Remineralization for a Healthy Planet

Remineralize the Earth

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"Soil Remineralization has the potential to play a critical role in sustainable agriculture, ecological restoration, carbon sequestration, and climate stabilization… Though simple and inexpensive, remineralization could revolutionize agriculture." -Joanna Campe

Introduction

The UN expects the world population to exceed 9.7 billion people by 2050.[1] To meet the growing demand for food, agricultural production will need to double within the same time frame.[2] While crop yields have increased in recent decades, intensive farming has depleted soils of potassium, zinc, and other trace elements. Agriculture contributes to climate change and the release of carbon dioxide (CO_2) through the conversion of native forests to agricultural land in the tropics, and the production of nitrogen fertilizers from fossil fuels. Also, the excessive use of fertilizers and manure can pollute surface waterways and groundwater.

Feeding a growing world population while preserving the soil, air, and water for future generations requires: 1. halting the expansion of agricultural lands into native forests, 2. increasing yields without the heavy use of conventional fertilizers, 3. efficient use of resources such as water, and 4. reducing waste.[2] Soil remineralization meets all of these criteria.

Remineralization improves depleted soils by adding natural or manmade minerals from rock dust. Soils form when water, wind, and other physical processes break down the minerals found in rocks. As rocks are weathered into smaller pieces, they become more susceptible to chemical changes that release ions into the soil. We can dramatically accelerate this process by crushing rocks into fine-grained dust.

Grain size is critically important. While a grain of sand sounds small (about 2000 microns), it is actually too large to break down quickly. For example, Hawaii's famous Papakōlea beach gets its characteristic green color from sand grains made of the mineral olivine. This delicate mineral survives the constant onslaught of ocean waves because of its relatively large grain size. However, if we crushed the sand from 2000 microns down to dust (20 microns), the entire beach would disappear in a single year. That is the power of grain size.

Plants, microbes, and fungi use the ions released through weathering as nutrients and enhance the soil by adding organic material. Earthworms, insects, and burrowing animals change the texture and physical properties of the soil (see Figure 1). Together, they create a diverse and fertile soil ecosystem, but it all begins with the weathering of rocks and minerals.

The chemical changes rocks undergo in the soil also have a profound effect on Earth's climate and atmosphere. Soils are part of our planet's carbon cycle which limits the amount of carbon dioxide in the atmosphere and regulates the climate. Carbon dioxide reacts with minerals in the soil to form bicarbonate (HCO_3^-) and calcium carbonate ($CaCO_3$). Bicarbonate is soluble in water and may eventually make its way into the oceans where it counteracts ocean acidification. Calcium carbonate, the main component of limestone, is a solid mineral that can store carbon for millions of years. 80% of all the carbon on Earth (approximately 60 million gigatons) is stored in rocks as calcium carbonate.[3] Climate models suggest we will need to reduce atmospheric carbon dioxide by up to 10 Gt per year by 2030 to avoid the worst effects of climate change.[4] Meeting this target will require large-scale solutions that can be deployed within the

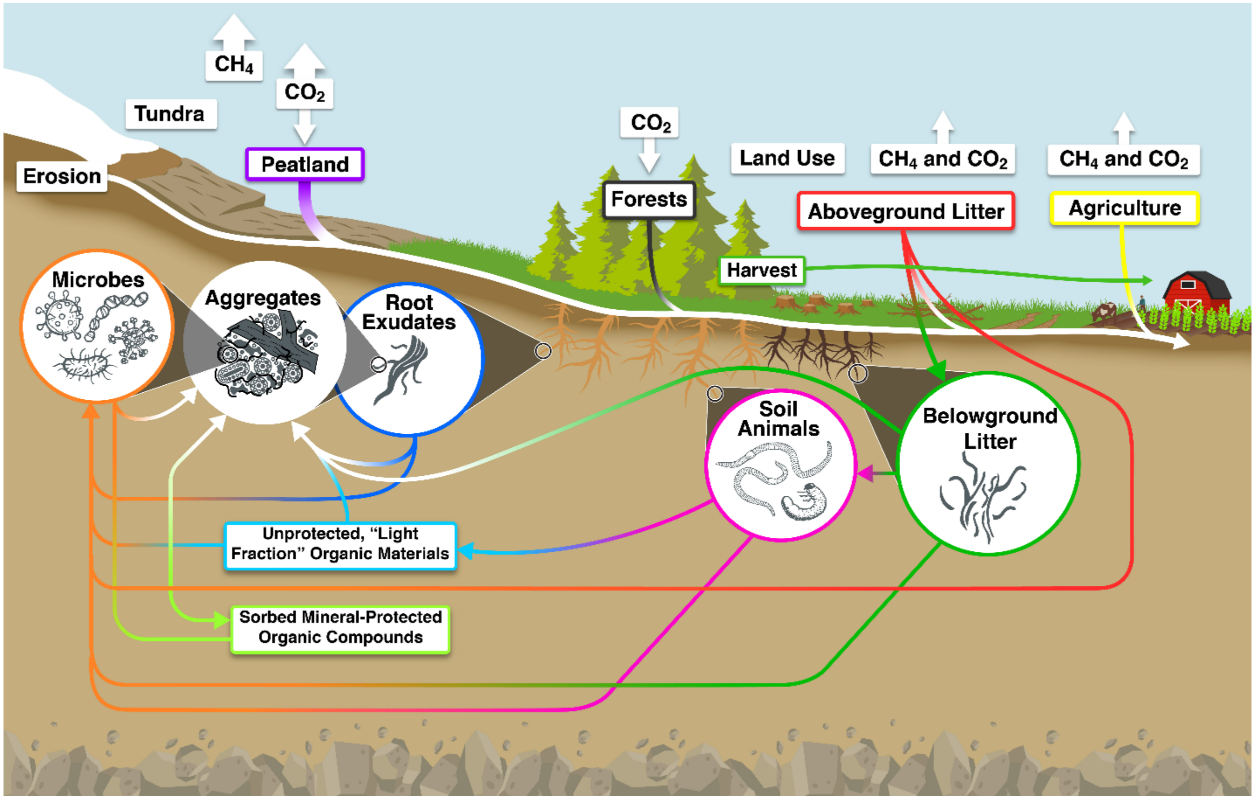


Figure 1: *Soil carbon processes. Carbon dioxide enters the soil through plant roots. More carbon is added to the soil as leaf litter. Some of this carbon will remain in the soil for many years if it is protected from decomposition. Land-use (such as no-till farming or afforestation) plays an important role in preserving soil carbon. Reproduced from Lajtha 2018*

next few years. Rock dust takes advantage of the most abundant carbon sink on the planet using low-cost, readily available technology. It provides the raw materials needed to remove carbon dioxide from the atmosphere on a global scale while also improving soil fertility.

Soil Fertility

Soils are home to a biomass at least as large as the plant mass we see above ground.[5] The soil biomass includes a rich variety of life such as microbes, fungi, plant roots, insects, worms, and burrowing animals. They interact with each other to create the soil food web: the ecological network in the soil that supports life above and below ground. "Soils are considered among the most biologically diverse habitats on Earth" according to the Food and Agriculture Organization of the United Nations. The diversity of soil life is mirrored by the wide range of soil micro-habitats from bacteria living on the film of water covering a plant root to megafauna such as voles living in air-filled pockets a few inches away. Bacteria and fungi form the center of the soil food web and are essential to carbon fixation, nutrient cycling, and promoting soil fertility by converting minerals (and other soil solids) into bioavailable nutrients that plants can use. In soil science, the process of converting organic material into bioavailable nutrients for plants is called mineralization. This should not be confused with remineralization which refers to adding new minerals to the soil by applying rock dust.

Like all living things, plants need nutrients to grow and thrive. They get some of these nutrients—primarily carbon, oxygen, and hydrogen—directly from the air. Other nutrients come from the soil such as nitrogen (N), phosphorus (P), and potassium (K) along with trace amounts of other elements. Plants absorb nutrients through their roots and release chemical compounds called exudates back into the soil. Exudates contain enzymes, organic acids, and carbohydrates that help the plant extract nutrients and promote the growth of beneficial microbes.[5] The soil influenced by root exudates, called the rhizosphere, acts like an external digestive system for the plant. Minerals are the food.

Nitrogen

Every molecule of chlorophyll requires four atoms of nitrogen, making nitrogen an essential nutrient for photosynthesis.[6] The vibrant green color we associate with plants is due to nitrogen. In undisturbed soils, nitrogen-fixing bacteria convert atmospheric nitrogen (N_2) into ammonium (NH_4^+) and nitrate (NO_3^-) which plants use to grow. Plants use a type of chemical signaling called quorum sensing to encourage soil microbes to produce the right kind of nitrogen at the right time in the plant's growth cycle.[7] Very little goes to waste.

In contrast, excessive use of conventional nitrogen fertilizers produces N_2O, a potent greenhouse gas.[5] Furthermore, commercial nitrogen fertilizers are produced through the Haber-Bosch process which requires methane (also a greenhouse gas) as an input.[8] Soil microbes can provide plants with the nitrogen they need while limiting greenhouse gas emissions. Rock dust provides these microbes with the mineral nutrients they need to create new soil[9] and complete the soil food web.

