical fertility. *Science of the Total Environment*, 954, Article  
850 176297. <https://doi.org/10.1016/j.scitotenv.2024.176297>

851 Gerstner, K., Moreno-Mateos, D., Gurevitch, J., Beckmann, M., Kambach, S.,  
852 Jones, H. P., & Seppelt, R. (2017). Will your paper be used in a meta-analysis?  
853 Make the reach of your research broader and longer lasting. *Methods in Ecology  
854 and Evolution*, 8(6), 777–784. <https://doi.org/10.1111/2041-210X.12758>

855 Gholamahmadi, B., Ferreira, C.S.S., Gonzalez-Pelayo, O., Bastos, A.C.,  
856 Verheijen, F.G.A. (2025a). Soil conservation benefits of biochar in Mediterranean  
857 vineyards: enhancing the soil sponge function and mitigating water erosion.  
858 *Biochar* 7, 106. <https://doi.org/10.1007/s42773-025-00483-x>

859 Gholamahmadi, B., Gonzalez-Pelayo, O., Isaka, S., Campos, I., Martins, M.,  
860 Bastos, A. C., Jongen, M., & Verheijen, F. G. A. (2025b). The impact of biochar  
861 application on sponge function, water erosion, and vegetation cover in a  
862 Mediterranean vineyard soil. *Journal of Environmental Management*, 388, Article  
863 125916. <https://doi.org/10.1016/j.jenvman.2025.125916>

864 Gholamahmadi, B., Jeffery, S., Gonzalez-Pelayo, O., Prats, S.A., Bastos, A.C., J  
865 Keizer, Verheijen, F.G.A. (2023). Biochar impacts on runoff and soil erosion by  
866 water: A systematic global scale meta-analysis, *Science of The Total  
867 Environment*, 871,161860. <https://doi.org/10.1016/j.scitotenv.2023.161860>

868 Goll, D. S., Ciais, P., Amann, T., Buermann, W., Chang, J., Eker, S., Hartmann,  
869 J., Janssens, I. A., Li, W., Obersteiner, M., Peñuelas, J., Tanaka, K., & Vicca, S.  
870 (2021). Potential CO<sub>2</sub> removal from enhanced weathering by ecosystem  
871 responses to powdered rock. *Nature Geoscience*, 14(8), 545–549.  
872 <https://doi.org/10.1038/s41561-021-00798-x>

873 Harley, A. D., & Gilkes, R. J. (2000). Factors influencing the release of plant  
874 nutrient elements from silicate rock powders: A geochemical overview. *Nutrient  
875 Cycling in Agroecosystems*, 56, 11–36.  
876 <https://doi.org/10.1023/A:1009859309453>

877 Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-  
878 Gladrow, D. A., Dürr, H. H., & Scheffran, J. (2013). Enhanced chemical  
879 weathering as a geoengineering strategy to reduce atmospheric carbon dioxide,  
880 supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, 51(2),  
881 113–149. <https://doi.org/10.1002/rog.20004>

882 Hillel, D. (1998). *Environmental Soil Physics: Fundamentals, Applications, and  
883 Environmental Considerations*. Academic Press, San Diego.

884 Hinsinger, P. (1998). How do plant roots acquire mineral nutrients? Chemical  
885 processes involved in the rhizosphere. *Advances in Agronomy*, 64, 225–265.  
886 [https://doi.org/10.1016/S0065-2113\(08\)60506-4](https://doi.org/10.1016/S0065-2113(08)60506-4)

