

# Soil Remineralization in Agroecological Systems: A Critical Review

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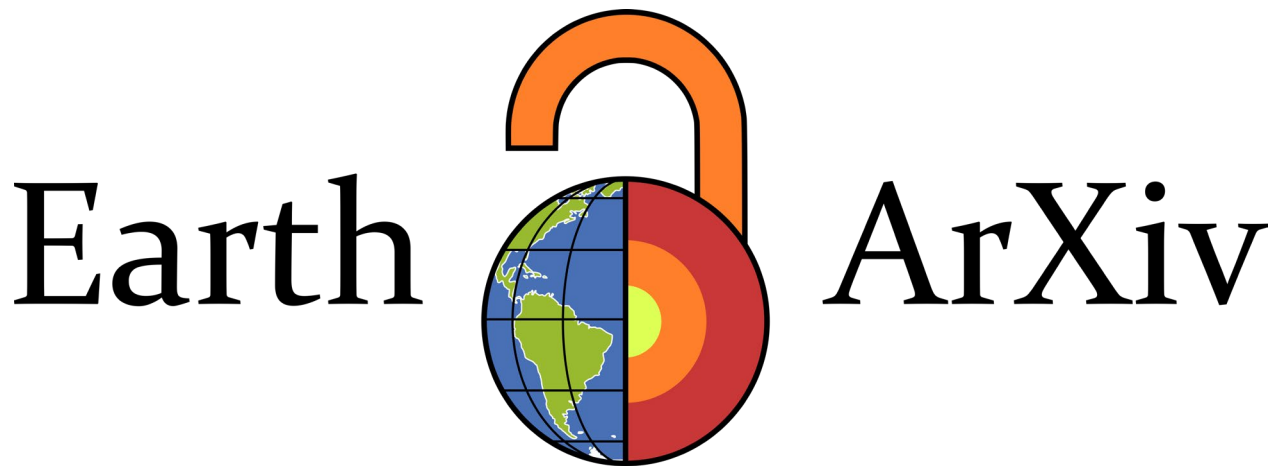
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## Abstract

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Soil degradation threatens global food security, human nutrition, biodiversity, water resources, and climate stability by depleting soil organic matter, exhausting nutrient reserves, and disrupting carbon and nitrogen cycles. Conventional input-intensive agriculture has delivered yield gains but has also contributed to widespread micronutrient deficiencies, nutrient loading of waterways, soil erosion, and greater vulnerability to climate extremes. Soil remineralization, using finely ground, often locally sourced silicate and related rock powders co-applied with organic and biological amendments, offers a nature-based strategy to rebuild soil health and resilience while reducing dependence on synthetic fertilizers. Historical and contemporary evidence indicate that soil remineralization can enhance crop yields, nutrient uptake, soil structure, and carbon storage, especially on highly weathered or degraded soils. However, the use of inappropriate rock types, excessive application rates, and narrow carbon-offset framings poses agroecological risks.

Here we review soil remineralization in agroecological systems by integrating biogeochemical theory, a historical survey, and a new synthesis of 191 experimental and field observations. The major contributions of our review are:

- 1) Of the 191 tests reviewed, 87% show yield or biomass increases and 89% show enhanced plant nutrient uptake. These results suggest that, when appropriately implemented, soil remineralization can serve as an effective agroecological strategy to address food security, nutrient deficiencies, and environmental impacts.
- 2) Outcomes depend critically on a dynamic biogeochemical/agronomic system in which mineralogy, biology, grain-size-controlled weathering kinetics, rhizosphere processes, and nutrient toxicity thresholds jointly govern benefits and risks over decadal timescales.
- 3) Experimental and field evidence show that the co-application of rock dusts with organic inputs, biochar, and microbial inoculants ("biomineral" amendments) consistently outperforms rock dust alone for yield, root growth, soil properties, and carbon sequestration.
- 4) Soil remineralization's greatest potential lies in enhancing a multifunctional suite of ecosystem services, including nutrient cycling, water regulation, biodiversity support, and lasting carbon storage.

**Keywords:** Soil remineralization, Rock dust amendments, Soil biogeochemistry, Agroecology, Ecosystem services, Enhanced rock weathering

# Contents

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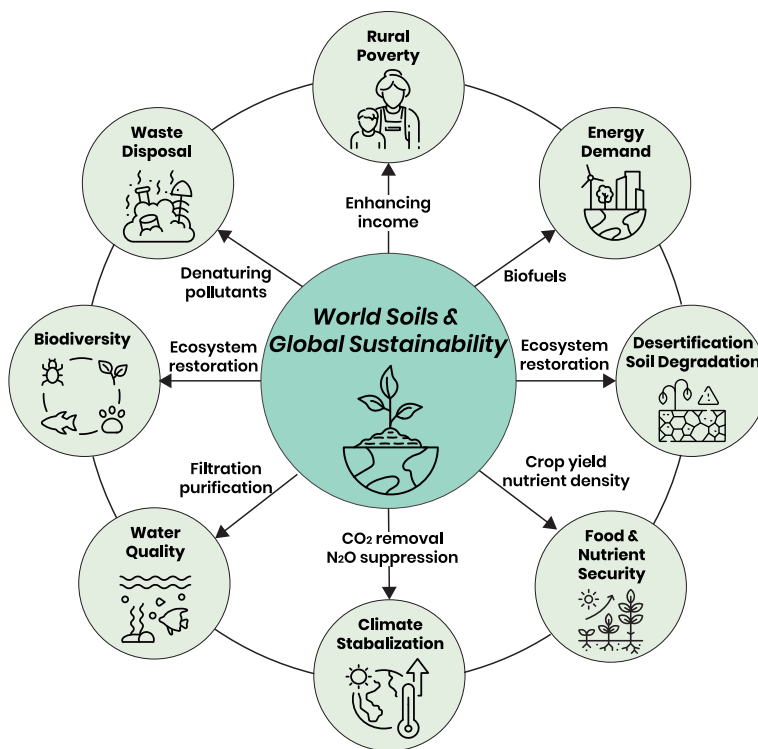
<b>Cover Page</b> .....	<b>i</b>
<b>Abstract</b> .....	<b>ii</b>
<b>I Introduction</b> .....	<b>I</b>
<b>2 Biogeochemistry of Soil Remineralization</b> .....	<b>4</b>
2.1 The Urgent Need for Improved Nutrient Balance in Soils .....	4
2.2 Soil Remineralization and Essential Nutrients .....	6
2.3 Nutrient Element Imbalance and Toxicity .....	8
2.4 Rock Dust Weathering and Nutrient Element Release in the Rhizosphere .....	11
2.5 Soil Remineralization and Climate Stabilization.....	15
<b>3.0 Review of Historical Observations and Scientific Findings</b> .....	<b>18</b>
3.1 Historical Observations .....	18
3.2 Survey of Research Findings.....	27
3.3 Evidence for Nutrient Uptake from Soil Remineralization.....	29
3.4 Combining Rock Dust with Biomass-Based Amendments: Biominerals .....	31
<b>4.0 Incentivizing Broad Adoption of Soil Remineralization</b> .....	<b>36</b>
4.1 Incentivization and Financing of Rock Dust-Based Carbon Dioxide Removal.....	36
4.2 Holistic Soil Remineralization for Soil Revitalization and Carbon Dioxide Removal.....	37
<b>5.0 Conclusion</b> .....	<b>40</b>
<b>Declarations</b> .....	<b>41</b>
Preprint Status.....	41
Availability of data and material .....	41
Authors' contributions .....	41
Conflicts of interest/Competing interests .....	41
Ethics approval .....	41
Funding.....	41
Acknowledgements.....	40
<b>Supplementary Information</b> .....	<b>42</b>
Equations and Parameter Sources for Reaction Path Model .....	42
<b>References</b> .....	<b>45</b>

# I Introduction

Soil health is central to solving humanity's most urgent sustainability challenges, such as food insecurity, nutrient deficiencies, water pollution, climate change, and declining biodiversity. World Food Prize recipient Professor Rattan Lal underscores the significance of the connection between soil health and human well-being:

*“Basic ecosystem services provisioned by soils include food, feed, fiber, fuel, water resources, industrial raw materials, construction materials, etc. Thus, sustainable management of soils is critical to achieving food and nutritional security, adapting to and mitigating climate change, enhancing rural income, eliminating poverty, empowering minorities, and promoting the overall sustainable development. In addition, soil is also important for numerous spiritual, cultural, and aesthetical uses and to the overall societal well-being. However, competing uses of soil and over exploitation can exacerbate degradation and jeopardize sustainability. Thus, soil use must be prioritized critically and objectively.” (Lal, 2014)*

The key relationships between world soils and pressing societal issues are summarized in Fig. 1.



**Figure 1.** Diagram of how world soils impact multiple global sustainability issues through ecosystem services (adapted from Lal, 2008).

It has been argued that restoring and maintaining soil health to obtain these societal benefits requires a whole system approach that accounts for the complex array of interdependent biological, geological, and chemical processes that underlie soil vitality (e.g., Lal, 2008; Fausak et al., 2024; Lal, 2020; Lehmann et al., 2020). What is needed for restoring and maintaining soil health is a nature-based holistic approach that i) minimizes soil disturbance, ii) removes or lessens the need for synthetic fertilizers, herbicides, and pesticides, iii) improves soil properties (chemical and physical), iv) bolsters plant health and v) boosts crop yield and nutrient density (Mrunalini et al., 2022). The following review offers an empirical, historical, and knowledge-based assessment of a traditional agricultural practice that can be an essential part of meeting these criteria for restoring and maintaining soil health.

The primary hypothesis we explore is that soil remineralization (SR), a well-studied approach

to soil restoration, meets the criteria listed above when practiced responsibly as a holistic biogeochemical

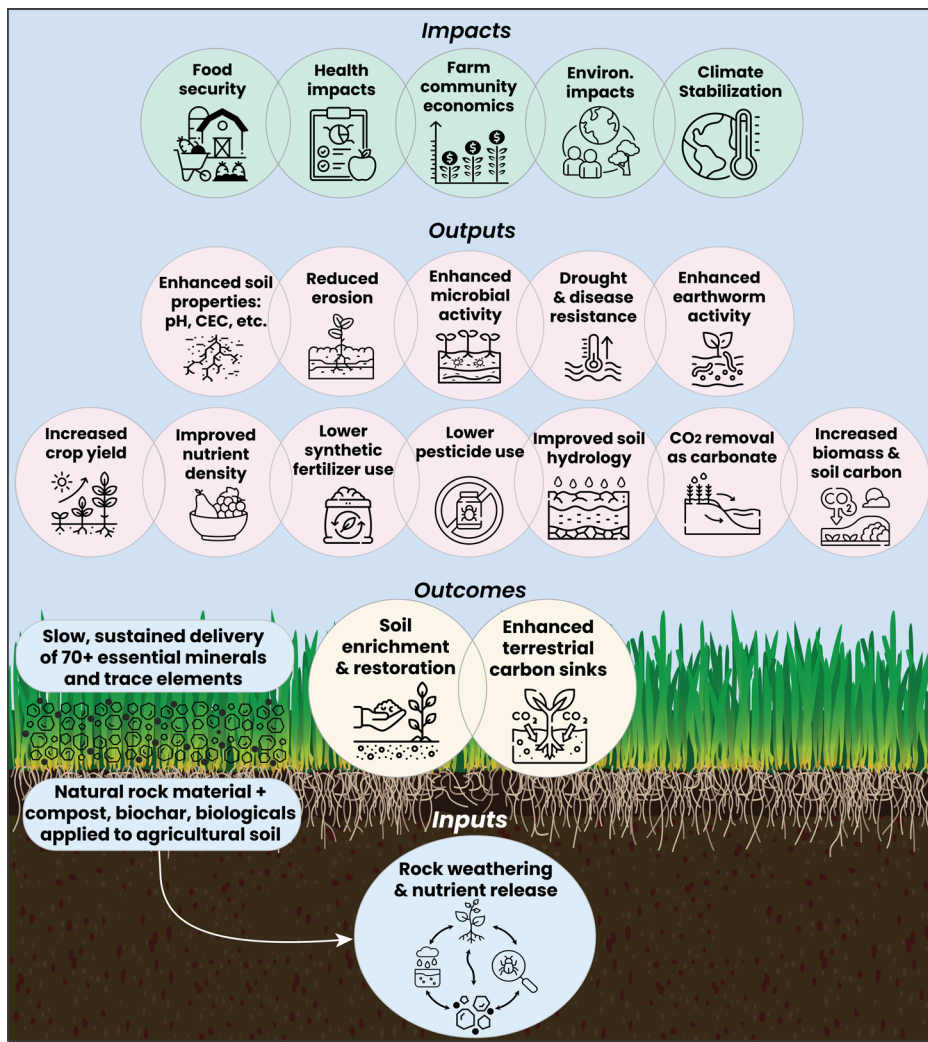
intervention. SR, as defined in this study, involves applying finely ground natural rock material (rock dust), often locally sourced, to agricultural lands and forest floors to enhance the soil's biological, physical, hydrological and chemical properties (e.g., Magnus, 1850; Hensel, 1894; Hamaker, 1982; Chesworth et al., 1983; Campe, 1986; Leonardos et al., 1987; Leonardos et al., 2000; Harley and Gilkes, 2000; van Straaten, 2002; van Straaten, 2006; van Straaten, 2007; Winiwarter and Blum, 2008; Campe et al., 2014; Manning, 2015; Beerling et al., 2018; Theodoro et al., 2021; Swoboda et al., 2022; Ramos et al., 2022; Mir et al., 2024; Son et al., 2024; Bucka et al., 2024). Thus, SR is a nature-based approach that relies exclusively on natural materials such as rock dusts and mineral separates, rather than synthetic fertilizers.

Soil remineralization has been classed as a form of "geotherapy" (Goreau et al., 2014). Geotherapy practices differ from many types of geoengineering interventions in that they work in harmony with natural systems to reinvigorate and rebalance biogeochemical and ecological processes, rather than relying on technological solutions that replace or redirect these systems (Goreau et al., 2014). The geotherapy approach aims to provide low-cost, community-adopted sustainable solutions to complex problems such as soil degradation and climate change in ways that complement natural cycles at local and regional scales.

Soil remineralization is also the core practice within the field of agrogeology, which is defined as "geology in the service of agriculture" (van Straaten, 2007). Agrogeology is an interdisciplinary science combining expertise and methodologies from geology, soil science, agronomy, chemistry, and biology. This field of study is closely allied with agroecology, which emphasizes a holistic, integrated approach to agriculture that applies ecological and social principles to design and manage sustainable food and farming systems (e.g., Altieri, 1996). Agrogeology complements agroecology by focusing on the use of natural geological materials, often mill fines from quarries and mines, to restore and sustain soil fertility.

The effectiveness of SR has been especially recognized in predominantly tropical countries with highly weathered soils, such as Brazil. Researchers have noted that SR is effective in such areas because the locally and regionally available rock types offer broad spectrum nutrient profiles and improve chemical and physical soil properties in ways that the imported synthetic salt fertilizers do not. For example, in a 2000 review paper, Othon Leonardos, Suzi Huff Theodoro, and Maria-Leonor Lopes Assad make the following important observations:

*"A land management model has been developed with technology that has been transferred from countries with temperate soils without taking into account basic climatic, mineralogical, geochemical, ecological, and cultural differences, which are present in our tropical ecosystem. One such technology has been the indiscriminate use of highly soluble NPK fertilizers. Under deep leached conditions, this strategy does not bring nutrient conservation. As an alternative, or as a support to those "chemical" fertilizers, and as an important step towards sustainable development, we suggest the use of native rocks (stone meal) as the ultimate way to restore to the leached tropical soils, a balanced inorganic composition on which plant growth and biodiversity can thrive". (Leonardos et al., 2000)*



**Figure 2.** Logic model and graphical summary of soil remineralization.

Figure 2 shows a graphical summary and logic model illustrating how soil remineralization can restore leached soils and, in the process, provide ecosystem services and societal benefits.

In this review, we examine four hypotheses that affirm the effectiveness of traditional soil remineralization as practiced within the contexts of geotherapy and agroecology. The hypotheses posit that SR is capable of restoring degraded soil ecosystem services without the use of synthetic fertilizers and offers significant beneficial environmental outcomes and societal impacts (see Fig. 2). To evaluate these hypotheses, our review draws on an extensive body of scientific research and historical observations. The specific hypotheses examined in this study are:

- 1) SR represents an effective agroecological farming practice that can address multiple sustainability challenges simultaneously, including food insecurity, nutrient deficiencies, agricultural environmental impacts, and climate stabilization.
- 2) The successful implementation of SR and related practices, such as enhanced rock weathering, requires an integrated or whole-system approach that accounts for the dynamic interplay of biological, geochemical, agronomic, hydrological, and climatic processes.
- 3) The combination of rock dust with pyrogenic materials (i.e., biochar), organic biomass (e.g., composts), and biological additives (e.g., microbial inoculants) improves soil properties and fertility more than rock dust alone.

4) The ultimate benefit from SR is restoration of the full suite of soil ecosystem services, rather than a singular metric such as carbon removal or crop yield.

A corollary to hypothesis (4) is that the agronomic benefits of SR and the promise of its broader adoption among farming communities will not be realized if pressures for monetization lead to overapplications of rock materials and the use of rock types with imbalanced nutrient profiles and high levels of geogenic contaminants.

To establish a scientific framework for evaluating our core hypotheses, we will first, in Section 2, provide a biogeochemical overview of soil remineralization. Then, in Section 3, we build on this overview to provide a thorough assessment of our core hypotheses through a detailed historical survey of the practice of soil remineralization and a quantitative synthesis of findings from laboratory experiments, mesocosm studies, and field trials.