Rock dust can also serve as a direct source of nitrogen. Some rocks may contain nitrogen-bearing minerals in the form of salts (e.g., saltpeter) and ammonium silicates. Nitrogen may be found in gasses or fluids trapped between the mineral grains in the rock. Geologists believe the nitrogen in Earth's atmosphere ultimately came from deep within our planet's mantle and was released through volcanoes to form the air we breathe. The nitrogen in the atmosphere is cycled back into the Earth through the oceans and soil by nitrogen-fixing bacteria. The organic material found in marine shales, for example, can contain enough organic nitrogen to influence the surrounding ecosystem when these rocks are weathered at the surface. Marine shales are rocks that formed in the ocean from the remains of plankton and other organisms along with fine-grained sediments. Over time, these rocks are buried by younger sediments, trapping nitrogen compounds along with organic material, fluids, and gasses.[10] Weathering completes the cycle by releasing the nitrogen stored in these rocks back into the soil, oceans, and atmosphere.

The nitrogen contained in rocks varies greatly in terms of solubility and availability. Nitrogen gasses are probably lost to the atmosphere when the rock is crushed. Ammonium silicate minerals can remain stable for a long period of time. Nitrogen salts will dissolve very quickly in water. Some rocks, such as coal, can supply more nitrogen than plants and soil microbes can use, leading to the same problems associated with man-made nitrogen fertilizers.[10] No one is recommending using coal as a fertilizer[i].

The silicate rocks such as basalt which are most commonly used as rock dust fertilizer usually contain very low levels of nitrogen. Their primary benefit is to promote the growth of beneficial microbes in the soil, thereby enhancing natural nitrogen fixation.

Phosphorus

Phosphorus is essential to all living things. We get our phosphorus from the food we eat, and whether our diet is plant- or animal-based, the phosphorus we consume ultimately comes from plants. Phosphorus contributes to several growth factors in plants such as root propagation, flowering, and fruiting. Plants extract phosphorus from organic material like manure as well as common minerals such as apatite, feldspar, and mica. Conventional fertilizers usually come from apatite because it contains a high concentration of phosphorus which can be processed into quick-dissolving salts. Rocks rich in apatite also tend to have large amounts of contaminants such as fluoride, barium, cadmium, and uranium. Apatite mining can pollute waterways and starve lakes of oxygen. However, 50 to 90% of the phosphorus in the Earth's crust is contained in feldspars, making them a more important source of phosphorus in the natural environment.[11] Both feldspars and micas are found in rock dust.

Minerals differ in their ability to quickly release phosphorus into the soil. This is a product of their chemical structure. Silicate minerals like feldspars have very tight structures with strong bonds between their atoms.[12] As a result, they weather slowly in nature. Crushing greatly increases the surface area where chemical reactions occur, and only then do feldspars become a practical mineral fertilizer. Micas have a different structure. They form in thin sheets that are only loosely bonded together. Separating these sheets spills their chemical nutrients into the soil. Although micas release nutrients more easily than feldspars, they are still less soluble than salts.[12] Salts dissolve rapidly in water, but this quick influx of nutrients can overwhelm the soil ecosystem. Plants partly control the rate at which feldspars and micas are dissolved in the soil by exuding organic acids from their roots, limiting runoff that would otherwise pollute lakes and streams. Plants have no control over the dissolution rates of salts.

[i] Leonardite is a mineral derived from the oxidation of lignite coal which is used as a soil conditioner due to its high humic and fulvic acid content. Peat is also used for the same reason, but neither leonardite nor peat are coal. Lignite coal is sometimes used as a soil amendment, but the practice is not recommended due to the negative environmental impacts of extracting coal.

"It is impossible to have a healthy and sound society without a proper respect for the soil."

-Peter Maurin

Potassium

Plants use potassium for photosynthesis, enzyme activity, water regulation, and many other biological processes. Unsurprisingly, the availability of potassium is strongly linked to crop yields.[13] The most common potassium fertilizer is potash, a term that includes several potassium-bearing salts. Potash mines are concentrated in the northern hemisphere, and transportation costs make potash very expensive elsewhere. As a result, much of the world's agricultural lands, especially in the southern hemisphere, are deficient in potassium. Silicate rock dust is a cost-effective alternative. Experiments have demonstrated that the potassium feldspars and micas found in rock dust can be just as effective as potash in depleted soils.[14] Micas tend to dissolve more quickly, but feldspars deliver a slow release of potassium over a long period of time. As a result, rock dust fertilizers can be applied less frequently than potash.

Beneficial Trace Elements

Conventional fertilizers contain mainly N, P, and K, the three most important elements plants need from the soil. However, plants also need smaller amounts of trace elements and other nutrients to maximize their growth. Minerals in rocks are the source of these micronutrients (see table 1).

Trace elements serve many different roles in plants. For example, legumes use cobalt for nitrogen fixation and in the process produce vitamin B12. Plants require small amounts of copper for photosynthesis, respiration, and building cell walls. Manganese is used to make chlorophyll and metabolic enzymes. Trace element deficiencies stunt plant growth and impair crop yields. Some trace elements are not important nutrients for most plants, but they are for us. These include selenium and iodine.

More research is needed to determine the effectiveness of rock dust at delivering trace elements to plants and microbes in a usable form. Some crops are more efficient at absorbing mineral nutrients than others. One strategy for fortifying crops might be to selectively breed plants that are well adapted to absorbing the soil nutrients which are most beneficial to the people who consume them. Another strategy is to promote an active and diverse microbiome by inoculating the soil with specific microbes to help plants utilize mineral nutrients.[15] "Well-balanced fertilization of agricultural soils is a critical component in successful crop production. Very low levels of trace elements in soils need to be recognized regarding both the sufficiency for crops and for human diets.[16]" When plants are deficient in micronutrients, so are the animals and people who rely on them for food.

Soil Fertility and Food Nutrition

In 2004, the Journal of the American College of Nutrition published a landmark study demonstrating a decline in the nutritional value of commonly eaten vegetables, grains, and fruit between 1950 and 1999.[17] Over a 49-year period, America's garden crops lost vitamins and minerals in all but a few categories.

Table 1: Mineral Nutrients Essential or Beneficial to Plants and Humans

Plant Nutrients (a)	**Typical concentrations found in basalt (b)**	**Deficiency symptoms in plants (c)**	**Deficiency symptoms in humans (d)**
Macronutrients (>2 g/kg of dry plant tissue)			
Nitrogen		Yellow leaves, stunted growth	
Potassium	8,001 ppm	Dry/yellow leaves, stunted growth, low protein content	High blood pressure, poor bone density, kidney stones
Phosphorus	1,121 ppm	Discolored leaves, stunted growth, root rot	Weak bones and teeth
Sulfur	677 ppm	Yellow (young) leaves, weak stems	
Magnesium	2,402 ppm	Yellowing between leaf veins	Fatigue, muscle weakness, cramps
Calcium	60,938 ppm	Brittle leaves, weak stems, poor germination	Low bone mass, osteoporosis
Micronutrients (<100 μg/kg of dry plant tissue)			
Iron	45,000 ppm	Yellowing between (young) leaf veins	Anemia, weakness, lack of energy, memory problems
Manganese	1,300 ppm	Yellow (young) leaves	Weak bones, skin rashes, mood changes
Zinc	103 ppm	Pale leaves, stunted growth, poor yields	Hair loss, weight loss, poor wound healing
Copper	91 ppm	Stunted growth, delayed maturity, poor yields	Extreme tiredness, high cholesterol, weak bones
Boron	18 ppm	Brittle/dead leaves, stunted growth, prone to disease	
Molybdenum	1.5 ppm	Stunted growth, discolored leaves	
Chloride	472 ppm	Leaf Spotting	
Nickel	120 ppm	Yellowing between leaf veins, poor yields	
Non-essential nutrients important for human health			
Selenium	2.54 ppm		Keshan disease, male infertility, thyroid problems
Iodine	1.92 ppm		Thyroid problems, goiter
Cobalt	50 ppm		Related to vitamin B12 deficiency (anemia)

(a) International Fertilizer Association: www.fertilizer.org

(b) GeoRoc Database: georoc.mpch-mainz.gwdg.de/georoc

(c) McCauley, Ann, Clain Jones, and Jeff Jacobsen. "Plant nutrient functions and deficiency and toxicity symptoms." Nutrient management module 9 (2009): 1-16.

(d) National Institutes of Health Office of Dietary Supplements: ods.od.nih.gov

The authors looked at several possible reasons for this and concluded America switched from growing more nutritious "heirloom" varieties to less nutritious but higher-yielding or more showy varieties, and subsequent research has supported that observation.[15] Americans favor size, attractiveness, and shelf-life in their food over nutritional quality—something that is hard for consumers to determine when buying seeds or produce. The problem is made worse by commercial agricultural practices that favor yield over nutritional content. Davis noted, "yield increases produced by fertilization, irrigation, and other environmental means tend to decrease the concentrations of minerals in plants.[18]" That shiny red apple you see in the grocery store might be bigger than the same variety grown years ago, but the extra weight is mostly water. Nutrition has been undervalued by both consumers and growers.