- 887 Jha, A., Kumar, P., McDowell, N. G., & O'Donnell, J. J. (2023). Linking soil  
888 structure, hydraulic properties, and organic carbon dynamics: A theoretical  
889 framework and field observations. *Journal of Geophysical Research:*  
890 *Biogeosciences*, 128, e2023JG007389. <https://doi.org/10.1029/2023JG007389>
- 891 Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M.  
892 G., Lomas, M. R., Cotton, T. E. A., ... & Beerling, D. J. (2020). Increased yield and  
893 CO<sub>2</sub> sequestration potential with the C<sub>4</sub> cereal *Sorghum bicolor* cultivated in  
894 basaltic rock dust-amended agricultural soil. *Global Change Biology*, 26(6),  
895 3658–3676. <https://doi.org/10.1111/gcb.15089>
- 896 Kleber, M., Bourg, I. C., Coward, E. K., Hansel, C. M., Myneni, S. C. B., & Nunan,  
897 N. (2021). Dynamic interactions at the mineral–organic matter interface. *Nature*  
898 *Reviews Earth & Environment*, 2, 402–421. [https://doi.org/10.1038/s43017-021-](https://doi.org/10.1038/s43017-021-00162-y)  
899 00162-y
- 900 Medeiros, F. d. P., Carvalho, A. M. X. d., Gindri Ramos, C., Dotto, G. L., Cardoso,  
901 I. M., & Theodoro, S. H. (2024). Rock powder enhances soil nutrition and coffee  
902 quality in agroforestry systems. *Sustainability*, 16(1), Article 354.  
903 <https://doi.org/10.3390/su16010354>
- 904 Naseri, M., Peters, A., Durner, W., & Iden, S. C. (2019). Influence of stone content  
905 on soil hydraulic properties: Experimental investigation and test of existing model  
906 concepts. *Vadose Zone Journal*, 18(1), Article 180163.  
907 <https://doi.org/10.2136/vzj2018.08.0163>
- 908 Nimmo, J. R. (2004). Porosity and pore-size distribution. In D. Hillel (Ed.),  
909 *Encyclopedia of soils in the environment* (Vol. 3, pp. 295–303). Elsevier.
- 910 Obour, P. B., Dietzen, C., Oppong Danso, E., Arthur, E., Adu, M. O., & Rosing, M.  
911 T. (2024). Limited short-term benefits of glacial rock flour for enhancing the  
912 physical quality of tropical arable soils. *European Journal of Soil Science*, 75(6),  
913 Article e70028. <https://doi.org/10.1111/ejss.70028>
- 914 Oladele, S. O., Curaqueo, G., & Awodun, M. A. (2024). Co-amendment of silicate  
915 dust and manure improves soil health metrics and crop yield in coarser-textured  
916 more than medium-textured soils. *Geoderma Regional*, 39, Article e00887.  
917 <https://doi.org/10.1016/j.geodrs.2024.e00887>
- 918 Pavlů, L., Kodešová, R., Fér, M., Nikodem, A., Němec, F., & Prokeš, R. (2021).  
919 The impact of various mulch types on soil properties controlling water regime of  
920 the Haplic Fluvisol. *Soil & Tillage Research*, 205, Article 104748.  
921 <https://doi.org/10.1016/j.still.2020.104748>
- 922 Pihlap, E., Olagaray, N., Klöffel, T., Masters, M. D., D'Ascanio, R., Kantola, I. B.,  
923 Beerling, D. J., & Planavsky, N. J. (2025). Effects of rock amendment on soil  
924 physicochemical properties and organic carbon stabilization. *iScience*, 28(12),  
925 Article 114232. <https://doi.org/10.1016/j.isci.2025.114232>