## **2 Biogeochemistry of Soil Remineralization**

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The geochemical and biological foundations of soil remineralization have been thoroughly reviewed in previous articles (e.g., Leonardos et al., 1987; Harley & Gilkes, 2000; Basak et al., 2017; Lewis et al., 2021; Swoboda et al., 2022). Therefore, in this Section, we will provide an overview discussion of central topics rather than detailed scientific treatments. To underscore the need for improved soil treatments options, we will begin this with an overview of the urgent need for improved nutrient balance in soils.

### **2.1 The Urgent Need for Improved Nutrient Balance in Soils**

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Human-induced nutrient depletion of soils jeopardizes agricultural sustainability and is recognized as a global threat to food and nutritional security (Tan et al., 2005). For example, developing countries experienced a dramatic decrease in the efficiency of synthetic fertilizer (NPK) from the 1960s into the 2000s (Tan et al., 2005). The yield-to-NPK ratio plummeted from 494 kg of crop yield per kg of fertilizer in 1961 to just 71 kg of crop yield per kg of fertilizer in 2000 (Tan et al., 2005). This sharp drop can be attributed to two main factors: (i) low nutrient input: insufficient application of fertilizers to replenish soil nutrients, and (ii) high nutrient depletion: excessive removal of nutrients from the soil due to intensive farming practices without adequate replenishment.

In the US, concerns over nutrient depletion in soils and its implications for human health have been recognized since the 1940s. For example, a 1941 US Department of Agriculture study provided evidence that many nutritional diseases were being caused by the deficiencies or excesses of specific mineral elements in food plants grown in particular types of soils (Beeson, 1941). In the 2000s, a study by the University of Texas reviewed evidence of nutrient declines in fruits and vegetables in the United States and the United Kingdom over the past 50 to 100 years (Davis, 2009). The study found that nutrient content had decreased by varying amounts, ranging from 5% to more than 40%, depending on the specific nutrient and crop examined (Davis, 2009). Specifically, significant declines were observed in the nutrient element content of vegetables, with calcium and copper showing the most substantial decreases. Additionally, the vegetable content of vitamins C, A, and B2 showed declines of 15%, 18%, and 38%, respectively, over the 100-year study (Davis 2009). UK wheat grains have also decreased in zinc and copper concentrations by around 31% and 28%, respectively, since the early 1960s (Weil and Brady, 2017). However, it should be noted that some of the nutrient declines in crops can also be caused

by changes in genetics (varieties) in addition to nutrient depletion in soils. Furthermore, lower micronutrient concentrations in grain may result partly from a “dilution effect,” in which similar amounts of micronutrients are taken up but are distributed across a larger grain yield (Weil and Brady, 2017).

Regardless of the specific mechanisms, there is a clear need for improved nutrient balance in soils and nutrient density in crops. It is estimated that nearly 25% of the world's population is deficient in micronutrients (Thompson and Amoroso, 2011), and this deficiency has lasting, detrimental effects on children that persist into adulthood (Kiani et al., 2022). Micronutrient deficiencies have been shown to impair physical and cognitive development in children and weaken immune system function, leading to risks of acute and chronic diseases (Kiani et al., 2022). The low levels of bioavailable nutrients in agricultural soils are recognized as the major cause of nutrient deficiencies worldwide (Morton et al., 2023). For example, globally, around 50% of soils used for cereal production contain low levels of plant-available zinc (Fageria et al., 2002). This deficiency both reduces crop yield and results in nutritionally deficient grains.

Fageria et al. (2002) identify several factors causing nutrient element deficiencies in crop plants, including:

- Intensive farming practices and the use of high-yielding cultivars which often require more micronutrients.
- Cultivation on marginal soils that lack essential nutrients.
- Increased reliance on synthetic fertilizers containing minimal micronutrient concentrations.

As will be discussed in Section 3 below, there is substantial scientific and historical evidence supporting the hypothesis that soil remineralization using rock dusts is an effective nature-based practice for mitigating soil and crop nutrient deficiencies and thus represents a promising approach for improving global nutritional security (e.g., Bakken et al., 1996; Berge et al., 2012; Anda et al., 2013; Silva et al., 2014; Silva et al., 2014; Dahlin et al., 2015; Tavares et al., 2018; Crusciol et al., 2019; Kelland et al., 2020; Busato et al., 2022; Conceição et al., 2022; Krahl et al., 2022; Medeiros et al., 2024; Beerling et al., 2024; Richardson, 2025; see also studies listed in RTE Dataset available under Open Science Framework project: (<https://doi.org/10.17605/OSF.IO/8JTNM>)).

In this respect, SR can be thought of as a form of agronomic biofortification. As discussed below, widely available natural rock powders such as basalt are particularly well suited for agronomic biofortification because they contain a broad spectrum of nutrient elements contained in silicate minerals. Increases in crop yields in response to the application of micronutrient-rich fertilizers have been reported in many parts of the world (Fageria et al., 2002). However, correcting crop nutrient deficiencies is more complex than simply delivering the nutrient-dense rock materials to the soil; bioavailability is the key. As will be discussed below, rock dust amendments may do more than simply balance the total nutrient profile of the soil, they also (i) alter soil chemistry to improve nutrient element speciation, (ii) support beneficial microorganisms that symbiotically aid plants in nutrient uptake, (iii) produce clay minerals that enhance improve nutrient storage and cycling and (vi) increase in soil organic matter and water retention capacity (for a complete list of the potential beneficial outcomes of soil remineralization see Section 3).

That is, silicate rock dusts, such as basalt and compositionally similar lithologies, enrich the soil system as a whole, improving its biological, geochemical, hydrological, and physical properties. This is in contrast to

common synthetic fertilizers, which are typically lacking in essential micronutrients. Furthermore, the slow to moderate dissolution/weathering kinetics of rock dust minerals make them superior to the commonly used, highly soluble and acidic synthetic fertilizers (e.g., ammonium sulfates and phosphates) for long-term soil health (Ranva et al., 2022). The slow-release fertilization and broad suite of minor and trace elements in silicate rocks are particularly effective for building and maintaining beneficial micro and macro-organism communities (Ribeiro et al., 2020). In the following Section, we will present an overview of the major and minor nutrient elements that silicate rocks provide when used as agricultural amendments.

## **2.2 Soil Remineralization and Essential Nutrients**

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In addition to carbon, hydrogen, and oxygen, there are 15 nutrient elements that are essential for plant growth (Bindraban et al., 2015). The typical concentration ranges of these elements in the cereals maize, wheat, and rice are shown in Table I. This table also provides the concentrations of essential nutrient elements in some typical rock types used for soil remineralization. In general, nutrient elements present in crop plants at levels of thousands of ppm (mg/kg) are considered macronutrients, while those present at levels of hundreds to tens of ppm are considered micronutrients.

In addition to the crucial roles that the elements shown in Table I play in plant growth, health, and resilience, they are also essential for human and animal health, where they play key roles in metabolic processes (Fageria et al., 2002; Bindraban et al., 2015; Monib et al., 2023). Thus, by enriching soils in these elements through the addition of broad-spectrum nutrient sources such as basaltic rock dust, farmers can both improve crop health and produce healthy, nutrient-dense foods. This relates to our first hypothesis, that SR can address food insecurity, nutrient deficiencies, in addition to environmental issues. Scientific and historical observations supporting this hypothesis will be presented in Section 3 below.

**Table 1.** Nutrient elements in typical crop plants and major rock types. The composition range abstracted from (Dobermann, 2000; Campbell, 2000; Schwab et al., 2007; Bindraban et al., 2015). Rock compositions are from Johnson, et al., 1999 (USGS reference materials), with N, Mo, S, Cl and B concentrations derived from (Earley, 1958; Moore and Fabbri, 1971; Fuge, 1979; Muramatsu and Wedepohl, 1979; Mevel et al., 1996; Hall, 1999; Busigny et al., 2005; Bailey, 2006; Liang et al., 2017; Yang et al., 2017; Caruso et al., 2022; Ma et al., 2022; Evans et al., 2024). Differences between Basalt 1 and Basalt 2 provide an example of the compositional range for this rock type.

<b>Element</b>	<b>Range for typical cereals<sup>1</sup> (mg/kg)</b>	<b>Granite (mg/kg)</b>	<b>Basalt 1 (mg/kg)</b>	<b>Basalt 2 (mg/kg)</b>	<b>Peridotite (mg/kg)</b>
Nitrogen	30,000-40,000	~35	1-4	1-4	0
Potassium	15,000-30,000	37,605	166	14,527	0
Phosphorus	2,000-5,000	611	131	1,615	44
Calcium	1,500-8,000	13,937	95,774	50,889	4,145
Magnesium	1,500-8,000	4,462	58,795	21,046	280,890
Sulphur	1,500-6,000	~50	~100	~100	~400
Silicon	1,000-5,000	327,104	223,383	259,608	206,368
Chloride	1,000-5,000	50-500	50-500	50-500	~1,000
Iron	30–250	18,811	83,482	94,519	60,940
Manganese	15–150	232	1,394	1,471	929
Zinc	20–70	84	70	128	50
Boron	5–20	12	5	5	5-80
Copper	5–25	8	126	16	22
Molybdenum	0.1–2.0	~1	1-5	1-5	<1
Nickel	0.05–5	6	161	<1	2,378

It should also be noted that, beyond the 15 core major and minor elements, highlighted in Table 1, recent research demonstrates that several additional trace elements, including lanthanum and other rare earth elements (REEs), perform crucial functions in plant physiological and genetic processes. For example, He et al. (2019) showed that lanthanum can influence DNA methylation, gene expression, and seed germination at extremely low concentrations, acting as a regulator of cell division and affecting root architecture in model plants such as *Arabidopsis* and crop species like *Brassica*. Increasing evidence highlights that while the essentiality of these trace REEs is under ongoing debate, their positive and dose-dependent impacts on DNA replication, enzyme activity, and plant development underpin their emerging significance in plant biology and biofortification discussions (e.g., He et al., 2019; McGaughey et al., 2025).

As shown in Table 1, common rock types such as granite and basalt can be excellent sources of potassium, phosphorus, calcium, magnesium, silicon, manganese, zinc, copper, and molybdenum. Common rock dusts also contain nickel, which is an essential trace nutrient but can become toxic at relatively low soil concentrations (~50 mg/kg). Therefore, the selection of rock types for SR should involve careful analyses of the whole rock chemistry, including trace elements. It is also important to note that not all of the nutrient elements provided by rock dust will be bioavailable to plants as the rock dust weathers. For example, some elements may be

incorporated into secondary minerals that form during rock weathering, and some elements may be irreversibly adsorbed to mineral surfaces, depending on pH. The geochemical speciation and action of plant-symbiotic microorganisms play key roles in determining the phytoavailability of these nutrients in soil; therefore, they must be understood to optimize SR projects.

Rock dusts used for SR do not supply all essential nutrient elements, for example, most contain little or no nitrogen. However, their balanced, broad spectrum of macro- and micro-nutrients can enhance the cycling and plant availability of key elements (especially nitrogen) by enhancing the activity of beneficial microbial communities and by providing reactive mineral surface area for bioavailable nutrient storage. Specifically, iron, manganese, copper, zinc, molybdenum, and nickel are recognized as essential micronutrients for the health and function of plant-beneficial microbial communities within soil ecosystems. These metals serve as cofactors in a broad array of microbial enzymatic processes that underpin critical biogeochemical cycles, such as nitrogen fixation, organic matter decomposition, and respiration (Fageria et al., 2002).

Rock dust applications also contribute significant amounts of calcium and magnesium to soils, and in many cases can nearly saturate the soil's cation exchange sites with these key elements. Calcium, in particular, improves soil aggregation by binding to organic matter and clay particles, supporting soil organic carbon stabilization (Weil and Brady, 2017). However, it is important to keep the calcium-to-magnesium ratio within the range of 1:1 to 15:1 for optimal plant growth (Weil and Brady, 2017). This suggests that when soil remineralization practitioners use magnesium-rich ultramafic rock such as dunite or olivine mineral separates, soil compositions should be monitored to ensure that calcium-to-magnesium ratios remain in the optimal zone.

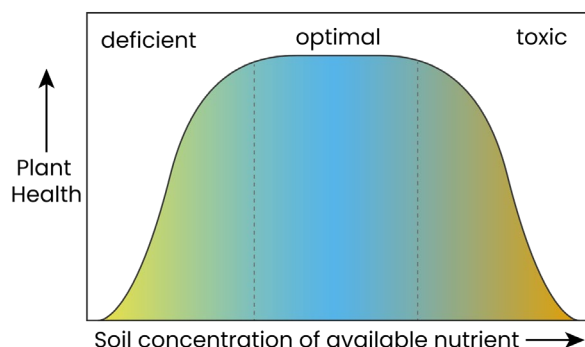
Silicon is not universally recognized as an essential plant nutrient, but is included in Table I because of its ubiquity in silicate rocks and its crucial role in plant resistance to biotic and abiotic stresses. Silicon polymerizes in plant cell walls to form phytoliths, which prevent pathogen penetration and reduce disease severity (Song et al., 2021). Silicon also boosts plants' physical and chemical defences by increasing the activity of defence-related genes and compounds, making them less vulnerable to being eaten by herbivores (Singh et al., 2020). Relatively high silicon concentrations in plants have also been observed to improve drought tolerance by reducing transpiration rates, enhance heat stress tolerance, and mitigate heavy metal toxicity by modulating metal uptake and distribution within plants (Mir et al., 2022; Soni et al., 2024).

### **2.3 Nutrient Element Imbalance and Toxicity**

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As mentioned above and reiterated below, there are many beneficial effects of amending soils with rock materials containing a broad spectrum of beneficial nutrient elements. However, using natural rock materials can come with some risks as well. One of the primary risks is overapplying rock dust, especially if it contains moderate to high concentrations of geogenic contaminants (e.g., Hartmann et al., 2013; Dupla et al., 2023). It is therefore essential for soil remineralization applications to be guided by a systems approach that accounts for site-specific soil properties (physical, chemical, biological) and the potential for element toxicities. Soil biogeochemistry is complex and dynamic, involving both negative and positive feedback loops that affect nutrient element bioavailability and potential toxicity. This topic thus relates to hypothesis (2) of this paper: that the successful application of SR requires an integrated or whole-system approach.

For every nutrient element–crop plant combination, soil concentrations range from deficient at the low end, which restricts plant growth, to toxic at the high end, which causes damage. The intermediate zone represents the optimal concentration range for plant health (Fig. 3). It is important to note that nutrient toxicity and deficiency are not determined solely by individual elements. Instead, interactions among multiple elements can influence deficiency-toxicity ranges for a particular plant/soil biogeochemical scenario. For example, enzymatic and biochemical reactions that depend on a specific micronutrient may be inhibited if another trace element is present at toxic levels. Likewise, adverse effects can occur when one element competes with or interferes with the root’s ability to absorb another element (Weil and Brady, 2017). These observations again underscore the need for a whole-system approach that accounts for micronutrient balancing in planning SR applications.



**Figure 2.** Conceptual figure showing the relationship between deficient, optimal, and toxic ranges for bioavailable nutrient elements (adapted from Weil and Brady, 2017, Figure 15.11).

As an example of the type of information needed to plan a soil remineralization application successfully, Table 2 summarizes the optimal, toxic, and deficient soil concentration ranges of bioavailable essential nutrient elements for maize (*Zea mays*). Values are given per kilogram of dry soil and based on commonly used extraction methods. It should be noted that toxicity thresholds ultimately depend on soil type, pH, and crop variety; some nutrients may cause toxicity at lower or higher concentrations, so that local calibration may be required.

**Table 2.** Bioavailable (extractable) nutrient element deficiency and toxicity ranges in soils for maize (*Zea mays*). Ranges from Amjad et al., 2020; Aliyu et al., 2021; Chrysargyris et al., 2022; Lakhneko et al., 2024.

<b>Nutrient</b>	<b>Deficiency</b> (mg/kg in soil)	<b>Optimal</b> (mg/kg in soil)	<b>Toxicity</b> (mg/kg in soil)
Nitrogen (N)	<15	15-40	>50 (rare)
Phosphorus (P)	<10	10-30	>50
Potassium (K)	<80	80-200	>250
Calcium (Ca)	<400	400-2,500	>3,000
Magnesium (Mg)	<50	50-300	>400
Sulfur (S)	<10	10-50	>60
Zinc (Zn)	<0.9	0.9-5	>5
Copper (Cu)	<0.2	0.2-2	>5
Manganese (Mn)	<2	2–20	>100
Iron (Fe)	<5	5–100	>200
Boron (B)	<0.1	0.1–1	>1
Molybdenum (Mo)	<0.05	0.05-0.2	>0.5
Nickel (Ni)	<0.1	0.1-1.5	>50-100
Silicon (Si)	<10	40-150	>2,500

Soil contamination from SR is a concern mainly when rocks with high concentrations of potentially toxic elements are used (e.g., the Ni content of peridotite; Table 1). The risk also increases under deployment scenarios with high and repeated application rates, such as those proposed for the rock powder-based carbon dioxide removal strategy referred to as enhanced rock weathering (ERW). For example, Dupla et al. (2023) conclude that repeated applications of basaltic rock powder at rates typical of proposed large-scale ERW (10–100 t ha<sup>-1</sup> yr<sup>-1</sup>) could substantially increase soil concentrations of copper, nickel, chromium, and zinc. Their models predict that these accumulations would likely exceed national regulatory thresholds within a decade. This rapid approach to environmental limits is especially pronounced for copper and nickel, increasing the likelihood of regulatory issues due to high and repeated application rates. Such accumulations of potentially toxic elements could compromise both agricultural productivity and food safety. Given these constraints, Dupla et al. (2023) highlight the urgent need for re-evaluation of ERW deployment strategies to align with environmental stewardship and regulatory compliance. They suggest that sustainable ERW implementation may require lower application rates, extended intervals between rock additions, or the use of basalt sources selected for reduced concentrations of potentially toxic elements.