Americans' preference for factors other than nutrition goes beyond choosing one variety of vegetable over another. The bigger problem is getting people to eat any vegetables at all. According to the Centers for Disease Control and Prevention,[20] only 12.3% of adults surveyed in 2019 ate the recommended amount of fruit, and just 10% met the recommendations for vegetables. One possible explanation is that the watery fruits and vegetables available in most grocery stores are turning people away from these foods entirely. Consumers value taste more than any other factor when buying food.[21]

Going Bananas for Rock Dust

In Nigeria, scientists tested a mixture of granite and basalt dust on banana plants. The plants treated with basalt rock dust grew much faster, emerging after 16 days compared to 33 days for the untreated plants. The plants grown in soil treated with basalt produced higher density leaves when compared with those grown in granite. The soil with basalt rock dust had higher pH (8.1) than the soil with granite rock dust (5.7). Hence, basaltic rock powder effectively buffers pH to a safer level.[19]

Taste is a personal preference, but anecdotal evidence suggests soil mineral content enhances the flavors of fruits and vegetables. In wine-making, *Terroir* refers to the hard-to-define quality imparted to the grapes by the place in which they are grown. In a taste test, consumers preferred the taste of remineralized apples compared to organically grown apples.[22] In Oregon, a blueberry farmer reported higher Brix measurements in his fruit by using organic farming practices and remineralization.[23] Brix is a measurement of total dissolved solids and is used as a proxy for the sugar and nutrient content of the foods we eat.

Tastier, more nutrient-dense food could help address the problem of inadequate nutrition in the US. Nutrient deficiencies causing overt symptoms of deficiency disease (e.g., scurvy) are rare in the developed world.[24] However, nutrient inadequacies (when nutrient intake is below the estimated average requirement) are quite common in America. Nutrient inadequacies can contribute to health problems such as cancer, cardiovascular disease, type 2 diabetes, osteoporosis, and age-related eye disease. Yet four out of every ten adults in the US are not getting adequate amounts of calcium, magnesium, and vitamins A, C, D, and E.[25]

"Mineral malnutrition must be addressed from the starting point: the diet. It can only be solved by holistic measures, involving agriculture, commerce, education and health organizations, representing the government, community and individuals.[26]" Biofortification refers to increasing the nutritional content of plants while they are still in the ground. It starts with mineral fertilizers to replenish the supply of essential elements in the soil. It can also include the selective breeding of crops that both absorb minerals from the soil more effectively and retain mineral nutrients in a bioavailable form when eaten. The essential elements most often deficient in the world population are iron, zinc, copper, calcium, magnesium, selenium, and iodine,[15] all of which can be found in rock dust. With the exception of selenium and iodine, these elements are also vital for plant growth. Biofortification with mineral fertilizers would benefit both plants and people.

Inert Rock Dust for Pest Control

Some types of rock dust are very effective at controlling insects and other agricultural pests. Diatomaceous earth is a common natural insecticide that contains a high percentage of silica. It kills insects by drying out their waxy outer shell.[28] It is also abrasive and may act as an irritant when it becomes trapped between the insect's body segments. Other rock dusts may act in a similar fashion. Diatomaceous earth and other silicates (such as wollastonite) are good sources of silica that plants use to strengthen their cell walls, making them resistant to pests long after the initial application. Research also suggests that silica acts as an undigestible filler, slowly starving insects of nutrients.[29] Many plants incorporate silica into phytoliths, microscopic structures that make the plant harder to eat.[ii] Carbon is sometimes occluded within phytoliths as they form inside the plant. Phytolith occluded carbon is very stable and acts as a permanent carbon sink even after the plant dies and decomposes. In one study, amending soil with basalt rock dust increased phytolith occluded carbon flux by 150%.[30] Other types of rock dust used for insect control include zeolites, clay, volcanic ash, and lime.

Application

Researchers have quantified increases in crop yield, higher leaf chlorophyll content, and fewer symptoms of disease in plants treated with rock dust and compost.[31,32] Compost and rock dust work together by

[ii] The grittiness you feel when you bite down on a blade of grass is because of phytoliths in leaf.

enhancing microbial activity and providing complementary nutrients. Plants growing in soils depleted of nutrients will respond best to treatment.[32] Well-managed soils may already have maximized their growth potential, which explains why some studies fail to show improvements after an application of rock dust. Any potential benefit relies on matching the minerals in the rock to the needs of the soil and plants.[33]

Better Pest Control with Rock Dust

Plants grown in vegetable greenhouses are susceptible to spider mites. Researchers tested granite dust on tomato plants to prevent spider mites from infecting the leaves. The granite rock dust was naturally high in silicon and behaved as a repellent. When the rock powders were distributed on the leaf surface, the mites' mortality increased to 6-16%. The experimental trials suggested that when applying granite rock powder on the leaves, the silicon contents in plant tissues increases.[27]

The key difference between rock dust and conventional fertilizers is the rate of release. Plants and microbes regulate the release of nutrients from minerals in the soil as needed. There is a biological cost for secreting the organic acids and enzymes that break down the rock, and it makes sense for these organisms to only pay for what they need. This creates the potential for perennially fertile soils with just the right amount of nutrients being released. Weathering rates are strongly dependent on pH. The more acidic the soil, the faster the rate of weathering. Rock dust makes the soil less acidic which slows down the release of nutrients until the weathering rate is in balance with the soil biology.

Conventional fertilizers, however, are highly soluble, and anything not taken up by plants leaches out of the soil. This pollutes waterways, costs money, and wastes resources. Rock dust can be used instead of conventional fertilizers as the basis of sustainable and organic agriculture. For conventional farmers, rock dust may reduce or eliminate the need for chemical fertilizers and liming.

Depending on the jurisdiction, rock dust might be defined as either a fertilizer, organic fertilizer, or soil amendment. Its composition will depend on the source rock. Rock dust made from igneous rocks or marine sediments contains a variety of minerals beneficial to plants. Lime (limestone dust) is commonly applied to soils to increase the pH but is not a silicate and does not contain the macro-and micronutrients referred to in this paper. Fertilizer efficiency decreases when the soil pH is out of balance, forcing farmers to use even more fertilizer (see Figure 2). Nitrogen fertilizers cause the soil to become even more acidic, making the problem even worse. Silicate rock dust breaks the cycle. Rock dust is an effective alternative to lime for balancing soil pH which also limits aluminum toxicity in the soil.[34]

Some rocks might be inappropriate for agricultural applications because they contain heavy metals, salts, or other contaminants. Sulfide minerals which are associated with some ore deposits can lead to acid mine drainage when weathered. Rock dust should be sourced from a reliable supplier and tested for impurities before being used in an agricultural setting.

Rock dust can be applied dry as a top dressing, foliar application, or in pellets using the same machinery farmers currently use to apply lime and other soil amendments to their fields. It can also be mixed with water and applied as a slurry or through drip irrigation. The application will depend on the soil type, management style (e.g., till versus no-till), and the crop species. Suggested rates for rock dust as a fertilizer range from 3 to 50 metric tons per acre.[35] This wide range in application rates reflects different soil needs, rock types, and goals. For example, farmers who want to maximize the carbon capture potential of their fields will want to use a heavier application of rock dust than farmers who want to replenish nutrients lost due to harvesting. Soils will benefit from a single application, but repeated applications every 2 to 3 years may have additional benefits. Areas where the natural rate of weathering is very rapid, such as in the tropics, may require more frequent applications.

Limestone makes your fertilizer work. Fertilzer efficiency goes up as soils acids go down.

SOIL ACIDITY	NITROGEN	PHOSPHATE	POTASH
Extremely Acid 4.5 pH	30%	23%	33%
Very Strong Acid 5.0 pH	53%	34%	52%
Strongly Acid 5.5 pH	77%	48%	77%
Medium Acid 6.0 pH	89%	52%	100%
Neutral 7.0 pH	100%	100%	100%

*Four Year Rotation of Corn, Soybeans, Wheat and Clover

Figure 2: *Taken from the Ohio Aglime Council (www.ohioaglime.org)*

Remineralization in Brazil

Brazil offers us an example of how policymakers can support farmers, consumers, and the environment by establishing a framework for remineralization. In Brazil, remineralizers are defined by legislation as "material of mineral origin that has only undergone size reduction and classification by mechanical processes and that alters soil fertility rates through the addition of macro and micronutrients to plants, as well as promotes the improvement of physical or physicochemical properties or biological activity of the soil.[36]"

According to this definition, remineralizers are materials of geologic origin used as agricultural inputs. The raw rock is altered only by comminution (crushing). This distinguishes remineralizers from heavily-processed conventional fertilizers. Remineralizers contain macro and micronutrients essential for the growth of plants and to help the maintenance or replacement of soil fertility.