- 926 Richardson, J. B. (2025). Basalt rock dust amendment on soil health properties  
927 and inorganic nutrients—Laboratory and field study at two organic farm soils in  
928 New England, USA. *Agriculture*, 15(1), Article 52.  
929 <https://doi.org/10.3390/agriculture15010052>
- 930 Rowley, M. C., Grand, S., & Verrecchia, É. P. (2018). Calcium-mediated  
931 stabilisation of soil organic carbon. *Biogeochemistry*, 137, 27–49.  
932 <https://doi.org/10.1007/s10533-017-0410-1>
- 933 Schiedung, M., Harrington, K. J., Dupla, X., Möller, B., Facq, E., Sweere, T., Don,  
934 A., Hilton, R. G., Doetterl, S., & Hemingway, J. D. (2026). Uncertainties of  
935 enhanced rock weathering for climate-change mitigation. *Nature Reviews Earth  
936 & Environment*. <https://doi.org/10.1038/s43017-026-00761-7>
- 937 Slessarev, E. W., Chadwick, O. A., Sokol, N. W., Nuccio, E. E., & Pett-Ridge, J.  
938 (2022). Rock weathering controls the potential for soil carbon storage at a  
939 continental scale. *Biogeochemistry*, 157, 1–13. <https://doi.org/10.1007/s10533-021-00859-8>
- 941 Sokol, N. W., Sohng, J., Moreland, K., Slessarev, E. W., Goertzen, H., Schmidt,  
942 R., Samaddar, S., Holzer, I., Almaraz, M., Geoghegan, E., Houlton, B. Z.,  
943 Montañez, I. P., Pett-Ridge, J., & Scow, K. M. (2024). Reduced accrual of mineral-  
944 associated organic matter after two years of enhanced rock weathering in  
945 cropland soils, though no net losses of soil organic carbon. *Biogeochemistry*, 167,  
946 989–1005. <https://doi.org/10.1007/s10533-024-01160-0>
- 947 Steinwider, L., Boito, L., de Schutter, A., Frings, P. J., Miladinović, N., Niron, H.,  
948 Rijnders, J., Roussard, J., van Acker, K., van Gerven, T., Vienne, A.,  
949 Watjanatepin, P., & Vicca, S. (2026). Higher inorganic CO<sub>2</sub> removal despite  
950 slower weathering in an enhanced weathering experiment with steel slags and  
951 basalt. *Global Change Biology*, 32, e70666. <https://doi.org/10.1111/gcb.70666>
- 952 Steinwider, L., Boito, L., Frings, P. J., Niron, H., Rijnders, J., de Schutter, A.,  
953 Vienne, A., & Vicca, S. (2025). Beyond inorganic C: Soil organic C as a key  
954 pathway for carbon sequestration in enhanced weathering. *Global Change  
955 Biology*, 31, e70340. <https://doi.org/10.1111/gcb.70340>
- 956 Taylor, L. L., Quirk, J., Thorley, R. M. S., Kharecha, P. A., Hansen, J., Ridgwell,  
957 A., Lomas, M. R., Banwart, S. A., & Beerling, D. J. (2016). Enhanced weathering  
958 strategies for stabilizing climate and averting ocean acidification. *Nature Climate  
959 Change*, 6, 402–406. <https://doi.org/10.1038/nclimate2882>
- 960 Vereecken, H., Weihermüller, L., Assouline, S., Šimůnek, J., Verhoef, A., Herbst,  
961 M., Archer, N., Mohanty, B. P., Montzka, C., Vanderborght, J., Balsamo, G.,  
962 Bechtold, M., Boone, A., Chadburn, S., Cuntz, M., Cuxart, J., de Rosnay, P., de  
963 Vrese, P., Dietrich, O., ... Xue, Y. (2019). Infiltration from the pedon to global grid

- 964 scales: An overview and outlook for land surface modeling. *Vadose Zone Journal*,  
965 18(1), 180191. <https://doi.org/10.2136/vzj2018.10.0191>
- 966 Vereecken, H., Huisman, J. A., Bogaen, H., Vanderborght, J., Vrugt, J. A., &  
967 Hopmans, J. W. (2008). On the value of soil moisture measurements in vadose  
968 zone hydrology: A review. *Water Resources Research*, 44(4), W00D06.  
969 <https://doi.org/10.1029/2008WR006829>
- 970 van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic  
971 conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44(5),  
972 892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>
- 973 Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A.,  
974 Peñuelas, J., Poblador, S., Rijnders, J., Sardans, J., Struyf, E., Swoboda, P., van  
975 Groenigen, J. W., Vienne, A., & Verbruggen, E. (2022). Is the climate change  
976 mitigation effect of enhanced silicate weathering governed by biological  
977 processes? *Global Change Biology*, 28(3), 711–726.  
978 <https://doi.org/10.1111/gcb.15993>
- 979 Vienne, A., Frings, P. J., Poblador, S., Steinwider, L., Rijnders, J., Schoelynck,  
980 J., Vindušková, O., & Vicca, S. (2024). Earthworms in an enhanced weathering  
981 mesocosm experiment: Effects on soil carbon sequestration, base cation  
982 exchange and soil CO<sub>2</sub> efflux. *Soil Biology and Biochemistry*, 199, 109596.  
983 <https://doi.org/10.1016/j.soilbio.2024.109596>
- 984 Xu, T., Li, H., Vicca, S., Goll, D. S., Beerling, D. J., Chen, Q., Bi, B., Yang, Z.,  
985 Wang, X., & Yuan, Z. (2025). Enhanced rock weathering promotes soil organic  
986 carbon accumulation: A global meta-analysis based on experimental evidence.  
987 *Global Change Biology*, 31, e70483. <https://doi.org/10.1111/gcb.70483>
- 988 Yang, Y., Kosaka, G., Uchibayashi, H., Zhu, Y., Kuramochi, K., Shinano, T.,  
989 Watanabe, T., Maruyama, H., Hamamoto, S., Nakao, A., & Toma, Y. (2025).  
990 Enhanced CO<sub>2</sub> removal and improved carbon budget by enhanced rock  
991 weathering: A field experiment in Hokkaido, Japan. *Nutrient Cycling in*  
992 *Agroecosystems*, 131, 47–64. <https://doi.org/10.1007/s10705-025-10414-8>
- 993 Yapa, L. G. G., Fritton, D. D., & Willatt, S. T. (1988). Effect of soil strength on root  
994 growth under different water conditions. *Plant and Soil*, 109, 9–16.  
995 <https://doi.org/10.1007/BF02197574>
- 996 Zhou, Z., Wang, J., Wu, Y., Xue, J., Hua, J., & Yu, C. (2025). Rock powder  
997 amendment mitigates microplastic-induced destabilization of soil organic carbon  
998 by modulating molecular composition and microbial assembly. *Geoderma*, 462,  
999 Article 117534. <https://doi.org/10.1016/j.geoderma.2025.117534>
- 1000 Zhu, Y., Tatsuno, T., Yang, Y., Uchibayashi, H., Toma, Y., Shinano, T., Maruyama,  
1001 H., Kashiwagi, J., Nakao, A., Nishimura, T., & Hamamoto, S. (2025). Soil physical  
1002 properties and soil CO<sub>2</sub> dynamics at soybean field under basalt powder