Macronutrient elements can also lead to toxicity under certain circumstances. For example, significant magnesium-calcium imbalances occur in soils derived from ultramafic rocks, which often exhibit very high magnesium levels and deficient calcium concentrations. This chemical imbalance can lead to magnesium toxicity and severe calcium limitation, creating an inhospitable rhizosphere for most plant species (Weil and Brady, 2017). Only a small subset of plants adapted to these conditions can thrive, resulting in naturally sparse and stunted vegetation compared with that of adjacent non-ultramafic soils. Such environments illustrate the potential ecological impact of pronounced magnesium dominance, while also underscoring the need for field-based evidence to clarify magnesium’s role in more typical agricultural contexts (Weil and Brady, 2017). These

observations underscore the necessity for a comprehensive, whole-system approach to SR applications that considers the balance of all essential nutrient elements and avoids detrimental overapplication.

## **2.4 Rock Dust Weathering and Nutrient Element Release in the Rhizosphere**

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The nutrient elements in rock dust become available to crops (and thus to animals and humans) through chemical, physical, and biological weathering. The effectiveness of a particular type of rock dust for soil remineralization and carbon sequestration depends on a complex web of interdependent rock and soil properties and processes. For example, soil pH, texture, moisture content, redox conditions, microbial activity, plant root exudations, organic matter content, and the mineralogy and chemistry of both rock and soil are crucial in determining weathering rates, nutrient cycling, and chemical speciation in the rhizosphere. This directly impacts the bioavailability of rock dust-supplied nutrients to plants and microorganisms. Additionally, the biological influence on rock dust mineral weathering rates plays a key role in the effectiveness of specific SR applications, as will be discussed in Section 3 below.

It is important to recognize that the various mineral grains within a single rock do not weather at the same rate. In other words, the chemical weathering and release of nutrient elements during soil remineralization are differential: minerals rich in iron and magnesium, such as olivine and pyroxene, weather much faster than minerals richer in sodium, potassium, and silicon, such as feldspar and quartz. Understanding this differential weathering process, along with the diverse roles played by microbes, is essential for developing a comprehensive and predictive, systems-level view of a specific soil remineralization application. This understanding is particularly critical for ensuring the long-term balance of macro- and micronutrients as rock amendments undergo gradual weathering processes in soils over decadal timescales.

To demonstrate the weathering behavior of a typical basaltic rock type used for soil remineralization, we present results from a simplified, reduced-order kinetic reaction path model implemented using the thermodynamic/kinetic modeling software *Geochemist's Workbench™* (Bethke et al., 2025). The model details are presented in the Supplementary Materials. For demonstration, we chose idealized basalt mineralogy (Table 3). This model rock is based on the basalt used by Conceição et al. (2022) in their soil remineralization study in Mato Grosso do Sul State, Brazil. For this reaction path model, we assume a single application of 10 kg of basalt rock dust to one hectare of agricultural soil.

This reaction path demonstration model is intended to provide general insights into the weathering behavior of basalt for different grain sizes, with and without biological influence. It does not include seasonal variations in temperature or moisture content, nor does it simulate the flow of solutions infiltrating through the soil. Thus, this instructional model represents the generalized behavior of the system by accounting for pH, aqueous speciation, adsorption (surface complexation), and simplified biological processes, while assuming that water content does not limit dissolution rates.

**Table 3.** Mineral and whole rock composition for idealized model basalt (composition based on Conceição et al., 2022).

	<b>Plagioclase</b>	<b>Augite</b>	<b>Basaltic Glass</b>	<b>K-feldspar</b>	<b>Apatite</b>	<b>Iron Oxides</b>	<b>Whole Rock</b>
<i>Mass fraction (g / g rock)</i>	0.51	0.25	0.09	0.11	0.02	0.02	1.00
<i>Composition (Wt.%)</i>							
SiO <sub>2</sub>	53.05	52.40	60.58	64.81	0.00	0.00	52.74
TiO <sub>2</sub>	0.00	2.57	1.15	0.00	0.00	0.00	0.75
Al <sub>2</sub> O <sub>3</sub>	30.01	2.34	14.74	19.57	0.00	0.00	19.37
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.00	100.00	2.00
FeO	0.00	3.30	6.23	0.00	0.00	0.00	1.39
MnO	0.00	0.00	1.28	0.00	0.00	0.00	0.12
MgO	0.00	18.50	4.37	0.00	0.00	0.00	5.02
CaO	12.38	19.77	6.08	1.03	55.00	0.00	13.01
Na <sub>2</sub> O	4.56	0.71	4.48	3.40	0.00	0.00	3.28
K <sub>2</sub> O	0.00	0.00	0.00	11.19	0.00	0.00	1.23
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.35	0.55	0.00	0.00	0.00	0.14
NiO	0.00	0.07	0.54	0.00	0.00	0.00	0.07
P <sub>2</sub> O <sub>5</sub>	0.00	0.00	0.00	0.00	40.00	0.00	0.80
F	0.00	0.00	0.00	0.00	5.00	0.00	0.10

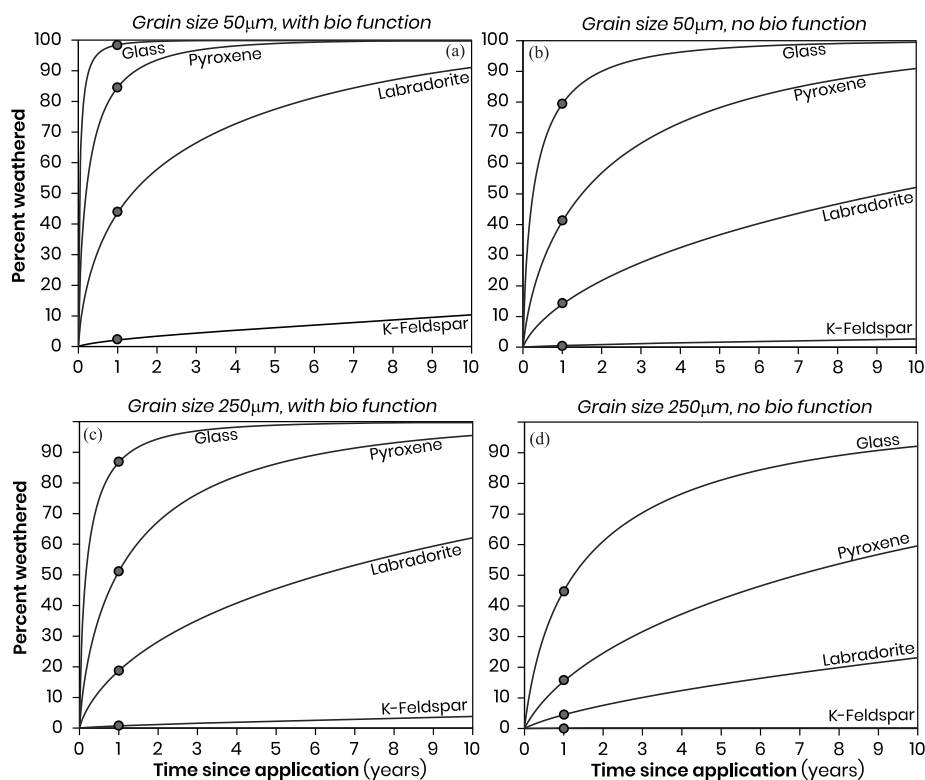
Our simple demonstration model also accounts for biological influences on weathering as discussed below. The influence of macro and microbiological processes on mineral weathering rates has been studied for decades (e.g., Schatz et al., 1954; Henderson and Duff, 1963; Boyle and Voigt, 1973; Huang and Schnitzer, 1986; Banfield et al., 1999; Harley and Gilkes, 2000; Hoffland et al., 2004; Verbruggen et al., 2021; Manning and Renforth, 2013; Zaharescu et al., 2020; Wild et al., 2022; Fang et al., 2023).

As discussed in the Supplementary Materials, the model incorporates a biological function that accounts for a range of rhizosphere processes that can significantly accelerate mineral weathering, including the effects of mycorrhizal fungi and root exudates (e.g., organic acids and chelating agents) (Beerling et al., 2020). As shown in the model results (Fig. 4), incorporating these organic rhizosphere processes (as represented by the biological function) has a significant effect on the predicted mineral weathering rates and is thus essential for accurately estimating nutrient release over time. For example, Akter and Akagi (2005) found that biological processes associated with rice, maize, and soybean growth increased nutrient release rates from basalt by 2 to 7 times for calcium and 6 to 112 times for magnesium relative to a “no-plant” baseline.

The plots in Fig. 4 show the mass percent weathering of each mineral over 10 years following rock dust application. The points shown on the left sides of the graphs indicate the percentage weathered after one year. Fig. 4(a) shows model results for a case in which the basalt powder has an average grain size of 50 micrometers and the full biological function is used. The pH of the soil changes with time as the minerals dissolve. The pH

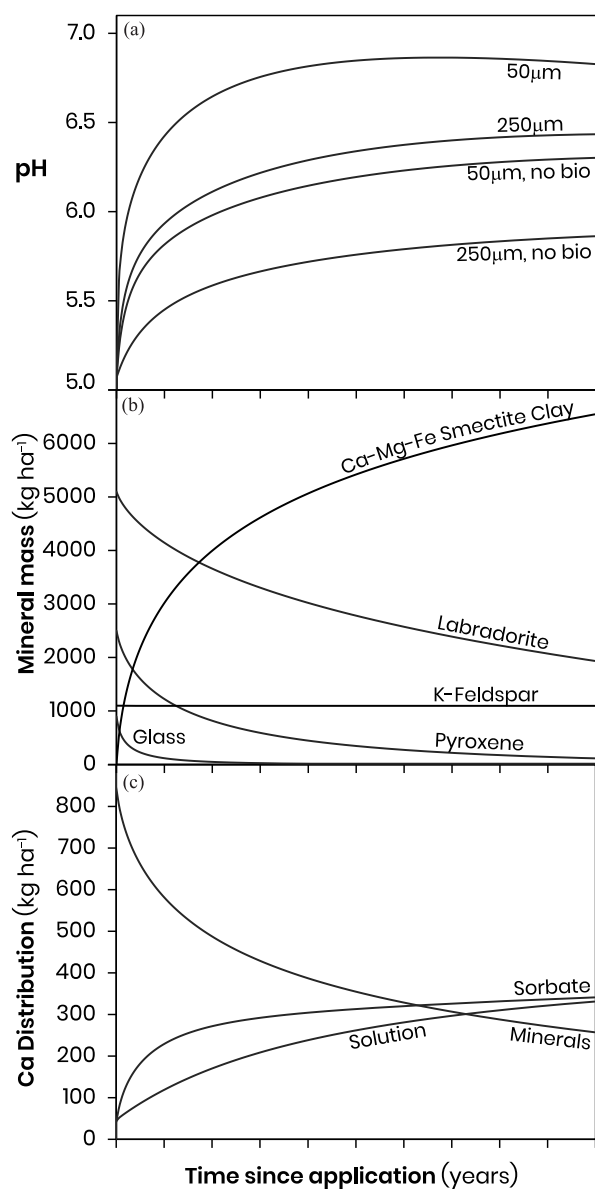
evolution for the case shown in Fig. 4(a) is given in Fig. 5(a). The model predicts that nearly 100% of the basaltic glass phase will have weathered in the first year after application, thus releasing its nutrients (silicon, magnesium, calcium) into the soil over that time interval. For this case, the model also predicts that approximately 84% of the augite pyroxene will weather within the first year (another key source of magnesium). Approximately 43% of the labradorite (a key source of calcium) and less than 5% of the potassium-feldspar are predicted to weather over the first year for this case (Fig. 4a). In all cases, the calcium phosphate mineral apatite weathers completely within the first year (not shown in the figure).

Contrast these predictions with Fig. 4(b), which is also for a 50-micrometer average grain size but does not account for biological processes (i.e., the biology function was not included). For this “no bio function” case, only 80% of the basaltic glass is predicted to weather in the first year, along with around 40% of the pyroxene, 15% of the labradorite plagioclase, and around 1% of the potassium feldspar. These results indicate that microbial and organic chelation processes, represented by the biological function, more than double the rate of mineral weathering and nutrient release. The same trend is noted for Fig. 4c and 4d, which are model cases that predict the mineral weathering rates for rocks with an average grain size of 250 micrometers. As shown in Fig. 4, grain size significantly affects weathering rates because finer grains generally have a larger surface area, which increases the rate of mineral weathering. The kinetic equations that quantify how grain size and mineral surface area influence mineral dissolution reactions are presented in the Supplementary Materials.



**Figure 4.** Results from a reaction path model implemented in Geochemist’s Workbench™ for the chemical weathering of an idealized basalt. Figure 4a shows the mineral weathering rates for a rock with an average grain size of 50µm and includes the biological function discussed in the text and in the Supplementary Materials. 4b shows results for the 50µm case without the biological function. 4c shows results for a rock with an average grain size of 250 µm with the biological function, and 4d is for the 250 µm case without the biological function.

Understanding the association between average grain size (mineral grain surface area) and mineral dissolution rates is crucial for determining nutrient release rates for soil remineralization. As demonstrated in Fig. 4, finer-grained powders (e.g., the 50 $\mu\text{m}$  rock dust in case 4a) weather considerably faster than coarser powders (e.g., the 250 $\mu\text{m}$  rock dust in case 4c). Having a mix of fine and coarse grain sizes can be beneficial because fine grains may provide a quick release of nutrients during the first growing season, while coarser grains slowly release nutrients over several years as they weather more gradually. Thus, quantifying a rock dust's grain size distribution is important for predicting how effective it will be for both short-term and long-term nutrient release.

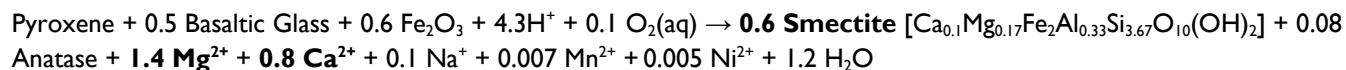


**Figure 5.** Results from a reaction path model implemented in Geochemist's Workbench™ for the chemical weathering of an idealized basalt. Fig. 5a shows the pH evolution for several different model runs for the model basalt with different average grain sizes. 5b. Shows the mineral how the mineral masses evolve over time, note the importance of the secondary smectite clay that forms during weathering. 5c. gives an example of the distribution of calcium among different phases. Where “Solution” refers to calcium dissolved as  $\text{Ca}^{2+}$ , “Sorbate” refers to  $\text{Ca}^{2+}$  adsorbed to mineral surfaces (clays, iron and aluminum oxides) and “Minerals” refers to  $\text{Ca}^{2+}$  locked up in primary or secondary minerals.

This demonstration reaction path model also accounts for the chemical speciation of the elements released from mineral weathering and tracks how the soil pH changes due to speciation and the adsorption of cations and anions onto mineral surfaces such as clays and aluminum and iron oxyhydroxide mineral surfaces. The model also predicts the formation of secondary phases that form during weathering, such as the Ca-Mg-Fe smectite clay shown in Fig. 5b. This observation indicates that not all of the calcium and magnesium released by the weathering of the basalt go into plant-available forms. Some of it is locked up in non-exchangeable crystallographic sites in secondary minerals (Fig. 5b). For example, the reaction below describes the mass balance of the simplified, but instructive, weathering process for the idealized model basalt. Note the assumed composition of the secondary smectite clay mineral is  $\text{Ca}_{0.1}\text{Mg}_{0.17}\text{Fe}_2\text{Al}_{0.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2$ , and the

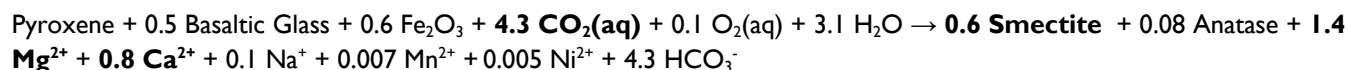
assumed compositions of pyroxene and basaltic glass are shown in Table 3.

### **Reaction 1**



Assuming that the acidity present in the soil is predominantly carbonic acid, the weathering reaction can also be shown to consume significant amounts of carbon dioxide. For example:

### **Reaction 2**



In addition to dissolving in soil pore solutions, the calcium and magnesium released during weathering reactions adsorb onto (or complexes with) soil colloids, such as clay minerals, organic matter, and iron and aluminum oxyhydroxides. This adsorption/surface complexation process contributes to the base saturation pool available for crops. Alternatively, these cations may be leached from the soil by infiltrating water, particularly in soils with low cation exchange capacity or high rainfall, or they can be taken up by microorganisms and plants.

The reaction path model also provides the distribution of nutrient elements among different phases, such as soil solution, mineral surface sorption sites (exchangeable), and crystallographic sites in minerals (non-exchangeable). An example plot of this type of distribution diagram is shown in Fig. 5c for calcium. The changes in calcium speciation with time are associated with changing pH conditions as the minerals weather.

Field, mesocosm, and experimental studies show that mineral weathering rates in soils remain highly uncertain (Amann et al., 2020; Rinder and von Hagke, 2021; Cipolla et al., 2021), possibly ranging from 1-25% of applied rock per year depending on rock variables, local climate, and soil conditions (Gaucher et al., 2025). A four-year field study of basaltic rock dust applied to maize and soybean plots measured basalt cation losses of around 16%, which equates to weathering rates of 3–6% per year (average grain size was 267 $\mu\text{m}$ ) (Beerling et al., 2020). However, values may vary considerably from these depending on site conditions (e.g., soil pH, moisture content, microbial activity, plant root exudates, etc.) and rock characteristics (e.g., mineralogy, grain size distribution, mineral grain surface area, etc.).