Brazil currently has more than 28 companies producing remineralizers registered with the Ministry of Agriculture, Livestock and Supply. Twenty of these companies already have their products registered

Table 2: Rock Types Used for Remineralization in Brazil by State

State	Main Rocks and Minerals Used in Production
Bahia	Gneiss and pyroxene
Goiás	Basalt, calcischist and mica schist
Maranhão	Basalt
Minas	Kamafugite, saprolite, amphibolite, serpentinite, glauconite
Gerais	Siltite, phyllite, limestone, phonolite, and syenite
Mato Grosso do Sul	Basalt
Santa Catarina	Varve (ancient lake) deposits
Paraná	Basalt, serpentinite, phyllite, microgabbro, and dacite
São Paulo	Dacite, diabase and basalt

Source – Statistical yearbook 2021: Brazilian non-metallic processing sector statistical yearbook[36]

Table 3: Thresholds For Declaring Micronutrients in Remineralizers in Brazil

Nutrient	Minimum Total Content by Weight Percent
Boron (B)	0.03%
Chlorine (Cl)	0.1%
Cobalt (Co)	0.005%
Copper (Cu)	0.05%
Iron (Fe)	0.1%
Manganese (Mn)	0.1%
Molybdenum (Mo)	0.005%
Nickel (Ni)	0.005%
Selenium (Se)	0.03%
Silicon (Si)	0.05%
Zinc (Zn)	0.1%

Source – Normative Instruction 5th, March 10, 2016[37] and for sale in Brazil. The market for remineralizers is expected to grow by about 30% per year in Brazil according to the Ministry of Mines and Energy.

In 2020, Brazil produced 458 thousand tons of remineralizers, a 65% increase from 2019. The Southeast region stood out the most, with 52% of the production share, followed by the Central-West region with 31% and the South and Northeast regions with 9%. The Brazilian states that produced the most were Minas Gerais, Goiás, and São Paulo. See Table 2 for more details.

Certification guidelines define the properties of remineralizers in Brazil and could serve as a starting point for similar legislation in other countries. Remineralizers must contain at least 9% of the following bases as determined from a geochemical assay: CaO, MgO, K_2O. Geochemical information is often presented in the form of its most common oxide. Potassium (K_2O) should be at least 1% by weight. Remineralizers cannot be contaminated with heavy metals and must be under the legal thresholds for arsenic, cadmium, mercury, and lead. The silica content of the rock should be less than 25% by volume. Although silica itself is not a contaminant, only small amounts are used by plants. Although phosphorous is not required for designation as a remineralizer, products containing more than 1% phosphorous (P_2O_5) can declare it. See Table 3 for a summary of the reporting requirements for micronutrients.

Fighting Climate Change

Enhanced rock weathering (ERW) is "the process by which CO_2 is sequestered from the atmosphere through the dissolution of silicate minerals on the land surface.[38]" Silicates make up 90% of the Earth's crust.[12] The silicates frequently studied for their carbon sequestration potential are olivine (found in mafic and ultramafic rocks), wollastonite (found in metamorphic rocks), and man-made silicates such as portlandite (used in cement), all of which weather rapidly when crushed into a fine powder. Not all silicate minerals can be used for carbon sequestration, only those containing calcium or magnesium. Silicates remove carbon dioxide from the air in three ways: increased biomass due to improved soil fertility, enhanced weathering, and carbonation. The previous sections in this paper discussed how rock dust improves soil fertility and increases biomass. The soil fertility pathway increases the amount of organic carbon in the soil which usually accounts for the majority of soil carbon near the surface, especially in acidic soils. The enhanced weathering and carbonation pathways contribute to the *inorganic* carbon in the soil. Inorganic carbon is sometimes overlooked, but it is an important carbon sink in the deeper soil horizons and in arid climates.

Enhanced Weathering Pathway

The enhanced weathering pathway refers to the reaction between silicate minerals, carbon dioxide, and water that forms dissolved bicarbonate.[39] Bicarbonate (HCO_3^-) is similar to the baking soda you might have in your kitchen. The weathering reaction for wollastonite ($CaSiO_3$), a type of olivine mineral is shown here:

$$CaSiO_3 + 2CO_2 + 2H_2O \longrightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O$$

Other calcium or magnesium silicate minerals will behave similarly. If the bicarbonate created by enhanced weathering washes into the ocean, it will counteract another problem caused by climate change: ocean acidification. When carbon dioxide dissolves in seawater, it forms carbonic acid which lowers the pH of the ocean and harms marine organisms that use calcium carbonate to build their shells and skeletons.[40] Coral reefs are particularly sensitive to changes in pH. Enhanced weathering using rocks such as basalt has the potential to stop or even reverse the decline of coral reefs in the tropics while also addressing the root cause of the problem—high levels of carbon dioxide in the atmosphere.[41]

Dissolved bicarbonate moves through the soil with the flow of water. Because of its mobility, it is very difficult to measure compared to other carbon stocks.

Carbonation Pathway

Not all of the bicarbonate from the weathering pathway will leave the soil. Instead, some (or all) of it will combine with any available calcium or magnesium to form the solid mineral calcite ($CaCO_3$) or magnesite ($MgCO_3$) respectively. These minerals are stable in the soil and will safely sequester the carbon dioxide used up during the reaction. The carbonation equation looks like this:

$$Ca^{2+} + 2HCO_3^- \longleftrightarrow CaCO_3 + CO_2 + H_2O$$

The carbonation pathway is not as efficient as the weathering pathway when it comes to removing carbon dioxide from the air. Some of the carbon dioxide is lost back to the atmosphere during the reaction. The carbonation pathway also does not reduce ocean acidification. According to Professor David Manning, the amount of calcium in the soil largely determines whether carbon dioxide will end up as bicarbonate in the oceans (weathering pathway), calcite in the soil (carbonation pathway), or re-released as carbon dioxide back into the atmosphere.[42] Some silicate minerals, like wollastonite, and man-made hydroxide-bearing minerals, like portlandite, add calcium to the soil. Other silicates, like forsterite, release magnesium instead.

Healing the Climate Through Remineralization

Soil biology can increase the rate of weathering and the speed at which carbon is sequestered in the soil through ERW. The mineral nutrients released into the soil by enhanced rock weathering promote the growth of plants, microbes, and fungi. These biota release enzymes and organic acids which further break down the minerals in the rock dust. The cycle is beneficial to both the plants and the atmosphere.

“Essentially, all life depends upon the soil...There can be no life without soil and no soil without life. They have evolved together.”

-Charles E. Kellogg
USDA Yearbook of Agriculture, 1938

Soil-dwelling animals and insects also play an important role in accelerating soil carbonate formation. In one study, the amount of calcium carbonate in the soil surrounding ant colonies was 50 to 300 times greater than on barren ground.[43] The difference was so pronounced as to lead researchers to speculate that the boom in the variety and number of ant species over the last 66 million years could have contributed to lower CO_2 levels and planetary cooling during the Cenozoic era.

The amount of carbon dioxide that can be sequestered through enhanced rock weathering depends on the type of rock, application rates, water availability, temperature, and soil biology. That makes it hard to predict exactly how much carbon dioxide will be captured. Measuring the amount of carbon is also difficult because some of it will be washed away as bicarbonate and what remains in the soil and plants will be comingled with other stores of carbon. Researchers have estimated theoretical values using geochemical equations. One ton of pure olivine (forsterite) can sequester 1.25 tons of CO_2 without any additional contribution from plant growth or other biological inputs.[45] Basalt is a far more practical alternative to olivine, though, due to its abundance. Strefler estimates one ton of basalt can sequester 0.3 tons of CO_2. A case study in Brazil found the basalt there to have a different composition and an estimated sequestration rate of 0.175 tons of CO_2 per ton of basalt.[39] However, either scenario should be viewed as a base-case not a best-case scenario because neither includes any contribution from soil life like plants, micro-organisms, or fungi.

Crops Pop with Rock Dust!

Researchers conducted a study to test silicate rocks as a soil amendment. They chose to plant sorghum because it grows in partnership with a type of fungus (arbuscular mycorrhiza) known to dissolve minerals in the soil. After 120 days, crop yields of sorghum increased by 21% when treated with rock dust. No more potassium or phosphorus was added. The treated soil also showed lower amounts of toxic elements than the soil without rock dust. The researchers estimated the soil treated with rock dust would capture 4 tons of CO_2 per hectare in just five years—a fourfold increase compared to the untreated soil.[44]

Rock dust stimulates ecosystems to store organic carbon in addition to the inorganic carbon captured through weathering. Adding both pieces together and looking at the ecosystem as a whole potentially doubles the amount of carbon dioxide sequestered by a single application of rock dust.[46] Rock dust acts as a fertilizer, helping to increase plant mass above and below ground. Even if the above-ground plant material is harvested, what is left underground acts as a carbon sink.

Although rock dust increases microbial activity, it does not increase the amount of CO_2 released from the soil through decomposition. Instead, it preserves organic carbon in the soil mainly through the formation of soil aggregates and sorption sites on mineral surfaces.[47] Soil aggregates are tiny clumps of organic and inorganic material in the soil that protect carbon from would-be decomposers. Mineral sorption sites are the fly-paper of the geochemical world—broken chemical bonds to which compounds like organic carbon can easily stick. In this way, soil organic carbon can remain stable for long periods of time. Rock dust also provides a source of silica which plants use to form phytoliths which can also preserve carbon long after the plant has died (see section on Pest Control). Biology is difficult to predict, but fortunately, organic carbon is a little easier to measure in soils than its more soluble inorganic counterpart because it sticks around longer. The carbon that *does* leave the soil through respiration, decomposition, or erosion is not considered sequestered.