1003 application. Soil Science Society of America Journal, 89(5), Article e70136.  
1004 <https://doi.org/10.1002/saj2.70136>

## **Supplementary information**

# **Impacts of enhanced rock weathering on soil sponge function: a global synthesis of soil physical and hydrological responses**

*Behrouz Gholamahmadi, Lucilla Boito, Laura Steinwider, Sara Vicca*

## **Contents**

Figure S1. PRISMA flow diagram of study identification and selection

Table S1. Study-by-variable coverage matrix

Supplementary Figures S3–S5. Explanation and guide to the observation-level distribution plots provided in the accompanying ZIP archive

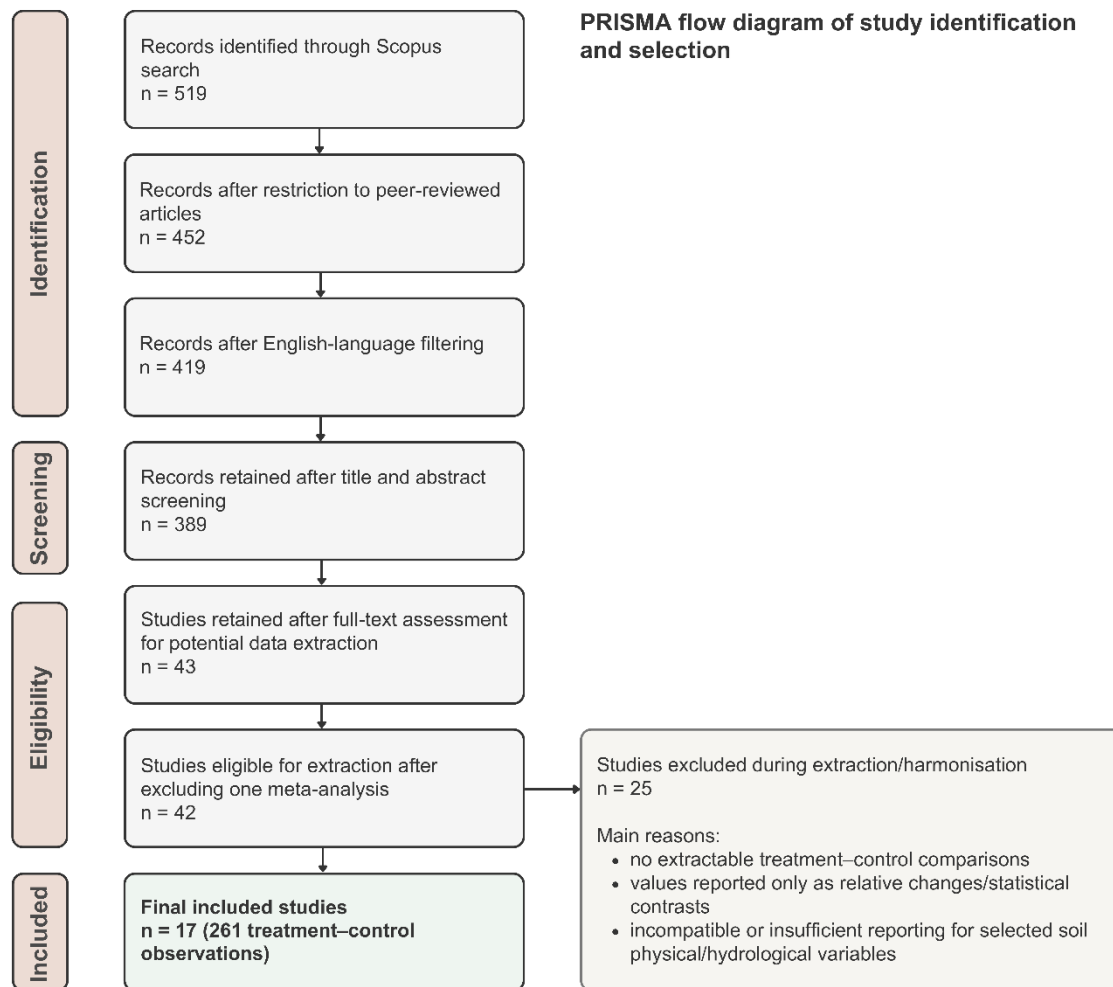


Figure S1. PRISMA-style flow diagram of study selection. The literature search identified 519 records in Scopus. After filtering for peer-reviewed articles and English-language publications, 419 records remained. Title and abstract screening retained 389 records for full-text assessment. Forty-three studies were initially

retained; one was excluded because it was a meta-analysis rather than an experimental study. Of the remaining 42 studies assessed for data extraction, 25 were excluded because they did not provide extractable treatment–control comparisons for the selected soil physical and hydrological variables, or because values were reported only as relative changes, statistical contrasts, or insufficiently compatible formats. The final dataset included 17 independent studies and 261 treatment–control observations.

Table S1. Study-by-variable coverage matrix for the structured evidence synthesis. Values indicate the number of treatment–control observations extracted for each soil physical or hydrological variable from each study. Dashes indicate that the variable was not extracted from that study. Abbreviations: AS, aggregate stability; BD, bulk density; PR, penetration resistance; SMC, soil moisture content; FC, field capacity; PAW, plant available water; PWP, permanent wilting point; WR, water retention at –100 kPa; RW, residual water content; P, porosity; IR, infiltration rate; Ksat, saturated hydraulic conductivity; Kunsat, unsaturated hydraulic conductivity.