Furthermore, as demonstrated in the simple reaction path model presented above, the weathering rates of different mineral constituents of rock dust can vary considerably. For example, the pyroxene constituent of a basalt may weather at a rate of 20% per year (for 250 micrometer grains) while the potassium feldspar constituent of the same rock may weather at a rate of just 1% per year, under the same conditions (e.g., Fig. 4c). Understanding the differential nature of the dynamic inorganic/biological weathering processes discussed above is essential for planning and implementing successful soil remineralization projects that benefit agriculture and contribute to climate stabilization.

## **2.5 Soil Remineralization and Climate Stabilization**

Studies quantifying the vast amounts of carbon stored in Earth's pedosphere were initiated in the 1930s and refined in the 2000s (Waksman, 1936; Lal, 2004; Lal, 2009). Soils hold nearly twice as much carbon as the

atmosphere (roughly 1,550 gigatons compared to around 800 gigatons), primarily in the form of organic carbon. (Lal, 2004). This striking difference highlights the crucial role that global soil health plays in maintaining climate stability. As the planet's largest active terrestrial carbon sink, even small losses from degraded soils can greatly increase atmospheric CO<sub>2</sub> concentrations. Conversely, restoring soil ecosystems offers a powerful lever to rebalance the global carbon cycle and mitigate climate change. As has been discussed in this Section and will be further supported in Section 3 below, soil remineralization can play a substantive role in the restoration of degraded soils, thus enhancing the capacity of Earth's pedospheric carbon sink (Wood and Wood, 1991; Goreau, 2015; Campe, 2015; Swoboda et al., 2022).

The weathering of silicate rock material also plays a key role in enhancing and maintaining global inorganic carbon storage pools. For example, in the late 19<sup>th</sup> century, Arrhenius and Holden (1897) recognized that silicate rock weathering is responsible for converting significant amounts of atmospheric CO<sub>2</sub> into dissolved and precipitated carbonate species stored in the geosphere. The key reactions were elucidated by Urey (1952), and their impact on the global carbon cycle was worked out in the 1980s (e.g., Walker et al., 1981; Berner et al., 1983). It is estimated that natural silicate rock weathering removes approximately 0.5 to 1.0 Gt CO<sub>2</sub> per year (Ciais et al., 2013; Zhang et al., 2021) in the form of inorganic carbonate species. These precipitated and aqueous species remain in geosphere/ocean pools for thousands to millions of years with only minor amounts re-released as CO<sub>2</sub> on shorter time-scales (e.g., Berner et al., 1983; Kanzaki et al., 2023).

In the early 1990s, it was recognized that the application of silicate rock dust to agricultural and forest soils (i.e., SR) could accelerate the natural inorganic CO<sub>2</sub> sequestration processes (e.g., Seifritz, 1990; Supkow, 1995). Grinding the rock material to a fine powder accelerates or enhances its weathering rate, thus speeding up the CO<sub>2</sub> removal process. As noted above, reducing mineral grain size through grinding enhances the weathering rate of rock material because mineral alteration and dissolution kinetics are strongly dependent on the effective surface area of the constituent minerals (Aagaard and Helgeson, 1982). Thus, as shown in Fig. 4 above, finer mineral grain sizes result in faster weathering rates, and hence faster nutrient release and more rapid conversion of CO<sub>2</sub> to carbonates in soil solutions (e.g., Reaction 2, above).

In the 2000s, several quantitative assessments and reviews were published demonstrating the large-scale potential of silicate rock powder weathering as a carbon dioxide removal (CDR) "technology". (e.g., Köhler et al., 2010; Renforth, 2012; Hartmann et al., 2013; Manning and Renforth, 2013; Moosdorf et al., 2014; Taylor et al., 2016; Kantola et al., 2017; Beerling, 2017; Taylor et al., 2017; Edwards et al., 2017; Beerling et al., 2018; Strefler et al., 2018; Beerling et al., 2020; Haque et al., 2021; Lewis et al., 2021; Vaklifard et al., 2021; Kantzas et al., 2022; Vicca et al., 2022; Eufrazio et al., 2022; Calabrese et al., 2022; Baek et al., 2023; Deng et al., 2023; Clarkson et al., 2024; Vandeginste et al., 2024; Cong et al., 2024; Levy et al., 2024; Power et al., 2025; Beerling et al., 2025; Manning, 2025). This promising CDR approach is commonly referred to as enhanced weathering (EW) or enhanced rock weathering (ERW). Recently several research groups and carbon removal companies have performed greenhouse, mesocosm and field trials to quantify the biogeochemical mechanisms behind ERW and verify its CDR potential (e.g., Dietzen et al., 2018; Kelland et al., 2020; Amann et al., 2020; Vienne et al., 2022; de Oliveira Garcia et al., 2020; Larkin et al., 2022; Chen et al., 2023; Holzer et al., 2023; Kantola et al., 2023; te Pas et al., 2023; Guo et al., 2023; Beerling et al., 2024; Wang et al., 2025).

It is important to note that soil remineralization and ERW are not synonymous. For example, ERW is commonly described as a geoengineering approach, whereas soil remineralization is more accurately characterized as a geotherapy or agroecological practice. This distinction arises because ERW has increasingly been framed in the scientific literature as a scalable climate intervention, primarily evaluated and financed on the basis of a single metric: carbon dioxide removal and associated offset credits in voluntary carbon markets, whereas soil remineralization is typically designed to enhance a broader suite of agroecosystem services. The geoengineering CDR framing thus risks incentivizing excessive or poorly targeted applications of rock dust to maximize carbon credits, potentially exacerbating environmental trade-offs, while an agroecological soil remineralization paradigm emphasizes multifunctionality, local context, long-term benefits and ecological limits.

More specifically, ERW projects, especially those focused on generating carbon credits, tend to emphasize the inorganic carbon sequestration process, which scales with the mass of rock applied. This incentivizes high application rates and the use of rock-types with high CDR potentials that may have imbalanced nutrient profiles and high levels of geogenic contaminants (e.g., ultramafic rock types). As mentioned above, the overapplication of rocks with imbalanced nutrient profiles can lead to detrimental agronomic effects and the potential buildup of potentially toxic metals (de Souza et al., 2019; Haque et al., 2020; Kierczak et al., 2021; Suhrhoff, 2022; Dupla et al., 2023).

Zhang et al. (2024) emphasize the need for rigorous assessments of ecological impacts before large-scale ERW deployment. Their research highlights potential risks such as microbial community shifts and metal toxicity, which could exacerbate global warming through unintended biological methane production. This observation provides another example supporting hypothesis (2): that the successful application of SR and related practices, such as enhanced rock weathering, requires an integrated or whole-system approach; and hypothesis (4): that the ultimate benefit of SR lies in restoring the full suite of soil ecosystem services, rather than achieving a single outcome such as carbon removal.

It is important to note, however, that more recent framings of ERW tend to emphasize the multidimensional applications of rock dust and biochar, alongside other greenhouse gas mitigation strategies such as point-source methane reductions (Planavsky et al., 2025). In this study, the authors also point out that, despite the significant scientific, social, and infrastructural advantages of ERW-based CDR, critical limitations remain. These limitations include the lack of well-established monitoring, reporting, and verification (MRV) frameworks, the absence of site-specific rock dust weathering rates, and the intrinsic delay between the release of cations from rock weathering and the conversion of CO<sub>2</sub> to bicarbonate in the geosphere.

This delay arises from the surface complexation of cations on clay and oxide soil minerals and forms of organic matter. Planavsky et al. (2025) note that, while empirical methods for estimating the ERW surface complexation-related CDR delay are lacking, model-based estimates suggest it can vary from approximately one year to several decades (e.g., Kanzaki et al., 2023). Uncertainties in rock weathering rates and the intrinsic geochemical delay in CO<sub>2</sub> drawdown directly affect annual CDR estimates and therefore cannot be ignored when producing durable ERW carbon credits or conducting carbon offset accounting. Consequently, ERW as a CDR strategy incentivized through voluntary carbon markets and emissions offsets requires new crediting

frameworks that account for geochemical delays in CO<sub>2</sub> drawdown. Planavsky et al. (2025) discuss several possible options, favoring an approach that couples CDR from ERW with point-source methane reductions.

In addition to persistent challenges related to delayed carbon dioxide removal and uncertainties in monitoring, reporting, and verification (e.g., Johnson et al., 2025) for ERW, fundamental questions have also emerged regarding the adequacy of financial mechanisms needed to drive the scale-up required for impactful global climate mitigation. Collectively, these critiques reinforce the view that the primary value of soil remineralization (and, by extension, ERW) should not be narrowly defined by maximizing a single outcome such as carbon removal or crop yield, but rather by restoring a broader suite of ecosystem services. We will return to the issue of financial incentivization for soil remineralization and ERW with a more detailed discussion in Section 4.0 below. However, before diving into incentivization, we will first further explore this paper's core hypotheses by providing a review of the historical and scientific literature on soil remineralization.

## **3.0 Review of Historical Observations and Scientific Findings**

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### **3.1 Historical Observations**

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*“As with most good, simple ideas in agriculture, somewhere in the world a farmer can be found to have anticipated the scientist”. (Chesworth, 1983)*

Soil remineralization using natural rock materials has been practiced by farmers for millennia (Tietz and von Minckwitz, 2023). Controlled trials investigating the efficacy of various types of rock dusts began in the mid to late 19<sup>th</sup> century (Magnus, 1850; Hensel, 1894) and continue to the present day (e.g., Mir et al., 2024; Medeiros et al., 2024; Richardson, 2025).

The replenishment of soil nutrients by natural fine-grained rock material played an important role in the development of early human civilization. For example, in predynastic Egypt, approximately 5,000 years ago, farming communities constructed dikes and channels to control Nile floodwaters, which deposited nutrient-rich volcanic rock fines from the Ethiopian Highlands onto their fields (Wetterstrom and Anne Murray, 2001; Krom et al., 2002). The regular natural deposition of these silt-sized volcanic rock particles allowed for the large-scale cultivation of wheat, barley, and flax on the Nile alluvial flats, requiring little to no soil preparation or irrigation (Wetterstrom and Anne Murray, 2001). Similarly, Mesopotamian farmers, also in the 6<sup>th</sup> century BCE, constructed complex canal networks to deliver silt-enriched waters from the Tigris and Euphrates to barley, wheat, millet, and emmer croplands (Jotheri et al., 2025).

By the Roman period, farmers in Europe were using natural rock material as agricultural amendments, as described by Pliny the Elder (23-79 CE) (Winiwarter and Blum, 2008). The rock amendments discussed by Pliny are marls, which consist of roughly 50% silicate clay minerals and 50% carbonate rock (mostly calcite or dolomite). In his “Natural History”, Pliny gives general recommendations for marl use, matching distinct types (e.g., tuff-like marl or sandy marl) with particular environments and applications (e.g., “best for grains” and “used for boggy places”) (Winiwarter and Blum, 2008). According to Pliny, the use of “marl” rock dust as agricultural amendments (specifically for cereals and pasture lands) was well established in Gall and the British Islands by the

1st century. Pliny recognized six general types of "marl" rock dust: white, red, sandy, columbine, argillaceous, and tuffaceous. Of these, the tuffaceous marl appears to have actually been a volcanic rock composed of silicate minerals and glass rather than a true carbonate-bearing marl. It is noted that this tuffaceous material is only effective at improving soil fertility if co-applied with "vegetable earth", which likely refers to compost (The Natural History of Pliny, 1855, Bostock and Riley translation). Thus, even in the first century, there was observational evidence supporting our first three hypotheses, specifically that SR can provide agronomic benefits, that the practice is most successful when it involves an integrated approach that involves the coapplication of rock dusts with organic material.

In his recommendations, Pliny addresses many of the same issues currently debated regarding the optimization of rock dust use for soil remineralization. For example, he stresses the importance of applying specific rock types to specific environments, suggests that combining rock material with dung can make it more effective, and cautions that over-application will stunt agricultural productivity (The Natural History of Pliny, 1855, Bostock and Riley translation). These observations are as critical today as they were 2000 years ago and provide an initial strand of pre-scientific evidence supporting this paper's core hypotheses.

The use of marl for agricultural purposes is frequently mentioned in European agricultural treatises from late antiquity and the Middle Ages (Winiwarter and Blum, 2008). Other cultures also used rock material as soil conditioners or slow-release fertilizers during this period. For example, archaeological evidence shows that the Aztec (ca 1200-1500 AD) used sedimentary minerals (largely silicate clays) dredged from canals to maintain the soil fertility and structure of their chinampas, which are human-made islands for growing crops (Angelakis et al., 2020). The Mayan people also appear to have used canal sediments for this purpose (Angelakis et al., 2020).

Similarly, in India, there is an Indigenous and traditional nutrient management practice in which nutrient-rich mineral sediments deposited in natural or artificially formed catchments called "tanks" are excavated and used as agricultural amendments (Mrunalini et al., 2022). Tank sediments, consisting largely of silicate clay minerals, are deposited by monsoonal rainwater and excavated at the end of the wet season to both provide a natural nutrient source for crops and to optimize soil moisture storage capacity in the tank catchments (Mrunalini et al., 2022). What these types of Indigenous SR practices have in common is that they all increase the clay content of the soils, thus improving water retention as well as nutrient element storage, cycling, and phytoavailability. It has also been shown that the application of tank silts in India enhances crop yields and improves soil properties (Mrunalini et al., 2022).

Another example of rock dusts being used as part of traditional Indigenous practices was described by Lee Klinger in his ecological studies of the giant Sequoia groves in the California Coast Ranges (Klinger, 2006). Klinger presents evidence that several thousand years ago, the Miwok people mixed carbonate-rich rock dust into soils around giant Sequoia trees to promote their health and growth (Klinger, 2006). This practice may have had both ritualistic and practical importance as the great Sequoia stands were used as both sacred groves and as sources of tannins for hide tanning and bark for lodge construction (Klinger, 2006).

Soil remineralization with rock dust was also a common practice in Europe during the late Middle Ages. For example, on-farm trials of marl amendments were recorded in an English farmer/landowner's journal from

1499-1502. The farmer reports a successful trial, in which several tons of local marl were applied to wheat and barley fields near Newton, England, resulting in a two-fold increase in grain yields (Youngs, 2000). The use of clay-rich rock material for SR appears to have been a continuous practice dating back hundreds of years in Europe. During the Enlightenment, the process began to be studied scientifically. For example, in 1769, the Chemist Johann Gerhard Reinhard Andreae conducted a pioneering soil chemistry study, analyzing nearly 300 marl-like rock types for potential use as agricultural amendments (Andreae, 1769). Also, in the mid-1700s, the founder of modern geology, James Hutton, experimented with several types of natural fertilizers on his Berwickshire farm, including marl, salt, seaweed, dung, and coal ash (Jones, 1985).

By the mid-1800s, scientists were studying the application of silicate minerals for SR. For example, in 1850, the prominent German chemist and physicist Heinrich Gustav Magnus investigated the effect that potassium feldspar had on the growth and health of wheat and barley plants (Magnus, 1850). He compared the feldspar amendments to other nonsilicate minerals (apatite, gypsum, rhodochrosite, and magnesite), salts (sodium chloride and potassium chloride), and organic wastes. It was found that fine-grained feldspar amendments yielded the most vigorous and healthy barley plants, whereas relatively small doses of the salts were found to poison the plants (Magnus, 1850).

In 1887, Scottish agricultural chemist Andrew Peebles Aitken published a short paper on field experiments investigating the use of potassium feldspar as a soil amendment in Scotland (Aitken, 1887). Aitken offered a representative insight that is still relevant today:

*“At first sight, it might seem a foolish thing to expect that by merely grinding feldspathic rock, and strewing the powder upon soils deficient in potash, the long natural process should be so accelerated as to cause the feldspar to act as a source of potash for the immediate use of the growing of crops... Nevertheless, the striking results of an experiment made at the Society's Experimental Station at Pumpherston showed that such an expectation was not altogether unreasonable”.* (Aitken, 1887)

Aitken found in other experiments that the effectiveness of phosphate rock as a fertilizer was directly proportional to grain size, with finer material being significantly more efficient. He, therefore, offered the following hypothesis:

*“It therefore seemed reasonable to suppose that feldspar, although it is a very insoluble substance, might, if it were ground to an exceedingly fine powder in certain circumstances, be found to yield to the action of the solvents in the soil and in the roots of plants so rapidly as to be available as a source of potash to some crops even during the short period of a single season”.* (Aitken, 1887)

The hypothesis was confirmed by the experiments, which showed significant yield increases for Turnips grown in the feldspar-treated field vs. a negative control. The ground feldspar was also found to outperform a potassium sulfate salt amendment (Aitken, 1887). Also, in the late 19<sup>th</sup> century, the prominent German chemist and doctor of medicine, Julius Hensel, guided by previous experimental work and his own practical experience, published the foundational monograph: *Bread From Stones: A New and Rational System of Land Fertilization and Physical Regeneration* in 1894. In this book, Hensel discussed the important role that granitic rock dust, also known as Steinmehl (stonemeal), could play as a primary fertilizer.