Climate is probably the biggest factor in determining how much carbon stays in the soil and the one we have the least control over. "More rain is better," says Garrett Boudinot at Cornell University,[48] "this is a weathering process, and so in very arid conditions…you're not going to get the rate of weathering, and it's going to be a slower process." His statement is backed up by findings from other researchers that suggest the tropics have the best potential for enhanced rock weathering[4].[45] Enhanced weathering will still work in more temperate climates, but it may take longer.

Rock dust also fights climate change by reducing nitrous oxide emissions from the soil. Nitrous oxide is a greenhouse gas 300 times more potent than carbon dioxide.[49] It forms in the soil through microbial activity and is made worse by the excessive use of nitrogen fertilizers. Enhanced weathering of silicate minerals has been demonstrated to reduce nitrogen leaching[50] and nitrous oxide emissions.[51] The buffering effect of rock dust can also counteract nitric acid in the soil (which forms when nitrogen fertilizers react with water), but there is a trade-off. Silicate minerals that react with nitric acid are no longer available to react with carbon dioxide, effectively shutting down the carbon sequestration pathway. Of the two, reducing nitrous oxide emissions may have a more significant impact on fighting climate change.

Balancing Soil pH with Rock Dust

Managing soil pH improves fertilizer absorption and plant growth. It is common practice to add lime (calcite or dolomite) to acidic soils in the eastern US for this very reason. These soils tend to be acidic because high rainfall in the eastern US leaches buffering elements (like bicarbonate) out of the soil. Nitrogen fertilizers and organic acids from plants or manure acidify the soil even more. Soils in the arid parts of the western US contain more calcite and are naturally less acidic.[52]

Both lime and silicate rock dust buffer the pH of the soil, but silicate minerals are much better for the climate. An estimated 49% of the lime applied to agricultural lands in the Mississippi River basin ends up as CO_2 in the atmosphere.[53] By using lime for agricultural purposes, CO_2 that had been safely sequestered underground for millions of years is now being returned to the atmosphere. In contrast, the weathering of silicate minerals has a similar effect on soil pH while also improving soil fertility, lowering nitrous oxide emissions, and removing CO_2 from today's atmosphere.

Dietzen, et al (2018) conducted an experiment to see if olivine dust (with a grain size less than 20 μm) could be used as an alternative to agricultural lime. They demonstrated an increase in soil pH within three months of application. While the buffering effect from olivine was not as strong as lime, the olivine application lowered aluminum toxicity in the soil (a common problem in acidic soils) while also reducing greenhouse gas emissions. Rock dust can be applied using the same machinery as lime at a comparable cost, according to the researchers. However, pure olivine-containing rocks (dunites) are rare on land and may contain toxic levels of heavy metals. Basalt requires a higher application rate than dunite to achieve the same results but is less toxic and far more abundant.

West and McBride (2005) noted that in alkaline soils, liming is a net sink of CO_2, but in acidic soils (where it is used most often), it is a net source of CO_2. Silicate rock dust, on the other hand, removes at least twice as much CO_2 as lime.[54] Based on the weathering efficiency rates from Stefler,[45] approximately 3 tons of basalt rock dust would have the same buffering capacity as 1 ton of lime, but instead of emitting 0.22 tons of CO_2, it would sequester 0.9 tons of CO_2.

Remineralization in Forestry

The carbon sequestration benefits of rock dust are enhanced by combining it with the natural ability of trees to capture and store carbon. Earth's forests contain more carbon than the atmosphere, making them one of the largest reservoirs of terrestrial carbon.[55] Among foresters, terrestrial carbon refers to the organic carbon stored in soils and plants but doe not include inorganic (mineral) carbon stocks. The world's existing forests have the potential to store 1 to 3 Gt of carbon per year in biomass and an additional 0.4 Gt of carbon in forest soils.[56] That's up to a third of the 9.855 Gt of carbon released into the atmosphere every year from burning fossil fuels.[57]

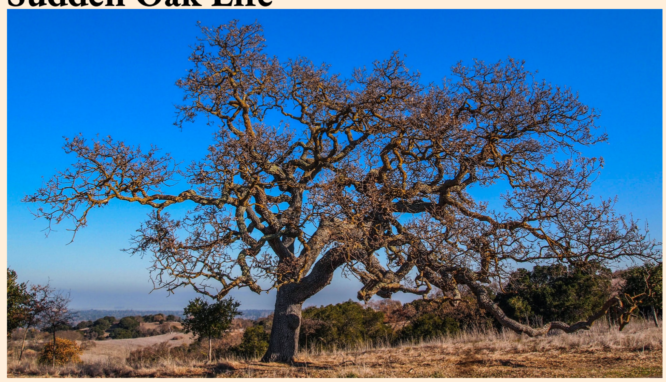
Changing land-use practices to replant forests or grow new ones has the potential to sequester and additional 2.7 to 17.9 Gt of CO_2, equivalent to 0.73 to 4.88 Gt of carbon.[58] According the Future Forest Company, enhanced rock weathering and biochar can increase the amount of carbon stored in reforested lands by up to ten times.[59]

While healthy forests are an important global carbon sink, unhealthy or mismanaged forests can actually be a net source of CO_2 emissions. A study published in Nature in 2021[60] brought to light a disturbing trend in the Amazon rainforest. Once considered the "lungs of the planet," parts of Amazonia are now emitting more carbon dioxide than they are taking in due to fire, drought, and deforestation. This upsets the delicate relationship between the forest and atmosphere. Fewer trees mean less water is being drawn up and respired back into the air, exacerbating the drier conditions caused by climate change.

Drought further stresses trees and reduces their ability to take up carbon dioxide through photosynthesis. Additionally, tropical rainforests tend to store more carbon above ground where it is more vulnerable to fire and decay compared to temperate forests which tend to store more carbon in the soil.[56] When trees die, warmer temperatures in the tropics increase the rate of decomposition in the soil which takes the carbon that was stored in the trees while they were alive and releases it back into the atmosphere.

Rock dust can break the cycle and restore forests' natural ability to store carbon. Fortifying forests with rock dust helps seedlings survive and allows adult trees to better withstand droughts, disease, and pests. As with agricultural applications, rock dust provides vital nutrients to the soil which trees use to grow and thrive. This is particularly important in areas of afforestation, where previously unforested land is reclaimed and planted with new trees. An experiment in Brazil demonstrated that while seedlings are quick to germinate even in poor soils, the young trees are more likely to survive into maturity when the soil is amended with rock and/or compost.[34]

Sudden Oak Life



The oak trees in California have been calling for help. They needed someone to take care of them, and a team from Sudden Oak Life answered the call. Dr. Lee Klinger, leader of the team, treated 21 oak trees in Big Sur using fire mimicry to simulate the restorative effects of a wildfire without the destruction. He cleared the surrounding underbrush, removed lichen from the bark, and applied volcanic rock dust to the surrounding soil. In 2020, his treatments were put to the test when a big wildfire happened in that area. Seventeen of the oak trees survived and eleven showed improvement in their canopies because of the treatment..[61]

Nutrient availability and carbon sequestration rise and fall together. One study estimated that in forests where soils are low in nitrogen and phosphorus, carbon sequestration is up to 100% less than the modeled prediction.[62] This has important implications for carbon credits relying on modeled rather than measured rates of CO_2 reduction. It also shows that we cannot take the health of our forests for granted if we want to rely on them as a carbon sequestration tool.

Rock dust can help forests indirectly by making existing agricultural lands more fertile and thus eliminating the drive toward deforestation. Rainforests are routinely cut down and burned to make space for agriculture and pasturelands. In the Chontales region in Nicaragua, cattle grazing is the main reason for deforestation. Although agriculture would be more lucrative and use less land than ranching, depleted tropical soils make it nearly impossible. An experiment using basalt rock dust to remineralize test plots in Chontales showed encouraging results despite an unfortunate invasion of insects.[63] Maximizing the growing potential of existing agricultural lands surrounding native rainforests would encourage farming over grazing and soil restoration over deforestation. Social obstacles might hinder the widespread adoption of rock dust as a soil amendment, though. In Nicaragua, cattle ranching conveys a higher social status than agriculture, and wealthy land owners have little motivation to switch.