Study	Year	AS	BD	PR	SMC	FC	PAW	PWP	WR	RW	P	IR	Ksat	Kunsat
Akortey	2026	8	–	–	–	8	8	8	–	–	–	–	8	–
Pihlap	2025	–	2	–	–	2	2	2	–	–	2	–	–	–
Armah	2025	–	7	–	–	7	–	–	–	–	7	–	–	–
Costanzo	2025	5	–	10	–	5	5	5	5	–	–	–	–	5
Zhou	2025	–	1	–	–	1	–	–	–	–	2	–	–	–
Richardson	2025	2	25	–	–	–	–	–	–	–	–	–	–	–
Zhu	2025	–	1	–	–	–	–	–	–	1	2	–	–	–
Boito	2025	–	–	–	6	–	–	–	–	–	–	–	–	–
Yang	2025	–	–	–	1	–	–	–	–	–	–	–	–	–
Obour	2024	–	9	–	–	–	–	–	–	–	–	–	–	–
Medeiros	2024	–	–	–	8	–	–	–	–	–	–	–	–	–
Oladele	2024	6	6	–	–	–	–	–	–	–	6	6	–	–
Dupla	2024	12	6	–	–	–	–	–	–	–	–	6	–	–
Chiaravalloti	2023	–	–	–	6	–	–	–	–	–	–	–	–	–
Pavlu	2021	2	2	–	–	–	–	–	–	2	2	–	2	–
Kelland	2020	–	–	–	–	–	–	–	–	–	–	1	–	–
Naseri	2019	–	13	–	–	–	–	–	–	–	13	–	–	–

### **Supplementary Figures S3–S5: Observation-level distributions**

Observation-level plots are provided separately in the accompanying ZIP archive, `Supplementary_Figures_S3-S5.zip`, because several figures are too long to be displayed clearly within the Supplementary Information PDF.

The archive contains:

Figures S3.1–S3.3: soil structural variables

Figures S4.1–S4.6: soil water variables

Figures S5.1–S5.4: soil hydraulic variables

Each point represents one treatment–control observation. The code shown for each point corresponds directly to the `observation_id` in the accompanying dataset, allowing every plotted value to be linked to its study, treatment, soil depth, sampling time, and experimental condition.

Relative changes greater than 0% indicate an increase under ERW, values below 0% indicate a decrease, and 0% indicates no difference from the corresponding control.

A README file included in the ZIP archive provides additional guidance for interpreting the figures.