In the early 1900s, the US Department of Agriculture published a short book entitled "The Use of Feldspathic Rocks as Fertilizers" (Cushman, 1907). The results presented in this monograph demonstrated the promise of rock dust as a soil amendment, but cautioned that the successful application of the practice requires an understanding of rock, soil, and crop (Cushman, 1907). The study concludes:

*"The evidence so far obtained appears to indicate that under certain conditions and with certain crops, feldspar can be made useful if it is ground sufficiently fine. On the other hand, it is highly probable that under other conditions the addition of ground felspar to the land would be a useless waste of money". (Cushman, 1907)*

The study notes that key conditions, such as soil chemistry, adequate moisture, and the character of co-applied materials like compost, as well as the root action of crop plants, will play an essential role in the effectiveness of rock dust as a fertilizer (Cushman, 1907). This again provides historical support for our hypotheses 2 and 3, which suggest that successful SR applications require an understanding of the interdependence of chemical, geological, and biological processes, and that combining rock material with organic material improves soil properties over rock dust alone.

Another early 20<sup>th</sup>-century study by de Turk (1919) showed that finely ground potassium feldspar increased buckwheat yields by 24% and increased the availability of potassium to the plant. The bioavailability of potassium from the ground feldspar was facilitated by root action, again reiterating the vital interplay of biological and geochemical processes in nutrient cycling. Haley (1923) recorded similar results for finely ground feldspar and buckwheat. Experimental work on feldspar and mica-rich rock dust as natural sources of potassium continued into the 1940s with the work of Lewis and Eisenmenger (1948) and others.

Additionally, in the late 1930s and early 1940s, researchers in Germany demonstrated that basaltic quarry waste rock dust is an effective amendment for forest soils (e.g., Hilf, 1937; Hilf, 1938; Albert, 1938; Gerth, 1939). By the early 1950s, soil remineralization had also gained recognition in the USA as a potentially effective agricultural practice. For example, in 1951, the Maine Geological Survey published a review article by American geologist Walter Keller, titled "Industrial Minerals and Rocks as Plant Nutrient Sources" (Keller, 1951).

In 1949, the organic and sustainable agriculture pioneer J.I. Rodale published "The Healthy Hunza," which uncovered connections between the renowned good health and longevity of the Hunza people (i.e., communities in the Hunza Valley, Pakistan) and the glacial rock dust supplied to their agricultural soils through irrigation. These irrigation waters flow from the glaciers of the Karakoram Mountains and contain finely ground silicate rock material formed from the glacial erosion of micaceous metamorphic and granitic bedrock. Rodale surmised that the glacial fines increase soil fertility and boost the nutrient density of Hunza crops (e.g., wheat, millet, vegetables, walnuts, almonds, and apricots), thus contributing to the Hunzas' remarkable health and longevity (Rodale, 1948). The connection between glacial rock dust deposition, soil health, nutrient density, and human health was also made by the eminent American soil scientist William Albrecht (Albrecht, 1962). In their influential book "The Survival of Civilization," Hamaker and Weaver describe Albrecht's contribution as follows:

*"He [Albrecht] praises these people [Hunza] highly as an example for the world, of a people thriving in adherence to the natural laws of biology, being supported on soils fertilized by pulverized rock and organic materials grown in place (as opposed to imported). Dr. Albrecht states that the emphasis on incomplete chemical fertilizers has distracted us from*

*seeing the basic nutritional role of powdered rock, which, when combined (“chelated”) with organic matter via microorganism activity, is then assimilated by the plant “in the form of organic complexities” (Hamaker and Weaver, 1982).*

Between the late 1940s and the late 1960s, one of the most significant soil remineralization field trials was conducted on sugar cane plantations in the island country of Mauritius (d’Hotman, 1947; Mauritius Sugar Industry Research Institute, 1958; d’Hotman, 1961). For the Mauritius study, various application rates of basaltic rock dust were applied to the highly weathered lateritic plantation soils in an effort to increase nutrient density and fertility. The basalt-treated soils showed up to 20% yield increases relative to untreated soils, and cane leaves showed increases in both calcium and silica relative to the negative control (Mauritius Sugar Industry Research Institute, 1958).

Also, by the 1950s, agronomists and agricultural chemists had realized the importance of rhizosphere microorganisms in determining the release and bioavailability of key nutrient elements from silicate minerals added to soils. For example, Eno and Reuzer (1955) showed that the fungus *Aspergillus niger* significantly increased the release of potassium from unweathered biotite, muscovite, and potassium feldspar, all common minerals in granitic rock dusts. In the early 1960s, studies on the role of microorganisms in mineral weathering and the release of nutrient elements gained momentum. For example, Duff et al. (1962) demonstrated that acid-producing bacteria from the oat plant rhizosphere can solubilize and chelate cations from both silicate and phosphate minerals.

Duff et al. (1962) studied a wide range of minerals, including wollastonite, serpentine, olivine, apatite, hornblende, vermiculite, epidote, and various feldspars, pyroxenes, and zeolites. Results showed that the most effective mineral-dissolving bacteria were motile, short, gram-negative rods that produce large amounts of 2-ketogluconic acid. This acid was noted to chelate divalent cations, thus keeping them in solution and enhancing their bioavailability (Duff et al., 1962). The minerals that were most readily solubilized by the bacteria were apatite, wollastonite, and olivine, while the most resistant were feldspars and iron and aluminum phosphates. Similar work by Moria et al. (1963) investigated the release of cations and silicate ions from rocks and minerals by various strains of fungi. By the 1970s, the roles of organic and biological processes in rock and mineral weathering and nutrient bioavailability were well established (e.g., Boyle and Voigt, 1973; Mojallali and Weed, 1978).

Also, in the 1960s, the ultramafic silicate rocks dunite and serpentine were investigated as plant nutrient sources (e.g., Chittenden et al., 1967). In field trials, it was observed that both rock types were excellent sources of both magnesium and calcium for tobacco, white clover, and rye-grass. It was also noted that the poisoning of plants from nickel and chromium, which are concentrated in ultramafic rocks, is unlikely at the relatively low application rates (e.g., < 10 tonnes per hectare) required for agricultural benefits (e.g., Chittenden et al., 1967). However, as discussed in Section 2.3 above, higher application rates involving repeated inputs may cause nutrient imbalances and plant poisoning.

In addition to the international work cited above, many modern pioneers of soil remineralization have worked in Brazil. For example, in a foundational review article, Leonardos et al. (1987) cite several groundbreaking SR

experiments and field trials performed by Brazilian workers. These studies showed that a wide range of rock types could be used to restore and nutritionally fortify the highly weathered lateritic soils typical of tropical agroclimatic zones. Frayha (1950) and Ilchenko and Guimarães (1953) performed successful trials with potassium-rich phonolites, Ilchenko (1955) studied ultramafic tufts, Lima (1969) and Horowitz et al. (1978) worked with mica schists, and Hardy (1962), Paccola et al. (1974), and Leonardos et al. (1982) investigated basalt.

By the 1980s, a group of pioneering scientists and soil remineralization practitioners had developed a global community centered on the use of silicates and other rock dusts for agricultural and climate stabilization purposes. This emergent interdisciplinary field, referred to as agrogeology (van Straaten, 2007), brought together experts in the fields of geology, chemistry, biology, agronomy, soil science and hydrology. Agrogeology is defined as: geology in the service of agriculture (van Straaten, 2007).

Some of the agrogeology pioneers of the 1980s provided review articles that compiled evidence strongly suggesting that rock dusts, when used appropriately, may be agronomically and environmentally superior to synthetic NPK fertilizers (e.g., Fyfe et al., 1983; Chesworth et al., 1983; Leonardos et al., 1987). A particularly important contribution of this time period was the previously mentioned book “The Survival of Civilization”, which consists of selected papers by the American engineer, ecologist, and farmer John D. Hamaker with annotations and supporting evidence by ecologist Donald Weaver (Hamaker and Weaver, 1982).

The book presents a comprehensive synthesis of Hamaker’s research across multiple disciplines, including soil science and paleoclimatology. The central argument is that modern agricultural practices have depleted soils, leading to forest decline and nutrient deficiencies in food. Hamaker and Weaver advocate for soil remineralization using rock dust (e.g., glacial gravel dust or rock flour) as a sustainable alternative to chemical fertilizers and pesticides. Hamaker presented SR as a powerful solution for ecological restoration, potentially averting crises such as climate instability and food shortages.

Other seminal SR projects of the 1980s include the Australian study of basalt applications to highly weathered soil (Gillman, 1980) and the Canadian/Tanzanian study “Agrogeology in East Africa: the Tanzania-Canada Project” led by Canadian geologists Ward Chesworth and Peter van Straaten and Tanzanian soil scientist Johnson Semoka (Chesworth et al., 1988; Chesworth et al., 1989). Of particular importance were observations from highly weathered soils in tropical regions (e.g., Tanzania, India, and Brazil), where SR can have a major beneficial impact on food and nutrient security. As stated by the eminent geochemist William S. Fyfe:

“In geologically stable equatorial regions, intense weathering produces, in a few million years, a soil both unproductive and vulnerable to erosion. If such regions where the climate is often very favourable are to be improved for food production, quite new fertilizer strategies are required. Conventional N-P-K fertilizer will not do the job and will almost certainly lead to intense pollution of local drainage... For all such soils, slow-release, relatively insoluble, wide-spectrum fertilizers are required. For many species, local rock products may provide much of what is needed”. (Fyfe, 1983)

Largely inspired by the work of Hamaker and Weaver, in the mid-1980s, Joanna Campe founded Remineralize the Earth (RTE), a community of SR researchers and practitioners. The RTE community was centered around a

network newsletter (Campe, 1986), which provided both scientific reflections and practical information on farming and gardening. In 1991, the newsletter became *Remineralize the Earth Magazine* (Campe, 1991), and in 1995, the organization became the US 501(c)(3) non-profit organization *Remineralize the Earth*. With its expansion in the 1990s, RTE began taking a leadership role in facilitating partnerships among SR researchers worldwide and providing educational materials on the science and practice of soil remineralization (“*Remineralize the Earth*,” 2026). For example, the *Remineralize the Earth* network and associated newsletter helped catalyze the formation of *Rock Dust Local* in 2010 in Vermont, USA, as an early for-profit supplier focused on locally sourced rock dust for soil remineralization with an explicit climate mitigation framing. Drawing on a long lineage of work by Hensel, Albrecht, Hamaker, Van Straaten, and others, as well as Brazilian research and policy support for “stone meal” as an alternative to synthetic fertilizers, these efforts began to link remineralization practices to broader discussions of climate stabilization. Taken together, they exemplify an emerging, nature-based approach to integrating rock dust use into agriculture, forestry, and environmental management at scale.

One of the most significant contributions RTE has made to the field of soil remineralization was its instrumental role in the 2014 publication of the 630-page CRC Press book “*Geotherapy: Innovative Methods of Soil Fertility Restoration, Carbon Sequestration, and Reversing CO<sub>2</sub> Increase*”. This book is a compilation of innovative and high-quality research projects and review articles by soil remineralization and Geotherapy experts from around the world. It was compiled and edited by RTE Board director, biogeochemist and marine biologist Thomas Goreau; engineer and biochar expert, Ronal Larson, and RTE executive director Joanna Campe (Goreau et al., 2014).

Other key SR works published in the 2000s include the comprehensive review article by Basak et al. (2017), which discusses research on the co-application of silicate minerals and potassium-solubilizing microorganisms (KSMs) as a bio-intervention for potassium-deficient soils. The review finds that the integrated application of potassium-bearing minerals (e.g., feldspar, illite, muscovite, and biotite) and KSMs (e.g., *Bacillus cereus*, *Bacillus mucilaginosus*, and *Bacillus pasteurii*) significantly improves crop yields and potassium uptake under field conditions and that the bio-intervention of silicate mineral inoculated with KSMs is an effective alternative to commercial potassium fertilizers (e.g., Badr 2006; Supanjani et al. 2006; Youssef et al. 2010)..

Another landmark SR review was provided by Swoboda et al. (2022). This review focused on clarifying how, and under what conditions, SR can help sustain crop production. Swoboda et al. (2022) note that although differences in experimental approaches make direct comparisons challenging, several important findings emerge. The article finds that silicate rock powders show particularly significant promise as soil amendments for strongly weathered soils in humid and subhumid tropical regions, which is consistent with the findings of the Brazilian researchers mentioned above. As discussed by Swoboda et al. (2022), soil remineralization is particularly applicable in many agroecological zones of the global south because it can address the growing need for affordable and accessible sources of potassium and micronutrients that current fertilizers and liming practices do not provide.

Swoboda et al. (2022) offer several important recommendations for the future refinement of soil remineralization, such as establishing statistically rigorous and methodologically consistent field trials, with

detailed reporting of soil and rock properties, particle size, and application rates, etc. They also note that long-term studies are needed to assess and quantify the cumulative effects and co-benefits of rock powder weathering in agricultural and forest soils. Additionally, the review mentions the importance of future studies aimed at enhancing nutrient release rates by combining rock amendments with organic materials; a practice that, as noted above, was recognized as being effective by Pliny the Elder nearly 2000 years ago (The Natural History of Pliny, 1855, Bostock and Riley translation).

As evidenced by the Swoboda et al. (2022) review and others, the past few years have seen a dramatic increase in the publication rate of studies focused on the application of silicate rock powders to agricultural soils. This is in part due to the recognition that the weathering of silicate rock represents a particularly promising CDR method. As mentioned above, Enhanced rock weathering, considered a branch of the broader soil remineralization field, is estimated to have the potential to remove between 0.5 and 2 gigatonnes of CO<sub>2</sub> per year if applied across millions of hectares worldwide (e.g., Beerling et al., 2020; Renforth et al., 2024).

It is not in the scope of this review to cover this more recent literature in detail as much of SR and ERW work of the past twenty five years has already been discussed in various review articles (e.g., Leonardos et al., 2000; Harley and Gilkes, 2000; van Straaten, 2002; van Straaten, 2006; van Straaten, 2007; Winiwarter and Blum, 2008; Hartmann et al., 2013; Manning and Renforth, 2013; Campe et al., 2015; Manning, 2015; Beerling et al., 2018; Theodoro et al., 2021; Swoboda et al., 2022; Ramos et al., 2022; Mir et al., 2024; Son et al., 2024; Bucka et al., 2024; Beerling et al., 2025; Manning, 2025). Instead, what we seek to offer in this historical and scientific review is a fresh perspective on the practice of SR that emphasizes the urgency of addressing the principles that lie at the core of our four hypotheses: 1) the equal importance of food security, nutrient deficiencies and climate stabilization; 2) accounting for the dynamic interplay of biological, geochemical, hydrological and climatic processes through an integrated, whole-system approach; 3) the importance of combining rock material with organic and biological amendments and 4) emphasis on careful SR project development that avoids mistakes that could damage its broader adoption among farming communities such as overapplication or the use of rocks with imbalanced nutrient element profiles and high levels of geogenic contaminants. The survey presented above provides extensive historical, scientific, and practical evidence supporting each of these hypotheses (Table 4).

**Table 4.** Summary of supporting evidence for the four primary hypotheses.

Hypothesis	Supporting Evidence (see discussion above for references)
<p>1. Soil remineralization represents an effective agroecological farming practice that can address multiple sustainability challenges simultaneously.</p>	<p>Soil remineralization has been practiced for millennia by diverse cultures to enhance soil fertility and crop productivity, supporting food security and addressing nutrient deficiencies. For example, ancient Egyptian and Mesopotamian farmers directed nutrient-rich rock fines and silt in irrigation water to cultivate staple crops, while Aztec, Mayan, and Indian farmers used mineral sediments to maintain soil structure and fertility. Modern scientific trials show that the application of fine minerals and rocks, such as feldspar and basalt, can significantly increase crop yields and improve soil nutrient content, especially in highly weathered or degraded soils. Additionally, the historical survey highlights that SR can reduce reliance on synthetic fertilizers, thereby mitigating environmental impacts and contributing to climate stabilization through enhanced rock weathering.</p>
<p>2. The successful application of SR and related practices, such as enhanced rock weathering, requires an integrated or whole-system approach that accounts for the dynamic interplay of biological, geochemical, agronomic, hydrological, and climatic processes.</p>	<p>Historical observations consistently emphasize that successful SR applications necessitate an understanding of the intricate interactions between biological, geochemical, agronomic, hydrological, and climatic processes. For instance, ~2000 years ago, Pliny the Elder recognized the importance of matching specific rock types to particular environments and combining rock materials with organic amendments for optimal results. Modern research confirms that the effectiveness of rock dusts depends on factors such as soil chemistry, moisture, microbial activity, and crop root action. Studies from the 20th century onward show that microorganisms, plant roots, and organic matter play crucial roles in releasing nutrients from minerals and rock powders, and that the benefits of SR are most pronounced when these biological and geochemical processes are considered together.</p>
<p>3. The combination of rock dust with pyrogenic materials (i.e., biochar) and organic biomass (i.e., composts, biologicals) improves soil properties and productivity more than rock dust alone.</p>	<p>Historical references, such as Pliny the Elder’s observation that tuffaceous marl was only effective when co-applied with “vegetable earth,” and modern studies on the synergistic effects of biochar, minerals, and compost, all support this view. The surveyed literature describes how these combinations enhance nutrient cycling, microbial activity, and soil structure, leading to increased yields and improved soil health. This demonstrates that SR is most effective as a nature-based biointervention that leverages multiple amendments, thus strongly supporting this hypothesis.</p>
<p>4. The agronomic benefits of SR and the promise of its broader adoption among farming communities will not be realized if pressures for monetization lead to overapplications and detrimental rock types. The ultimate benefit from SR is restoration of the full suite of soil ecosystem services, rather than a singular metric such as carbon removal or crop yield.</p>	<p>Historical and modern sources caution against overapplication, as this can hinder productivity and lead to nutrient imbalances or plant toxicity. For example, studies on ultramafic rocks show that excessive application rates can introduce harmful elements like nickel and chromium, while careful selection and moderate use are required for agricultural benefits. Historical observations also warn that the indiscriminate use of rock materials with imbalanced nutrient profiles or high levels of geogenic contaminants could undermine soil health and ecosystem services.</p>

### 3.2 Survey of Research Findings

To examine these hypotheses more quantitatively, we have compiled a database of peer-reviewed soil remineralization studies, including field trials, mesocosm studies, and laboratory experiments (Jerden et al., 2026). Our compiled Remineralize the Earth (RTE) database is not yet exhaustive, but it offers a representative cross-section of findings from a diverse range of research groups, approaches, and perspectives. The database, which is available in Open Science Framework project Soil Remineralization in Agroecological Systems—A Critical Review by Jerden et al., 2026, (<https://doi.org/10.17605/OSF.IO/8JTNM>) tabulates the following information for each study: rock/mineral type, grain size, crop type, initial and final soil pH, type of study (i.e., greenhouse pot studies, mesocosm experiments and field trials), location, soil type, nutrient uptake in plants and yield/biomass changes relative to negative controls. Each entry or observation (i.e., row) in the table is for a particular amendment type, soil type, or crop type, so a single study may have multiple database entries. The database will continue to be updated with both historic and new studies as they become available. The following discussion summarizes the key observations drawn from the database that are relevant to the four hypotheses presented in Table 4 above.