In North America, people have been enhancing forest fertility since prehistoric times. Throughout coastal North America, native peoples have left behind middens, piles of shells and bones left over from foraging and hunting for food. Studies of middens along the Chesapeake Bay show higher levels of soil nutrients such as calcium, nitrate, boron, manganese, and sulfur compared to undisturbed areas.[64] Heavy metal contaminants such as chromium and aluminum are lower. The midden sites also host a greater diversity of native and herbaceous plant species. The results are remarkable for the fact that some of the midden sites are more than 3,000 years old, demonstrating the endurance of slow-release fertilizers. There is some evidence to suggest native people had a deep understanding and appreciation for the benefits of forest remineralization. Middens and fire ash were used to deliberately to promote the growth of edible plants and trees.[65]

Treating wild forests with rock dust poses some obvious logistical challenges. Rock dust could, in theory, be applied with planes or drones, but this would probably be prohibitively expensive. A more practical solution would be to focus on the forest edges. Forest edges along roads, farm fields, and urban areas are more easily accessible than the forest interior. In the tropics, trees struggle to survive along forest edges because they are exposed to hotter, drier, and windier conditions. A single application of rock dust could potentially help these trees survive better in a harsh environment. In temperate forests, such as those in New England, the situation is different. Trees thrive along the edges of temperate forests because they have more sunlight to help them grow. As a result, these forests sequester more terrestrial carbon along their edges than in their interiors.[66] An application of rock dust would boost the carbon storage capacity of these forests even more through the formation of soil carbonates and dissolved bicarbonate. Trees in urban parks and yards have great potential to sequester carbon because the hotter, drier soils they grow in have slower rates of decomposition and higher rates of carbon storage.[67]

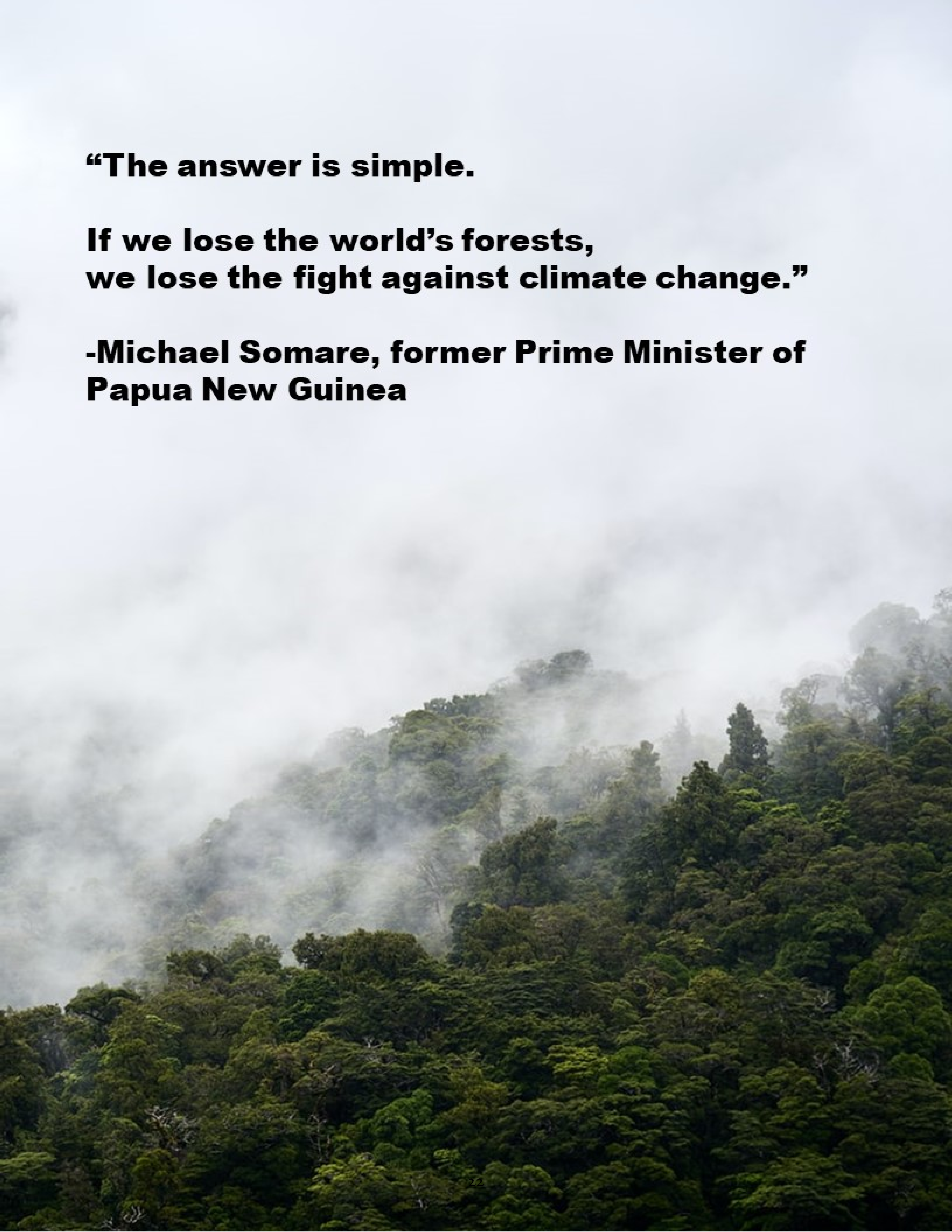
Soil Remediation with Rock Dust

Soils are susceptible to contamination from industrial chemicals, pesticides, and heavy metals such as lead or arsenic. Pollution from factories may be deposited in soils through the air or water. Even conventional fertilizers can harm the soil if not applied properly. In 2017, the United States released 1.72 billion Kg of untreated industrial pollutants, 70% of which entered the soil (the rest ended up in surface waters or the air).[68] Not only is there a high risk of damaging crops in agricultural areas, but contaminated soils also raise concerns about human health. Although the number of children in the US with elevated blood lead levels decreased to 2.6% in 2018 from 5.2% in 2012, this still represents tens of thousands of children under the age of six.[69] The contamination in urban soils is a legacy from the time before lead was strictly regulated, but old lead-based paint and dust from leaded-gasoline emissions continue to poison children

“The answer is simple.

If we lose the world’s forests,
we lose the fight against climate change.”

-Michael Somare, former Prime Minister of
Papua New Guinea



to this day. Exposure to lead may cause brain damage to babies, and lead to behavioral problems and developmental delays in children.

Cadmium (Cd) is another common heavy metal that is widely found in soils. Plants absorb cadmium from contaminated soils, and at high concentrations, the plants themselves also become toxic.[70] This can lead to steep economic consequences for farmers. In one example, polluted soils led to a financial loss of 60.4% due to declining yields.[71]

Experiments have shown rock dust is an effective tool for remediating contaminated soils. Rock dust can be applied as slurry to wash contaminated soils, immobilizing heavy metals and reducing uptake by plants. In Taiwan, phosphate rock dust was applied to 250 hectares of agricultural soil that was contaminated with lead.[72] The lead-phosphate reaction reduces the solubility of lead in water, effectively immobilizing it. In the Taiwan experiment, phosphate rock dust reduced the amount of extractable lead by 33% to 97% depending on the initial concentration.

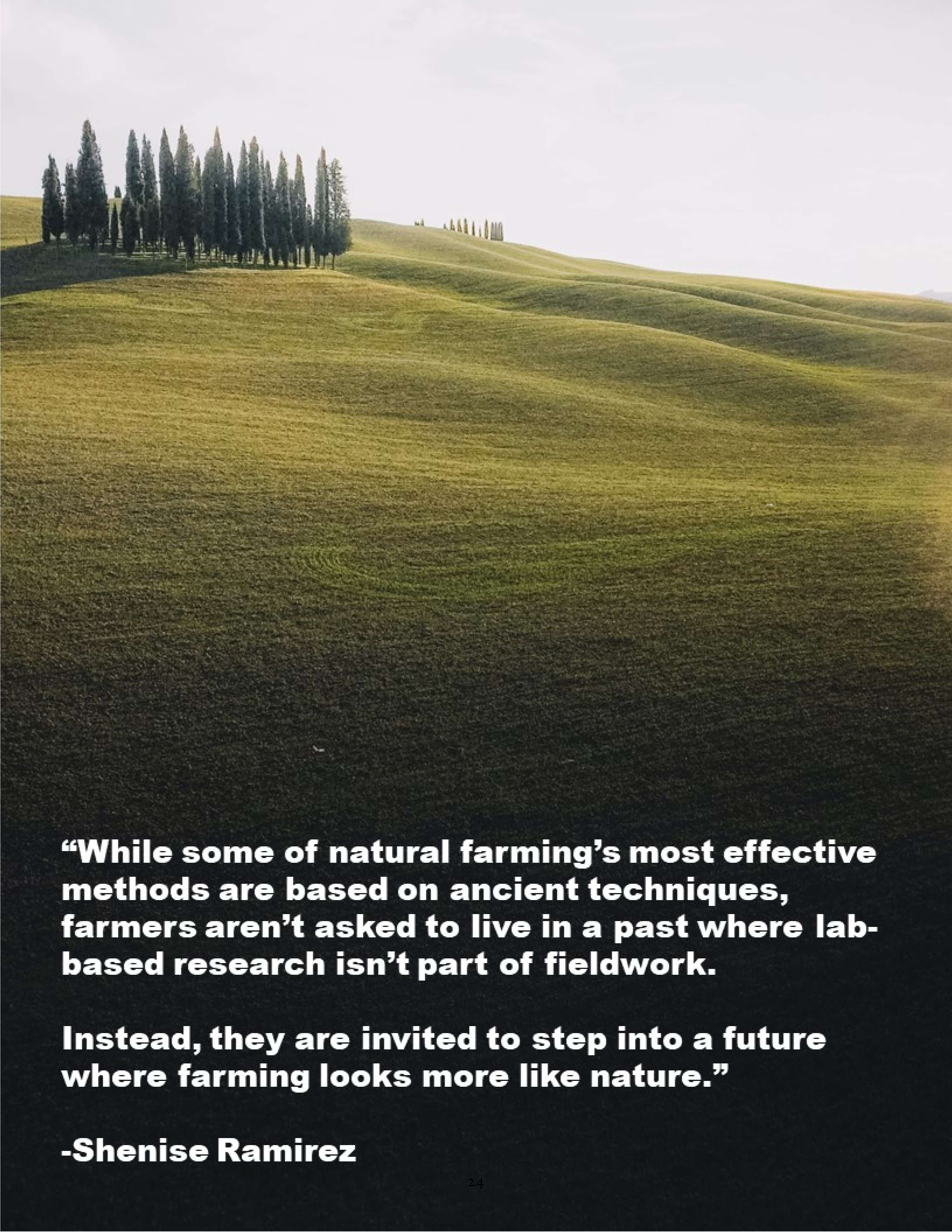
The effectiveness of rock dust for soil remediation depends on a number of factors. Chen et al. demonstrated that the mineral apatite absorbs lead, zinc, and cadmium in aqueous solutions and contaminated soil.[73] In the study, absorption rates varied depending on the type of the heavy metal and the soil's pH. At the end of the experiment, lead concentration in the soil had dropped to almost zero. The apatite treatment removed up to 98.7% of zinc and up to 97% of cadmium. As the pH of the soil increased, the presence of heavy metals decreased. The experimental trials proved that apatite immobilized contaminants and reduced their concentrations to below EPA thresholds.

Costs

One of the main benefits of rock dust is its affordability. In some places, it may cost nothing at all. Volcanic ash is a natural source of mineral nutrients that is already the right grain size and delivery is free (whether you ask for it or not). If you do not live in the shadow of a volcano, though, there are other options.

Quarry fines are a by-product available for free or at a minimal cost from rock quarries all around the world. Quarry fines should be sieved and tested for impurities before they are applied to the soil. It is also helpful to have some knowledge of the geologic formation being excavated to determine if it has the right mineral composition. Targeting specific minerals allows farmers to address specific deficiencies in their soils, but it does not have to be complicated. Basalt is good for both fertilization and carbon sequestration, and it is one of the most common rock types in the world. Concrete left over from demolition and construction sites often ends up in landfills, but crushing and mixing into the soil instead would sequester carbon at a rapid rate.[74]

For large-scale applications, such as those proposed to fight climate change, demand may outpace the fines produced by local quarries. The energy and cost to crush rocks (comminution) increases logarithmically



"While some of natural farming's most effective methods are based on ancient techniques, farmers aren't asked to live in a past where lab-based research isn't part of fieldwork.

Instead, they are invited to step into a future where farming looks more like nature."

-Shenise Ramirez

with decreasing grain size.[75] The flour-like consistency required to make enhanced weathering effective uses a lot of energy, but the cost of comminution depends on where the rock is being processed. Each country has a different cost basis for energy and labor. Along with comminution, transportation is the other major cost component associated with rock dust.

Several studies have estimated the costs of enhanced rock weathering on a global scale. Beerling estimated costs for enhanced weathering ranging from $55 per metric ton of CO_2 in India, China, Indonesia, Brazil, and Mexico to $190 per metric ton of CO_2 in Canada and Europe.[4] Strefler estimated the cost of ERW at $60 to $200 per metric ton of CO_2.[45] However, these studies did not consider the fertilization effect of rock dust. If remineralization can double the amount of carbon in the soil as predicted, the cost per ton of CO_2 would be cut in half. The true cost could be less than $60 per metric ton of basalt rock dust as delivered.[iii]

The cost of rock dust for agricultural applications would be similar but would be offset by increased yields and decreased costs for conventional fertilizers, herbicides, and pesticides. Indeed, widespread adoption of rock dust in the agricultural sector will only happen if the benefits outweigh the costs unless carbon credits are used to offset the difference. This is an area that needs more testing and research, and in all likelihood, there is no single answer. On a small scale, gardeners and hobbyists might be able to get rock dust for free from their local quarry. The most recent data from the USGS puts the cost of agricultural lime at $11.06 per metric ton compared to basalt (volcanic cinder and scoria) at $5.80 per metric ton.[77] This is only the cost of the raw material and does not include delivery and spreading. It takes at least twice as much basalt as lime to alter the soil pH,[78] but the total cost is about the same. If carbon sequestration is the goal, then the amount of carbon generated during comminution and transportation must be offset by the rate of carbon sequestration through ERW for there to be any net benefit.

Lowering Costs with Rock Dust

In 1990, two brothers from Australia (Kevin and Gary Harding) planted 4 hectare of bananas with rock dust and subsequently reduced their usage of potash and urea by 80%. Growth and production rates increased to 20% and 80%, respectively. The total cost-benefit was over $56,000 AUD per hectare per year. The benefits of rock dust run deep. A cyclone devastated neighboring banana plantations, but the Harding brothers' plants survived because their bananas had deeper, stronger root systems thanks to rock dust.[76]

[iii] $60 per metric ton of basalt dust assumes the upper end of Strefler's cost range: $200/t CO_2 x 0.3 t CO_2/t basalt. This cost basis is not affected by the increase in weathering efficiency when fertilization is included.

Future Research

Research into silicate rock dust is ongoing. Questions remain about the best type of rock to use and how to apply it. While it is clear enhanced weathering and the soil biome work together synergistically, the mechanisms are not well understood. Outcomes vary depending on a number of factors such as soil type, climate, and the type of rock dust used. Some researchers have observed positive effects on plant growth, while others failed to find any promising results. Pushing the research and development wheels further can provide stakeholders with clear insights and improve the effectiveness of rock dust in agriculture and carbon management.

For example, Ben Houlton, an environmental scientist with Cornell University, initiated a massive project on a 14-acre agricultural field which is managed by Bowles Farming Company in California.[79] The study will reveal the effect of spreading tons of pulverized rock dust on corn and alfalfa yields, as well as carbon sequestration. This is one of several on-going studies quantifying weathering rates in a real-world setting.

Weathering rates are largely theoretical at this point and mostly assume chemical weathering as the dominant mechanism. However, it seems increasingly likely that enhanced weathering is a biogeochemical phenomenon. Chemical weathering alone will not be fast enough to make a measurable difference in climate change.[80] Plants and microbes are critical to speeding up the weathering rates to a level that will have a meaningful impact on carbon stocks. If we give plants the mineral nutrients they want, they will help us reverse the damage we have done to the climate.

Major research institutions are taking a deeper look at the relationship between minerals and soils. Biosphere 2 is a 3.14-acre research facility, run and organized by University of Arizona, that mimics Earth's climate to study the long-term evolution of the ecosystem and organisms. It consists of several projects such as a controlled rain forest, artificial desert, and ocean.[81]

Landscape Evolution Observatory (LEO) is a laboratory experiment that incorporates three 30-meter-long, 1-meter-deep rectangular slabs with crushed basalt rocks.[81] The goal is to isolate the microbial and organic changes on mineral surfaces. Recently, the researchers started a new experiment that incorporates plants for the first time and manages artificial rain to develop further insight on water and carbon dioxide cycles in a closed ecosystem. This project will address multiple questions on the role of volcanic rocks in shaping life on Earth.

In Timburi, Brazil, a pilot project is underway to study the effects of rock powder and biochar in agroforestry. Wooderland is working to manage carbon removal and identify the constraints regarding mineral applications. The team expects to remove more CO_2 than it emitted through the application process. After spreading the rock dust, they plan to grow a wide variety of plants, sowing almost 300kg of seeds.[82]

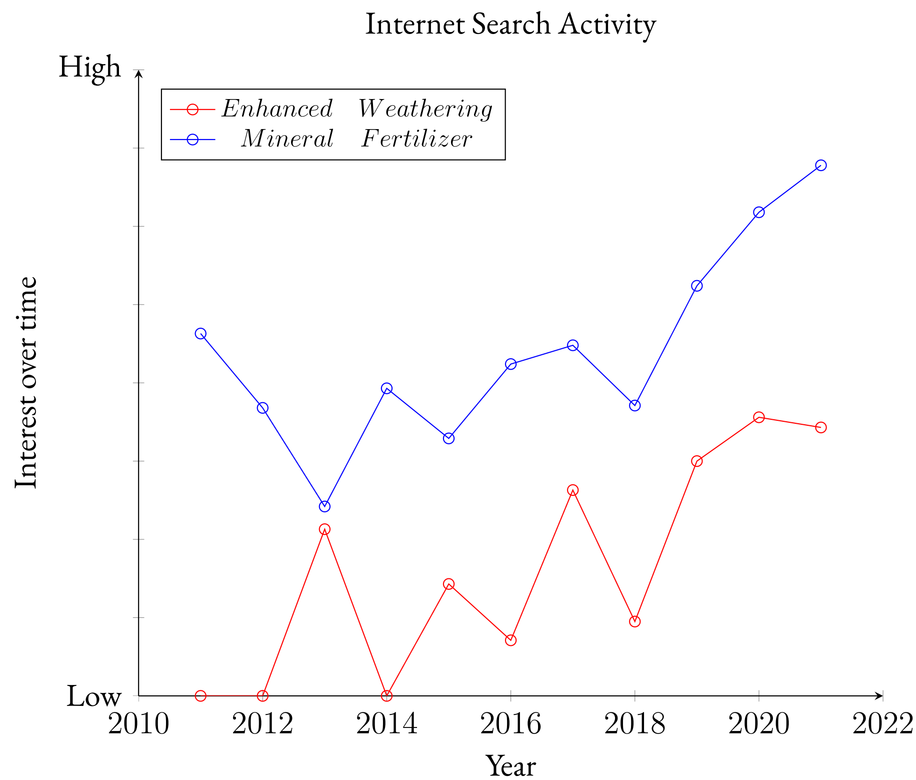


Figure 3: Internet search activity for the terms "Enhanced Weathering" and "Mineral Fertilizer"