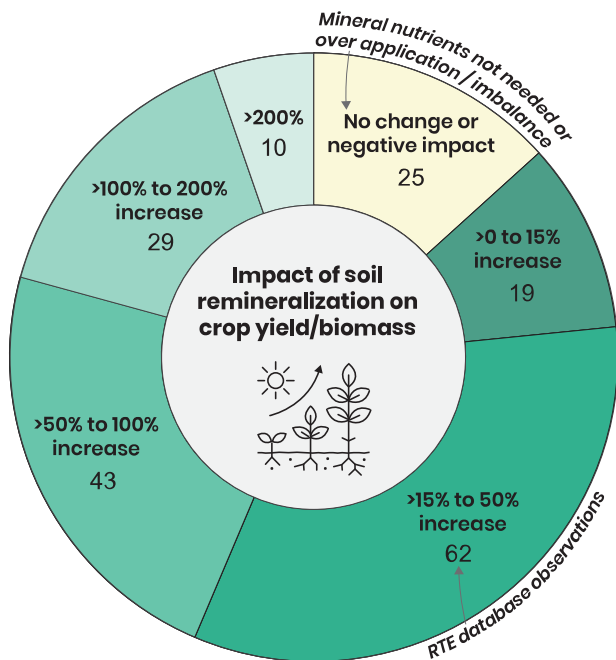
Of the current 191 individual observations represented in the database, 87% of them show an increase in crop biomass or yield due to rock dust amendment, relative to controls. Additionally, of the 83 tests that analyzed plant material, 89% showed increased nutrient uptake due to rock dust amendments, relative to controls. As observed in previous reviews, many studies showed improved physical and chemical soil properties as a result of rock dust amendment. Table 5 highlights the key soil and plant properties that have been observed to improve in response to soil remineralization.

**Table 5.** Major observed benefits of soil remineralization.

<b>Beneficial outcomes and impacts</b>	<b>Description</b>	<b>Example References</b>
Enhanced Soil Fertility and Nutrient Supply	Rock amendments release essential macro- and micronutrients (e.g., K, Ca, Mg, P, Fe, Zn, Si) needed for plant growth, often over a sustained period due to gradual weathering. Rock dust also improves nutrient availability, especially in nutrient-depleted or highly weathered tropical soils, and can be more effective when combined with organic amendments or biochar	Swoboda et al., (2022), Azeem et al., (2022)
Increased Crop Yields and Productivity	Field trials and meta-analyses report yield increases of 10–30% (sometimes up to 2–4 times) compared to conventional or unfertilized controls, particularly in nutrient-poor soils. Improved plant vigor, resilience, root development, and biomass production have been observed.	Goreau et al., 2014, Swoboda et al., (2022)
Soil Structure and Biological Activity	Rock dust application increases soil cation exchange capacity (CEC), enhances soil structure, and supports beneficial soil biology, including higher earthworm abundance and soil respiration. Enhanced microbial activity and soil biota stimulation have been linked to improved nutrient cycling.	Swoboda et al. (2022) Dupla et al. (2024)
pH and Soil Health Regulation	Rock dust applications can neutralize soil acidity, increase pH, and reduce aluminum toxicity, leading to better root growth and nutrient uptake.	Swoboda et al. (2022), Azeem et al., (2022)
Plant Health and Quality	Crops grown on remineralized soils may show increased resistance to biotic and abiotic stresses, improved nutritional value, flavor, shelf life, and some disease resistance.	Swoboda et al. (2022)

Inorganic Carbon Sequestration and Climate Mitigation	Enhanced weathering of silicate rocks captures atmospheric CO <sub>2</sub> by forming stable soil carbonates (inorganic carbon sequestration). Large-scale application has the potential to sequester hundreds of millions of metric tons of CO <sub>2</sub> annually in cropland scenarios.	Russel et al. (2024), Beerling et al. (2025)
Reduced Greenhouse Gas Emissions	Rock dust applications can reduce N <sub>2</sub> O emissions in situ. Emissions are also reduced by replacing or reducing synthetic fertilizer use, which also reduces the carbon footprint associated with fertilizer production and application.	Blanc-Betes et al. (2021), Beerling et al. (2018)
Mitigation of Soil Degradation	Remineralization can restore degraded soils, reverse nutrient depletion, and improve resilience to erosion and drought.	Ramos et al. (2021)
Soil water retention	Rock powder amendments help maintain soil moisture, benefiting crops during drought periods.	Medeiros et al., (2024)
Water Quality and Contaminant Adsorption	Rock powders can help adsorb contaminants from water and soil, reducing leaching of nutrients and pollutants into groundwater.	Ramos et al. (2021)
Waste Valorization and Circular Economy	Utilization of quarry and mining by-products as soil amendments diverts waste from landfills, transforming waste into valuable agricultural inputs.	Luchese et al. (2023)
Reduced Input Costs	Rock powders are often less expensive than synthetic fertilizers—cost savings of up to 50% or more have been reported, especially when using locally sourced materials. A single application can have multi-year residual effects, reducing the frequency and cost of reapplication.	Son et al., (2024)
Increased Profitability and Market Opportunities	Higher yields, improved crop quality, and reduced input costs can increase farm profitability. Expanding use of rock powders creates new markets for mineral and quarry industries, supporting local economies.	Campe, (1997), Catalano, (2007), Cardozo et al., (2024),
Fertilizer Self-Sufficiency and Food Security	Reduces dependence on imported or industrial fertilizers, enhancing regional food security and resilience, particularly in developing countries.	Swoboda et al., (2022), Luchese et al., (2023)
Improve soil texture	Rock powder amendments have been shown to increase soil aggregation and decrease compaction.	Reifschneider et al., (2021), (Salih, 2022)
Economic returns through ecosystem services	Successful SR applications offer a return on investment for practitioners and investors through increased yields and whole-system ecosystem services.	Russell et al. (2024)

As mentioned above, one of the key findings from the RTE soil remineralization database is the large number of studies reporting significant increases in crop yield or biomass following soil remineralization with rock dust. Fig. 6 summarizes these results, showing the number of database observations corresponding to different percentage increases in yield or biomass compared to controls. The majority of database entries showed yield and biomass increases ranging from 15% to 100% relative to the control. Specifically, 105 observations out of the 188 observations measuring yield/biomass are within this range. Twenty-five of the 188 observations showed no change or even a negative impact of rock dust amendment. These observations appear to represent studies in which the starting soil material was already nutrient-rich and therefore did not benefit from the addition of mineral nutrient sources. The negative impacts were likely caused by overapplication or the use of an inappropriate rock type.

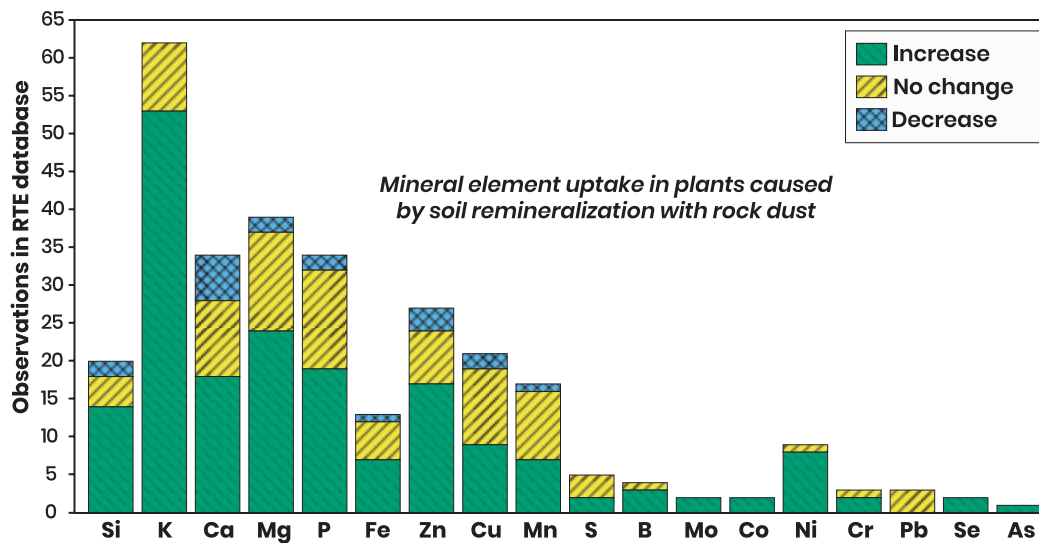


**Figure 6.** Breakdown of findings on how soil remineralization impacts crop yield/biomass from the RTE SR database (OSF repository project: <https://doi.org/10.17605/OSF.IO/8JTNM>).

Overall, the database findings strongly support our hypothesis 1 by clearly demonstrating that soil remineralization leads to significant, and in some cases dramatic, increases in crop biomass and yield compared to control groups, when implemented with a whole-system approach. That is an approach that accounts for rock dust chemistry and mineralogy, soil properties (both chemical and physical), and soil biology (including the microbial community). The observed yield improvements suggest that soil remineralization can play a crucial role in alleviating food insecurity, particularly in developing countries within the global South, where many agroecological zones are characterized by degraded and nutrient-depleted soils. These yield gains are achieved without the use of synthetic fertilizers, thereby greatly reducing the environmental impact of agriculture. By relying on locally sourced, abundant rock materials rather than expensive, imported fertilizers, soil remineralization can also enhance the economic sustainability of farming communities.

### 3.3 Evidence for Nutrient Uptake from Soil Remineralization

Several studies in the database also measured the uptake of key inorganic nutrients and some potentially toxic elements by crop plants. These results are summarized in Fig. 7. There were 83 total observations providing data on element uptake in crops; of these, 53 showed an increase in potassium, 24 an increase in magnesium, 19 an increase in phosphorus, 18 an increase in calcium, 17 an increase in zinc, and 14 an increase in silicon. There were also several observations showing increases in copper, iron, manganese, boron, and molybdenum. Uptake of potentially toxic elements was also recorded, with 8 observations showing an increase in nickel, 2 showing an increase in chromium, and one showing an increase in arsenic.



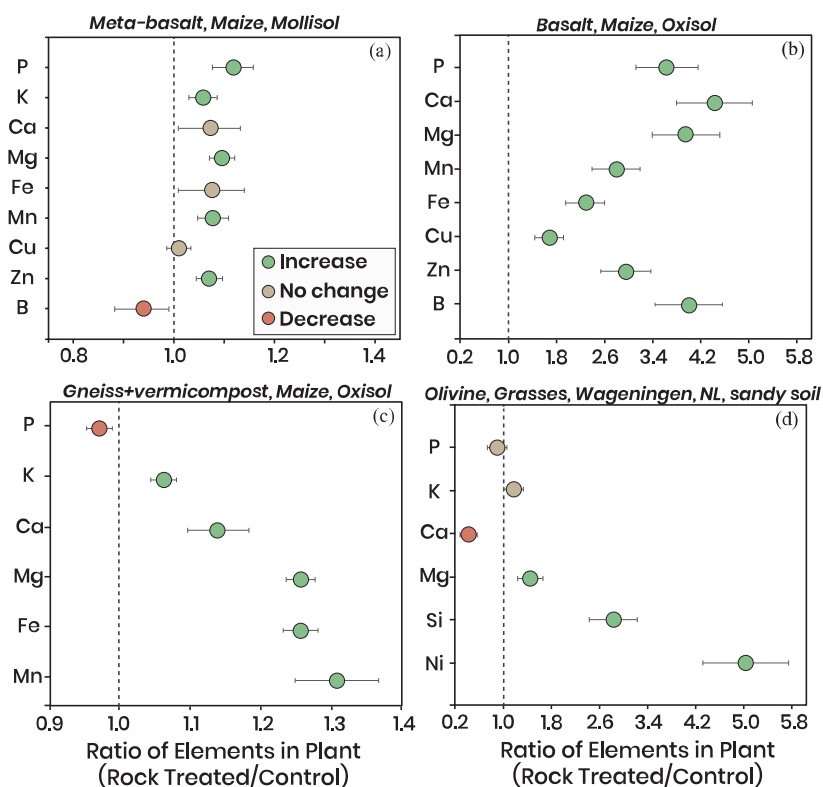
**Figure 7.** Breakdown of how soil remineralization impacts nutrient uptake as measured by analyses of plant material. The numbers indicate how many observations from experiments and field trials showed an increase, no change or decrease in key elements concentrations. The observations are from the RTE SR database (OSF repository project: <https://doi.org/10.17605/OSF.IO/8JTNM>).

The studies represented in the database demonstrate that soil remineralization with rock dust can enrich crops with essential elements, resulting in more nutrient-dense plants that are healthier and more resilient to both abiotic and biotic stressors. These results provide direct support for hypothesis 1 of this review. However, they also show that rock dust applications may increase the concentrations of potentially toxic elements in plant tissues, underscoring the need for an integrated, whole-system approach (consistent with hypothesis 2) that accounts for both rock and soil chemical compositions and properties, so that SR applications do not exceed the plant toxicity ranges discussed in Section 2.3.

In some studies, the results were more subtle. For example, Buss et al. (2024) found that the addition of a basalt-granite blend had no measurable effect on wheat plant biomass and no impact on the uptake of calcium and magnesium into the plant tissue. However, they did observe that the wheat grain calcium content increased by 28% due to rock dust amendment. In addition, it was found that the rock dust amendments led to a 33% increase in total silicon uptake into plant stems.

Analyzing four representative studies from the database in more detail reveals the magnitude of element enrichment in plants relative to control and also gives insights as to the role of rock type and soil type on element uptake (Fig. 8). Figure 8 presents the ratios of key element concentrations in rock dust-treated soils relative to those grown in untreated control soils. These studies demonstrate variable nutrient responses in plants following rock dust amendments. Beerling et al. (2024) observed in an Illinois field study (mollisol soils) that the application of meta-basalt rock dust enriched maize in phosphorus, potassium, magnesium, manganese, and zinc, though calcium, iron, copper, and boron showed no significant enrichment (Fig. 8a). Similarly,

Conceição et al. (2022) reported nutrient enrichments of phosphorus, calcium, magnesium, manganese, iron, copper, zinc, and boron in maize grown in oxisols treated with basaltic rock powder under greenhouse conditions (Fig. 8b). De Souza et al. (2018) documented enrichments of potassium, calcium, magnesium, iron, and manganese, and a slight depletion in phosphorus in maize for Brazilian field trials (Minas Gerais) using gneiss rock dust blended with vermicompost (Fig. 8c). The minor phosphorus depletion in this study may have been caused by the reaction phases between phosphorus and iron in the soil, leading to the formation of insoluble iron phosphate mineral phases.



**Figure 7.** Example plots from RTE database showing ratio between elemental concentrations in plants grown in rock-treated soils and untreated control soils. Data are from (a) Beerling et al., 2024, (b) Berge et al., 2012 and (c) Conceição et al., 2022, (d) De Souza et al., 2018.

Berge et al. (2012) found that olivine addition to sandy soils from central Netherlands enriched perennial ryegrass in magnesium and silicon but depleted the grass in calcium and increased nickel concentrations (Fig. 8d). The authors attributed calcium depletion to magnesium-induced uptake antagonism caused by the weathering of magnesium-rich olivine. This finding, along with elevated levels of potentially toxic nickel, suggests that rock/mineral

powders may cause nutritional imbalances if they misalign with soil nutrient requirements (as discussed in Section 2.3). This again underscores the necessity of a whole-system perspective (rock-soil-biology interactions) in remineralization projects.

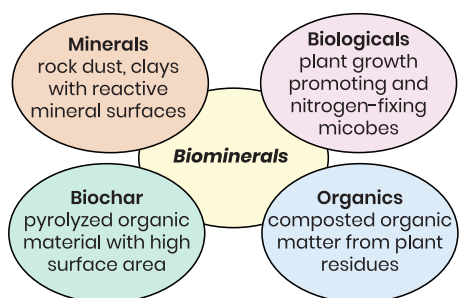
### 3.4 Combining Rock Dust with Biomass-Based Amendments: Biominerals

Our review of historical soil remineralization practices and literature review also shows that combining rock dust with biomass-based materials, such as organic composts, biochar, and microbial inoculants, generally produces better results than using rock dust alone.