Interest

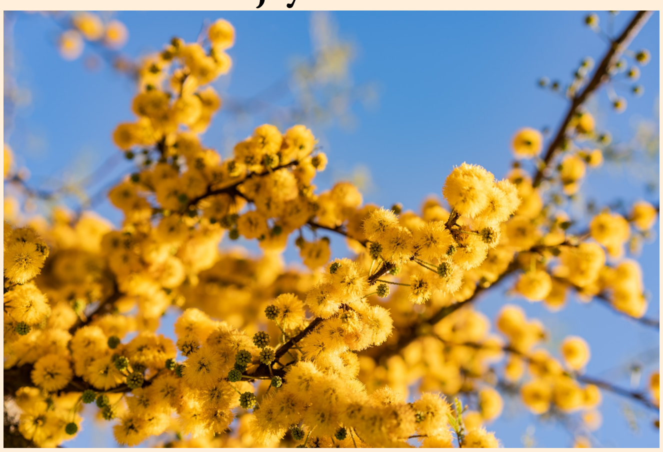
Public interest in soil remineralization and enhanced rock weathering is increasing. Figure 3 shows search engine activity for the terms “enhanced weathering” and “mineral fertilizer” from 2011 through 2021. Remineralize the Earth is uniquely positioned to respond to the heightened awareness by educating the public and promoting research through a coalition of volunteers, supporters, scientists, and farmers from around the world. Let’s Remineralize! Science Ed is a K-12 program developed by Remineralize the Earth to teach kids about minerals, soils, and climate. Remineralize the Earth has supported field studies in Panama and Brazil and is currently working on a pilot project in South Africa.

Considerations

The Effectiveness of Rock Dust in Agricultural Soils

Adding rock dust to agricultural soils has had mixed results. For example, one experiment looked at the effect of commercially available rock dust on wheat using several soil types. After three years, the researchers concluded no changes in the diversity of the microbial community and no increase in plant nutrient uptake other than sodium.[83] This study highlights some of the problems of evaluating the effectiveness of rock dust. The crushed rock used in this was too large (most of it larger than 600 μm). Sand (grain sizes between 62.5 and 2000μm) is often added to the soil mixture to increase drainage, but too much of it can cause the soil to dry out. Because sand is mostly inert, it can dilute the nutrient value of the soil if it replaces more reactive, finer grained materials. Researchers have used a wide variety of grain sizes when experimenting with rock dust, making it difficult to compare results. Finely ground rock dust has a large amount of surface area which helps release mineral nutrients faster. If the dust is too coarse, it will not dissolve fast enough to be an effective fertilizer and may stunt plant growth. This study highlights another issue: in countries where there are no standards in place for rock dust, even commercially available products need to be vetted before wide-scale implementation.

Did the trees enjoy their new soil?



Yes! Dr. Tom Goreau found out that Acacia trees in Panama love rock dust. Tropical soils are often low in nutrients because of high year-round temperatures and heavy rainfall. Dr. Goreau added basalt rock dust to tropical soil to improve fertility. Five years later, he noticed more earthworms, indicating the soil was rich in nutrients. The trees grown with rock dust were over two times taller than the trees grown in native soil, and the amount of biomass produced was over six times greater. Trees that were not treated with rock dust did not last long and died. This tells us that rock powders may help restore poor soils and improve the ecosystem.[76]

Strefler (2018) studied the costs and benefits of grain size for enhanced weathering and determined the ideal grain size is limited by the cost of grinding the rock, but 20μm (equivalent to a 635 mesh) is effective and "easy to achieve." Beerling (2020) used a range of grain sizes for his study on enhanced weathering on croplands where 100μm (140 mesh) represented the 80th percentile. Anecdotal evidence suggests 74μm (200 mesh) is sufficient. To be most effective, the grain size should be as small as economics allow.

Another common problem with rock dust experiments is the quality of the soil used for the control. For example, when sand is used as the control, almost any type of soil amendment is likely to show some improvement. These types of pot experiments (in which plants are grown in pots usually in a controlled environment) help demonstrate the bioavailability of rock dust nutrients, but do not reflect how most food crops are actually grown.[14] Field studies are more useful in that regard but involve many variables beyond the control of the researcher. In one case, the experiment was ruined by two hungry cows.[63] While the study did not achieve its intended goals, it at least proved that plants treated with rock dust are irresistibly delicious.

In field studies, the yields from rock dust amended plots are either compared against prior years or against another plot that was not amended. These studies more accurately reflect real-world conditions, but are usually site- and crop-specific. One such study involved an aging apple orchard in which the trees showed signs of stress and disease after years of poor management practices.[32] Part of the orchard received a combination of rock dust, compost, and NPK fertilizer and the rest received only fertilizer. After two years, the trees that received an application of rock dust and compost had increased yields by 187% over the untreated trees. The authors were quick to point out that rock dust may be particularly important in providing macro- and micronutrients to previously depleted soils, but this conclusion may or may not hold true for other types of soils. Like any soil amendment, rock dust requires a tailored approach specific to the needs of the soil and crops to which it is applied.

Heavy Metal Build-up in Soils

Not all rocks are appropriate to use as rock dust fertilizer. Geothermally altered rocks and metal ores may have high amounts of heavy metals or sulfide minerals (which generate sulfuric acid when they weather). Ultramafic rocks such as dunite are great for enhanced weathering because they contain mostly olivine, but they might have too much chromium and nickel to use on crop lands.

Almost all fertilizers can become contaminants if not managed properly. Conventional NPK fertilizers can "burn" plants if applied in excess. Animal manure, biosolids (treated sewage), and even compost can introduce cadmium, lead, chromium, mercury, and arsenic to the soil.[16] These elements can accumulate in the soil over time when fertilizer is applied too often. Overapplication of rock dust is not likely to be a problem, though, because rock dust releases its nutrients very slowly. Contamination can be avoided by sourcing rock dust carefully and testing its composition. It is important to remember that even rocks of the same type may have different compositions in different locations. Once a reliable quarry has been found, it can supply local farms with revitalizing dust for decades to come. Even a single application of rock can increase soil fertility for years.

Conclusion

Soil remineralization is a simple, scalable solution to improve soil fertility, reduce greenhouse gases, and usher in a more sustainable future. Suitable rock dust is readily available from existing quarries and can be applied to crops, forests, and pastures without the need for special equipment. It is even safe enough for home gardeners to apply with their bare hands. Rock dust has the potential to remove at least 4 gigatons of CO_2 from the atmosphere every year if adopted on a global scale.[45] That is about 11% of global annual emissions[iv], but the true potential of rock dust is far greater.

[iv] Global CO_2 emissions for 2021 were projected to be 36.4 gigatons according to Global Carbon Project

Rock dust helps plants grow and benefits the ecosystems and communities where it is applied. Plants can capture more CO_2 from the atmosphere and produce higher yields and more nutritious crops with an application of rock dust. Crops and forests treated with rock dust have the potential to sequester at least as much carbon dioxide as the rock dust itself in areas where soil nutrient deficiencies limit plant growth. Land use and climate change are deeply intertwined. Unless depleted soils are replenished, farmers are forced to expand croplands into native forests or use more aggressive practices that ultimately do more harm than good. Conventional fertilizers mainly supply nitrogen, phosphorus, and potassium, but plants also require the micronutrients found only in rock dust. The cost of conventional fertilizers is beyond the reach of many low-income or subsistence farmers and supplies can be disrupted by war and changing trade policies. Even for those who can afford it, conventional fertilizers come with a steep environmental burden.

The low-risk, low-cost nature of rock dust makes it accessible to almost everyone anywhere in the world. Widespread adoption of rock dust is more contingent on education and forming partnerships between quarries and farmers than it is about cost. However, in some places where the increased productivity does not offset the full cost, carbon credits may be necessary to cover the difference.

Remineralize the Earth is a non-profit dedicated to promoting the use of natural land and sea-based minerals to restore soils and forests, produce more nutritious food, and remove excess CO_2 from the atmosphere. Given the immediate and growing threats of climate change, desertification, and increased food insecurity, Remineralize the Earth, through soil remineralization, is helping to create better soils, better food, and a better planet. Through our research, education, advocacy, partnerships, and implementation we are: regenerating soils and forests around the world, increasing the nutritional quality and yield of food production, and stabilizing the climate. For more information, please visit: www.remineralize.org.

Remineralize the Earth

Remineralize the Earth—Local Partners

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Hampshire College, MA

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Grow Food Northampton, MA

New Harmony Farm CSA, MA

Paulo Freire Social Justice Charter School, MA

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Remineralize the Earth—Project Partners

USDA Trials, US

U.S. Bureau of Mines (now part of the Department of Energy), US

National Stone, Sand & Gravel Association, US

International Center for Aggregate Research (ICAR), US

U.S. State Department American Council of Renewable Energy (ACORE), US

Ocean Arks International, Costa Rica

University of Brasilia, Brazil

dryGrow Foundation, Brazil

Heifer International, Senegal

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