This observation echoes the findings of Basak et al. (2017) in their comprehensive review of the bio-intervention of silicate minerals as a natural source of potassium. Basak et al. (2017) find that the addition of biological materials enhances the performance of rock dust treatments through several key mechanisms. These

include selective element-solubilizing microorganisms such as *Bacillus mucilaginosus*, *Bacillus edaphicus*, and fungi (*Aspergillus spp.*) that produce organic acids capable of dissolving silicate mineral structures, thus releasing nutrient elements such as potassium. Microbes were also observed to form biofilms on mineral surfaces, creating microenvironments that concentrate weathering agents. The addition of compost was also observed to introduce enzymes that break down mineral structures, thus increasing cation exchange. It was also found by Buss et al. (2024) that the addition of rock dust combined with both compost and pyrogenic carbon (i.e., biochar) improved soil structure and nutrient retention, countering micronutrient deficiencies.

The combination of rock dust with biochar and organic materials that support plant growth-promoting microorganisms is referred to as a biomineral amendment (Davenport and Vanacore, 2024), a particularly effective form of soil remineralization. Biominerals (rock dust + organics) can be used as a soil conditioner, biofertilizer, and nutrient delivery system to enhance crop growth and sequester soil carbon (Davenport and Vanacore, 2024). The major components of biomineral soil remineralization are summarized in Fig. 9.



**Figure 9.** Conceptual diagram of biomineral components highlighting the importance of inorganic, organic and biological inputs (adapted from Davenport and Vanacore, 2024).

Biominerals are produced by combining organic (i.e., crop residues) and inorganic (i.e., basalt rock dusts and biochar) feedstocks in a way that cultivates a beneficial microbial community that functions in a mutualistic capacity and is capable of withstanding harsh environmental conditions (e.g., drought, high salinity, alkaline

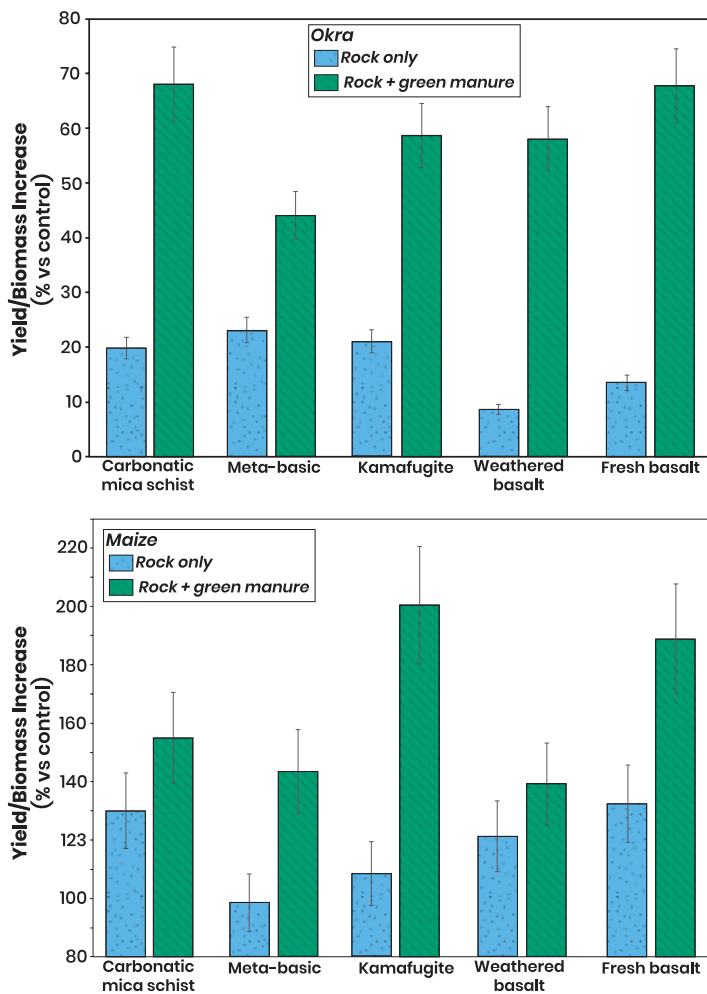
conditions, etc.). The microorganisms cultivated during biomineral production are generally gram-positive bacteria, meaning they lack outer cell membranes and are known for developing unique survival strategies in response to extreme environmental conditions (Davenport and Vanacore, 2024).

The mutualistic relationships of microorganisms cultured in biominerals are distinct from those of commonly used soil inoculants and biological amendments. Instead of one or a few microorganisms that perform one function, such as nitrogen fixation, the microbes cultivated in biominerals work together to perform numerous functions that are beneficial for plant growth. These functions include the production of ammonium (plant-available nitrogen) through urease-catalyzed hydrolysis of urea, nitrification of ammonium, dissimilatory nitrate reduction to ammonia, and nitrogen fixation. The key species involved in SR biominerals (e.g., Table 6) have also been shown to improve plant growth through several different mechanisms.

**Table 6.** Commonly abundant bacteria species identified using 16S rRNA amplification sequencing in biominerals (adapted from Davenport and Vanacore, 2024).

<b>Bacteria (Genus Species)</b>	<b>Plant growth-promoting characteristics</b>	<b>References</b>
<i>Bacillus species</i>	Nitrogen fixation, phosphate solubilization, siderophore production, plant growth hormone production, urease production, microbial induced calcite precipitation (MICP).	Anbu et al., 2016, Patani et al., 2024, Cruz et al., 2021.
<i>Brachybacterium paraconglomeratum</i>	Protects plant against salinity, mediates phytohormones, bioremediation of toxins and pollutants, urea and organic matter decomposition, ammonium production.	Barnawal et al., 2016, Djurić et al., 2017, Takeuchi et al., 1995
<i>Glutamicibacter nicotianae</i>	Degradation of antibiotics, cadmium and plasticizers, urea degradation, dissimilatory nitrate reduction, ammonification.	Wang et al., 2022, Li et al., 2024
<i>Saccharomonospora viridis</i>	Forms mutualistic relationships with other bacteria via production of cobalamin, resistant to abiotic stress.	Zhao et al., 2023
<i>Nocardiopsis species</i>	Production of metabolites and enzymes, bioremediation of soil heavy metals and pollutants, symbiotic relationships with nitrogen-fixing bacteria.	AbdElgawad et al., 2021, Shi et al., 2022, Bennur et al., 2015, Trujillo et al., 2015, Metcalfe et al., 1957
<i>Actinomadura species</i>	Production of plant growth promoting hormones such as indole-3-acetic acid (IAA), siderophore production, phosphate solubilization.	Oyedoh et al., 2023
<i>Pseudogracilibacillus endophyticus</i>	Nitrogen fixation, solubilization of inorganic phosphorus, production of plant growth regulators (IAA), and siderophore production for iron acquisition.	Park et al., 2018
<i>Sporosarcina pasteurii</i>	Urease production, calcite precipitation (MICP), soil aggregate formation via carbonate production.	Ghosh et al., 2019, Lapierre et al., 2020

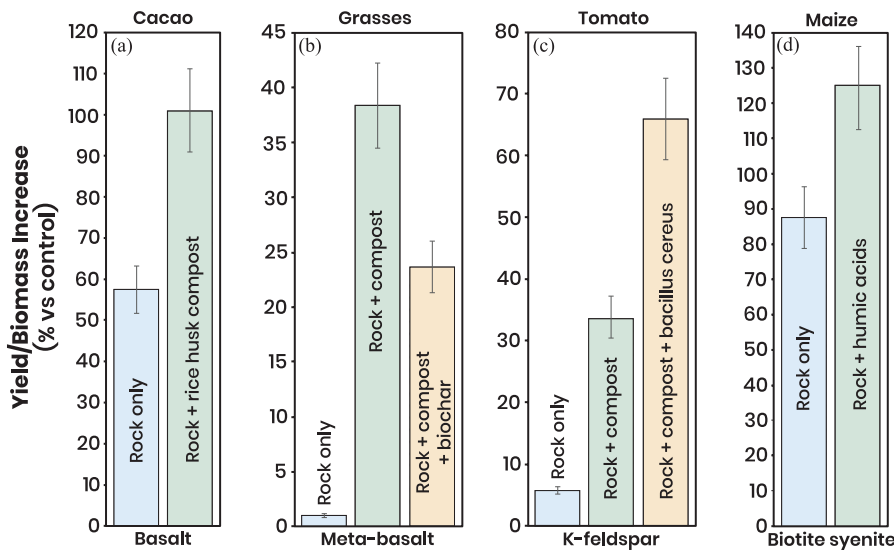
The RTE database contains ample empirical evidence supporting the hypothesis that combining rock dusts with organic and biological materials (i.e., biomineral amendments) improves soil properties and fertility more than rock dust alone. Thus, both the preceding discussion and the results presented below support hypothesis 3 of this paper, which asserts that SR is most effective when amendments contain both inorganic rock materials and organic/biological components. For example, Fig. 10 presents results from Theodoro and Leonardos (2014), indicating that the percent yield increase during the first growing season for okra and maize was significantly higher for most rock amendments when the geologic material was combined with green manure. This was especially true for fresh basalt, consisting primarily of plagioclase, pyroxene, basaltic glass, and zeolites and kamafugite, a rare Brazilian potassium-rich volcanic rock mainly composed of olivine, pyroxene, and phlogopite (magnesium-rich biotite mica).



**Figure 10.** Percent yield increases vs. negative control for okra and maize when five different rock dust types were applied with and without green manure. Adapted from Theodora and Leonardos (2014). Error bars are 10% for reference.

Theodoro and Leonardos (2014) posit that rock weathering during their field trials was likely accelerated by manure-supported microbial activity, thus remineralizing the highly leached soils in their study area. They also indicate that organic acids from root exudates were instrumental in breaking down the rock dust minerals and releasing their nutrient elements. The specific organic acid composition depends on the plant/crop species, soil properties (abiotic stress), and the activity of microorganisms. Overall, Theodoro and Leonardos (2014) conclude that the association of organic composts and green manure with rock dust amendments represents a powerful nature-based soil remineralization practice that can effectively supply all needed macro- and micronutrients to crops.

The results shown in Fig. 11 reiterate the observation that adding organic materials such as compost and biological agents such as humic acid and bacteria to rock dust amendments accentuates increases in crop yield and biomass relative to controls. The field study by Ananda et al. (2013) in Pahang, Malaysia, showed that Cacao yields increased (relative to control) from around 55% for basalt rock powder alone to around 100% when basalt was combined with rice husk composite (Fig. 11a). Anthony et al. (2025) performed a field study in California in which metabasalt combined with compost and biochar was used as a soil conditioner for rangeland grasses (Fig. 11b). The results showed that rock dust alone did not achieve a significant biomass increase; however, when applied with compost, the SR amendment resulted in a biomass increase of approximately 38% (relative to the negative control) (Anthony et al., 2025). When biochar was added, the biomass increase dropped to around 24%, possibly due to transient effects on soil microbial communities and nutrient cycling. It was also observed that the addition of compost and biochar significantly accelerated carbon sequestration within the soils relative to rock dust alone (Anthony et al., 2025).



**Figure 11.** Percent yield increases vs. negative control for six different combinations of rock types, crops, and organic amendments. (a) is from Ananda et al., (2013), (b) is from Anthony et al., (2025), (c) is from Badr, (2006), (d) is from Busato et al., (2022).

Fig. 11c shows results from a field trial aimed at increasing soil potassium using the mineral potassium feldspar for a tomato crop in Lower Egypt (Badr,

2006). It was found that the addition of K-feldspar alone increased crop yield by around 6% relative to the negative control; however, when the mineral was combined with compost, the yield increase was boosted to 34%. When the mineral-solubilizing bacteria *Bacillus cereus* were added to the mixture of K-feldspar and compost, the yield increase was further boosted to 66%. The increase in yield associated with the addition of organic and biological components is likely due to the acceleration of mineral weathering by organic compounds and the bacteria, resulting in solubilized and phytoavailable potassium (Badr, 2006). The addition of organic-sourced nutrients from the compost also aids in plant health and growth. This effective combination of silicate-dissolving bacteria, compost, and K-feldspar represents a successful field demonstration of biomineral fertilizations that can replace or supplement synthetic fertilizer use.

Busato et al. (2022) performed greenhouse tests in which the rock biotite syenite was added to oxisol soils in which maize was grown (Fig. 11d). The study found that the coapplication of the rock with humic-like acids significantly improved soil properties by increasing root and plant biomass compared to rock dust alone. The rock dust amendments performed well, resulting in an 88% increase in plant biomass relative to the control; however, when coapplied with the humic-like acid, the biomass increase was boosted to 125%. This increase is associated with the humic substance's ability to accelerate mineral weathering and optimize nutrient availability to the plants (Busato et al. 2022).

These results support the first three hypotheses of this review: 1) soil remineralization is a versatile agroecological practice that addresses food security, nutrient limitations, environmental impacts, and climate stabilization; 2) the successful application of SR depends on a whole-system approach that integrates biological, geochemical, agronomic, hydrological, and climatic interactions; and 3) the effectiveness of SR is enhanced when combined with pyrogenic materials, organic biomass, and biological additives rather than used alone. The following Section further addresses hypothesis 4, which states that the ultimate benefit from SR is restoration of the full suite of soil ecosystem services, rather than a singular metric such as carbon removal or crop yield.

More specifically, Section 4 considers how the adoption of soil remineralization can be incentivized and promoted to maximize and democratize its societal benefits.

## **4.0 Incentivizing Broad Adoption of Soil Remineralization**

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As discussed in Section 2.5, a relatively recent, but powerful incentive for broadening the use of rock dust as an agricultural input is monetary support from both private and public sources for developing and scaling enhanced rock weathering as a carbon dioxide removal technology. As mentioned, large-scale ERW has the potential to remove between 0.5 and 2 gigatonnes of CO<sub>2</sub> annually if implemented over millions of hectares globally (e.g., Beerling et al., 2020; Renforth et al., 2024). These estimates focus primarily on the inorganic conversion of CO<sub>2</sub> to carbonate species (e.g., Reaction 2 above). Modeling shows that these dissolved carbonate species (primarily HCO<sub>3</sub><sup>-</sup>) remain in the geosphere and hydrosphere (i.e., sequestered from the atmosphere) for hundreds to thousands of years (e.g., Renforth and Henderson, 2017) and potentially for millions of years if they are precipitated as limestones and other carbonate rock (e.g., Berner et al., 1983). It is important to note that this “solubility trapping” mechanism does not account for several additional co-benefits of soil remineralization, such as increased soil carbon accumulation and stabilization, synergistic effects from co-application with biochar, organic inputs, and biological additives, as well as diverse environmental and societal advantages (Fig. 2, Table 5). These factors can be critical motivators for farmers considering the adoption of soil remineralization practices. However, there is also a need for financial incentivization. As discussed in the following Section, the primary financial framework for the commercial deployment of SR as a carbon dioxide removal method involves voluntary carbon markets.

### **4.1 Incentivization and Financing of Rock Dust-Based Carbon Dioxide Removal**

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The early commercial-scale deployments of SR for carbon dioxide removal (i.e., ERW) have been predominantly incentivized and financed through voluntary carbon markets, which generate and trade carbon offsets from quantified net CO<sub>2</sub> removal projects. For-profit ERW companies typically collaborate with farmers to apply finely ground rock to agricultural soils, then sell the resulting credits to corporations and climate-focused funds via recognized carbon registries.

Recent work has called into question the adequacy of VCM-based offset mechanisms, highlighting compromised environmental integrity, risks of double counting and CO<sub>2</sub> leakage, inadequate transparency, and negative social impacts associated with power and information asymmetries and the commodification of nature (Meitner, 2024; Romm et al., 2025). Economic and carbon-finance research further indicates that, although carbon pricing and offset-based frameworks may represent an important first step, reliance on these mechanisms alone is likely to be insufficient to manage systemic climate risk and deliver deep decarbonization (Chen et al., 2017). These observations suggest that VCMs and offsetting schemes, as currently constituted, are unlikely to succeed as the principal framework for climate finance in general and ERW finance in particular.

This realization underpins proposals for alternative approaches that prioritize direct environmental improvements and a more comprehensive valuation of ecosystem services. One such proposal is Delton Chen’s Global Carbon Reward (GCR) framework, which builds on previous work (Chen et al., 2017). This framework

envisioning a supranational, central-bank–supported monetary system that directly values verified carbon mitigation as a global public good, explicitly avoiding offsetting and aligning more closely with Payment for Ecosystem Services models than with traditional carbon trading (Global Carbon Reward, 2025). This re-directed focus on incentivizing ecosystem services rather than single-metric CDR is consistent with our hypothesis that the ultimate benefit of SR (and, by extension, ERW) lies in restoring the full suite of ecosystem services rather than maximizing isolated outcomes such as crop yield or carbon removal.

## **4.2 Holistic Soil Remineralization for Soil Revitalization and Carbon Dioxide Removal**

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Transformative financing models such as the Global Carbon Reward framework could greatly facilitate the scale-up of soil remineralization and ERW. However, several potential pitfalls and risks associated with large-scale rock dust applications warrant systems-level evaluations from both mechanistic (i.e., biogeochemical) and life cycle assessment perspectives.

As discussed in Section 2.3, excessive application of rock materials can lead to imbalanced nutrient profiles and elevated levels of geogenic contaminants. Such issues could erode trust among farming communities and the general public, hindering the broader adoption of soil remineralization and ERW. For instance, in efforts to maximize CDR, some ERW studies assume annual application rates of up to 40 tonnes per hectare (e.g., Beerling et al., 2025). This far exceeds the rates used in several successful soil remineralization field trials (see Jerden et al., 2026, <https://doi.org/10.17605/OSF.IO/8JTNM>), where single applications typically range from 1 to 10 tonnes per hectare (e.g., Anda et al., 2013; Theodoro and Leonardos, 2014; Conceição et al., 2022; De Silva, 2007). Furthermore, Dupla et al. (2023) report that repeated applications of basalt rock powder at rates of 10–100 t ha<sup>-1</sup> yr<sup>-1</sup> could lead to substantial increases in soil concentrations of copper, nickel, chromium, and zinc. Their modeling results indicate that concentrations of these metals could surpass national regulatory thresholds within a decade, with copper and nickel posing the greatest risks. The rapid buildup of potentially toxic elements may threaten agricultural productivity and food safety, while also introducing significant regulatory challenges. To mitigate these risks, Dupla et al. (2023) advocate for a reassessment of ERW practices, suggesting that more sustainable approaches could include reducing application rates, extending intervals between applications, or selecting basalt sources with lower trace metal contents.

As established in our hypothesis (4) and the discussion of innovative financing models such as the GCR framework, incentivization of soil remineralization and improved ERW MRV can be achieved by developing more holistic approaches and platforms that embed environmental services and stack CDR mechanisms, such as increased soil carbon and the integration of biochar with rock dust applications (e.g., Planavsky et al., 2025). We thus conclude that emphasizing multidimensional agroecological services, such as enhanced soil biology, increased yields, drought resistance, and improved produce quality, makes the case for rock dust application more attractive to farmers and stakeholders. These benefits support both environmental and agricultural goals, creating diverse incentives for adoption in an economic framework, with or without subsidy.

Theodoro and Leonardos (2006) demonstrate how this type of holistic approach to soil remineralization can be effectively promoted on a community scale. Building on the earlier work of Ilchenko and Guimarães (1953), Guimarães (1955), and Leonardos et al. (1976), the researchers selected Mata da Corda volcanic rock dust for on-farm trials carried out by local farmers. These volcanic rock materials are abundant across Brazil's Central

Plateau and are naturally rich in both macro- and micronutrients, containing substantial whole-rock levels of silicon, magnesium, calcium, potassium, and phosphorus. They also provide zinc, copper, and nickel in concentrations of several hundred parts per million; sufficient to serve as valuable sources of essential trace elements, yet low enough to avoid issues of toxicity or contamination at the moderate application rates applied in the study (2.5 to 4 tonnes per hectare) (Theodoro and Leonardos, 2006).

In this study, the research team provided both rock materials and technical guidance, enabling local farmers to experiment directly and see for themselves the advantages of soil remineralization compared with sole reliance on imported synthetic fertilizers. The community involved comprised about 1,000 people across 220 families. The project aimed to do more than assess crop yields: researchers also monitored changes in the soil's physical and chemical properties, evaluated environmental and economic impacts, and examined the social, cultural, and psychological effects of remineralization within the family farming community. The studies were carefully designed and structured so that farmers could readily understand the results and appreciate their broader, real-world implications. By conducting the experiments themselves, farmers gained a strong sense of ownership in the process, while also developing practical expertise in optimizing soil remineralization for their own farms.

The research team guided the farmers in performing comparative experiments where one plot was fertilized with rock dust (with or without compost), another plot was treated with synthetic NPK fertilizer, and another plot was treated with a mixture of rock dust and NPK fertilizer. Crop types included maize, sugar cane, cassava, rice, and watermelon. The rock dust application rates were 2.5 to 4 tonnes per hectare. In some trials, farmers added organic composts with the rock dust. In addition to standard mineralogical, geochemical, and soil fertility measurements, the researchers also took photographs of the crop growth during various stages and conducted interviews with farmers to discuss successes, failures, and issues experienced during the trials. The soils and crops were monitored over two growing seasons with a five-year follow-up.

Soils treated with rock dust and composts showed significant increases in pH and bioavailable calcium, magnesium, potassium, and phosphorus. Even after five years, these and other soil properties, such as reduced aluminum toxicity, showed improvement relative to pre-treatment samples (Theodoro and Leonardos, 2006). It was also observed that the soil remineralization plots produced higher crop yields relative to the NPK-treated plots. The addition of organic compost with rock dust was found to be particularly beneficial for enhancing soil properties and fertility. Soils amended with rock dust also exhibited enhanced water retention capacity, attributable to increased clay content, and also developed more extensive and well-differentiated root systems compared to those grown under NPK fertilization. The application of rock dust was also associated with substantially reduced costs (exceeding 60% savings), primarily due to the sustained improvements in soil fertility. Farmers participating in the study reported these agronomic and economic benefits under field conditions, which served as a strong incentive for the adoption of soil remineralization practices.

The experiments also raised farmers' awareness of the numerous complex and interconnected ecological, social, cultural, and behavioral factors that support sustainable agriculture, ultimately improving the quality of both natural and human habitats. Shortly after the experiments began, positive changes became evident. A cooperative was established to improve cattle management, dairy production, and other local food products. A supermarket was also built, and thanks to responsible management and direct purchasing from producers,

prices on goods dropped significantly. Within the community, locally produced goods were sold at affordable prices. This kept money circulating within the community, strengthening the local economy. Surplus production, especially meat that met sanitation standards, was sold in larger cities, generating additional income and attracting new investments.

The study by Theodoro and Leonardos (2006) demonstrated that farmers rapidly adopted soil remineralization with rock dust due to its straightforward concept and easily observable benefits. Its effectiveness, affordability, and reduced environmental impact, particularly in terms of energy demand, established it as an appealing alternative to conventional practices reliant on synthetic fertilizers. The use of rock dust in combination with organic and biological inputs provides a more integrated and sustainable approach than industrialized farming methods, which have evolved in ways that distance production from ecological balance principles. This work serves as a pertinent example of how engaging community farmers directly in scientific research can accelerate the acceptance and widespread adoption of soil remineralization practices. With abundant suitable rock material available, Theodoro and Leonardos (2006) highlight the potential for this model to be replicated across Brazil, increasing the likelihood that the practice could achieve acceptance at regional, national, and even international scales.

The project further illustrated, through measurable productivity gains and the rapid adoption of remineralization by family farmers (whose livelihoods depend critically on land resources), that it is possible to transform long-standing patterns of natural resource use. From a technical perspective, combining rock powder with organic compost proved remarkably effective, not only enhancing nutrient availability but also reducing on-farm waste streams.

A key takeaway from the study is that producing healthier, more affordable food necessitates both agricultural innovation and social collaboration. Soil remineralization not only sustained productivity comparable to that of conventional systems but also simultaneously reinforced the social organization of family farmers. Within this framework, rock powder has been widely regarded as a viable strategy for enhancing resilience and achieving long-term economic, social, and environmental sustainability. Notably, the practice offered resource-poor farmers a stronger foundation for maintaining their participation in agricultural life. Successful harvest outcomes provided tangible evidence of the approach's legitimacy and offered support for broader sustainable development proposals in Brazil and comparable contexts. As stated by one of the participating farmers:

*“I very much like this material that comes from the stones. My joint rice and manioc plantation was much greener, and the plants grew more. In the veranico (a sudden drought period of 3 to 5 weeks in the wet summer; little summer) the plants got much greener in the patches where the material was employed. What we want now is government help to bring this material, which comes from the land itself, to all of us. Besides being cheaper, it brings better results. Family farmers need this help”. (interview conducted in 2000 with a local farmer participating in the Theodoro and Leonardos, 2006 study).*

## 5.0 Conclusion

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The evidence presented in this review offers substantial empirical backing for our four primary hypotheses. First, soil remineralization is demonstrated to be an effective agroecological farming practice that addresses multiple sustainability challenges simultaneously, including food insecurity, nutrient deficiencies, agricultural environmental impacts, and climate stabilization. Second, the successful application of SR and related practices, such as enhanced rock weathering, requires an integrated or whole-system approach that accounts for the dynamic interplay of biological, geochemical, agronomic, hydrological, and climatic processes. Third, the combination of rock dust with pyrogenic materials (i.e., biochar), organic biomass (e.g., composts), and biological additives (e.g., microbial inoculants) improves soil properties and fertility more than rock dust alone. Fourth, the ultimate benefit from SR is restoration of the full suite of soil ecosystem services, rather than a singular metric such as carbon removal or crop yield. Importantly, the agronomic benefits of SR and the promise of its broader adoption among farming communities will not be realized if pressures for monetization lead to overapplications of rock materials and the use of rock types with imbalanced nutrient profiles and high levels of geogenic contaminants. Collectively, these findings underscore the need for a holistic, systems science–based approach to implementing soil remineralization strategies that maximize ecological and societal benefits while minimizing unintended risks.

## Acknowledgements

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# Declarations

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## Preprint Status

This article is a non–peer-reviewed preprint submitted to EarthArXiv. It has not yet been formally accepted for publication in a scholarly journal, and subsequent versions may differ in content as a result of peer review and editorial processes. The findings and interpretations presented here should be considered preliminary rather than definitive. The authors welcome comments and feedback and invite readers to contact us with questions and critiques.

## Availability of data and material

All data underlying this review, including the compiled dataset of experimental and field results and associated supplementary materials, are openly available on the Open Science Framework (OSF) repository under the project “Soil Remineralization in Agroecological Systems—A Critical Review” (<https://doi.org/10.17605/OSF.IO/8JTNM>).

## Authors' contributions

All authors contributed to the study conception and design. Methodology, investigation (critical analysis and reaction path modelling), data curation, original draft preparation, and visualization were performed by James Jerden. Review and editing and provision of technical and practical expertise were carried out by Thomas Vanacore. Supervision, project administration, and review and editing were performed by Joanna Campe. All authors read and approved the final manuscript.

## Conflicts of interest/Competing interests

James Jerden and Joanna Campe declare that they have no competing interests. Thomas Vanacore is the founder of Rock Dust Local, a small business specializing in local and regional sourcing of rock dust for soil remineralization (SR) and enhanced rock weathering (ERW). Vanacore's contribution to this review was to provide technical and practical expertise on the implementation of SR and ERW with farmers, including real-world examples of potential pitfalls and risks when these practices are improperly applied. No specific commercial products are promoted in this article; Rock Dust Local provided no financial support for the work, and the analyses, data synthesis, and conclusions were developed independently by the authors without influence from any commercial interests.

## Ethics approval

This article is a review of published literature and does not involve any studies with human participants or animals performed by the authors; therefore, formal ethics approval was not required.

## Funding

This work was supported by the nonprofit organization Remineralize the Earth.

# Supplementary Information

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## Equations and Parameter Sources for Reaction Path Model

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The dissolution kinetics (weathering rates) of the minerals in the Geochemist's Workbench™ reaction path model discussed in Section 2.4 were defined using the equations and parameters from Palandri and Kharaka (2004) supplemented by parameters for basaltic glass dissolution from Pollyea and Rimstidt (2017) and a biological function from Beerling et al. (2020). The biological function accounts for a range of rhizosphere processes that can significantly accelerate mineral weathering, including the effects of mycorrhizal fungi and root exudates (e.g., organic acids and chelating agents) (Beerling et al., 2020). As shown in the model results (Fig. 4), incorporating these organic rhizosphere processes (as represented by biological function) has a significant effect on the predicted mineral weathering rates and is thus essential for accurately estimating nutrient release over time. For example, Akter and Akagi (2005) found that biological processes associated with rice, maize, and soybean growth increased nutrient release rates from basalt by 2 to 7 times for calcium and 6 to 112 times for magnesium relative to a “no-plant” baseline.

Our demonstration model was implemented using the “thermo.com.V8.R6.full” thermodynamic database derived from the Lawrence Livermore National Laboratory (LLNL) EQ3/6 thermodynamic database (Wolery and Daveler, 1992). The following rate laws from Palandri and Kharaka (2004) were used:

For dissolution under acidic conditions, the equation is as follows;

$$\frac{dm}{dt} = -SA \left[ k_{acid}^{298.15K} \exp\left(\frac{-E_{acid}}{R} \left(\frac{1}{T} - \frac{1}{298.15K}\right)\right) a_{H^+}^{n_1} (1 - \Omega^{p_1})^{q_1} \right] \quad (1)$$

Under neutral conditions:

$$\frac{dm}{dt} = -SA \left[ k_{neutral}^{298.15K} \exp\left(\frac{-E_{neutral}}{R} \left(\frac{1}{T} - \frac{1}{298.15K}\right)\right) (1 - \Omega^{p_2})^{q_2} \right] \quad (2)$$

And for basic conditions:

$$\frac{dm}{dt} = -SA \left[ k_{base}^{298.15K} \exp\left(\frac{-E_{base}}{R} \left(\frac{1}{T} - \frac{1}{298.15K}\right)\right) a_{H^+}^{n_3} (1 - \Omega^{p_3})^{q_3} \right] \quad (3)$$

Where  $\frac{dm}{dt}$  is the dissolution rate in mols per second,  $SA$  is the mineral or rock surface area in  $m^2$ ,  $E$  is the activation energy (Joules per mole), which quantifies the temperature dependence,  $R$  is the universal gas constant,  $T$  is absolute temperature,  $a_{H^+}$  is the activity of hydrogen ion,  $n$  is the reaction order with respect to hydrogen ion, and  $\Omega$  is the saturation index, which quantifies the mineral saturation state of the soil pore water ( $\Omega = \frac{Q}{K}$  where  $Q$  is the ion activity product, and  $K$  is the equilibrium constant). The exponents  $p_i$  and  $q_i$  are empirical, dimensionless parameters that describe specific reaction mechanisms. These exponents are only known for a few minerals. The default values for both of these parameters in the model are 1.0.

The rate constant, activation energies, and reaction order parameters for individual minerals were taken from the compilation of Palandri and Kharaka (2004), except for the basic mechanism parameters for labradorite and sanidine, which come from Heřmanská et al. (2022). The surface area, temperature, hydrogen ion activity (pH), and saturation index are all model variables that account for variations in soil conditions. The dissolution rate equation and parameter values for the basaltic glass phase, which makes up 10% of both the basalt and basaltic andesite model rocks, were taken from Pollyea and Rimstidt (2017). For the scenarios modeled for this study, it is assumed that precipitation levels (i.e., water flux through the soils) do not limit the rock powder weathering rates.

In our simple demonstration model, the biological effects on rock weathering rates are accounted for using the biological function derived by Beerling et al. (2020). This function is an empirical fit to experimental weathering data from mesocosm experiments. These tests investigated basalt weathering rates for pots containing either annual or woody crops, and the role of mycorrhizal fungi was also quantified (Akter and Akagi, 2005; Akter and Akagi, 2010; Quirk et al., 2012; Quirk et al., 2014). The biological function derived from these tests captures the effects of plant biology and rhizosphere processes. These processes, such as the bond-breaking action of mycorrhizal fungi at mineral surfaces and the chelating action of root exudates, have been shown to accelerate mineral weathering significantly (Beerling et al., 2020, references cited above). The use of the biological function in the mineral dissolution equation is shown in Equation 4, and its formulation is shown in Equation 5:

$$\frac{dm}{dt} = -SA \left[ k_i^{298.15K} \exp\left(\frac{-E_i}{R} \left(\frac{1}{T} - \frac{1}{298.15K}\right)\right) a_{H^+}^{n_3} (1 - \Omega^{p_3})^{q_3} \right] \times f(NPP) \quad (4)$$

$$f(NPP) = a(x_{normalized} \times NPP_{normalized})^b + 1 \quad (5)$$

Where  $NPP_{normalized}$  (abbreviated as  $NPP_n$ ) is the normalized net primary production of the crop plant, and  $a$ ,  $x_{normalized}$ , and  $b$  are fitted parameters (see Beerling et al., 2020, Supplementary Information Section 2.0).

The physical setup for the demonstration model assumes that the rock dust weathering occurs within the upper 25 cm of the soil profile and that the soil has a porosity of 0.4. The surface sites within the soil are assumed to be dominated by goethite and gibbsite, indicative of a highly weathered oxisol. The surface complexation of ions released from mineral weathering was simulated in the model using the Gibbsite+.sdat and Goethite+.sdat double-layer surface complexation datasets (Karamalidis & Dzombak, 2010, and Mathur, S.S., & Dzombak, D.A., 2006, respectively)

The model assumes that the weathering rocks maintain a constant specific surface area (m<sup>2</sup>/g) throughout the dissolution process. The conversion between grain size (particle diameter) and surface area is done using the Sauter mean diameter formula as described by Wang and Fan, 2013. This formula relates the diameter of a particle  $d_s$  to surface area  $SA$  by the following relationship:

$$SA = \frac{6 \sum V_i / d_i}{\rho \sum V_i} = 6 / \rho d_s \quad (6)$$

Where  $V_i$  is the relative volume ( $m^3$ ) of particle diameter  $d_i$  (m),  $\rho$  is the density of the material ( $g/m^3$ ) and  $d_s$  is the Sauter diameter, which is the mean diameter of the material based on its surface area. The Sauter equation yields a geometric surface area assuming spherical grains. This underestimates the actual reactive surface area of the mineral grains. Thus, to improve the accuracy of estimations of this key variable, the surface area calculations from the Sauter equation are multiplied by a surface roughness factor. This factor is determined using the method of Beerling et al., 2020. This method treats the mineral grain reactive surface as fractal. The fractal dimension used was empirically determined. The scaling of the surface roughness factor is determined as:

$$\lambda = \left(\frac{\beta}{a}\right)^d \quad (7)$$

Where  $a$  is a spatial constant that accounts for the scale of the true surface area of the grain ( $10^{-10}$  m),  $\beta$  is the particle radius for a particular portion of the grain size distribution, and  $d$  is the fractal dimension. The value used for the  $d$  is 0.33, following the work of Beerling et al., 2020.

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