Enhanced Rock Weathering in the Global South: **Exploring Potential for Enhanced Agricultural Productivity and Carbon dioxide Drawdown**

Authors: F. Garrett Boudinot, Gabrielle Dreyfus, Caitlan Frederick, Yifan Powers

F. Garrett Boudinot: Previously Department of Ecology and Evolutionary Biology, Cornell University; currently Vycarb Inc.
Gabrielle Dreyfus: Institute for Governance & Sustainable Development
Caitlan Frederick: Institute for Governance & Sustainable Development
Yifan Powers: Precision Development

PxD PRECISION DEVELOPMENT

IGSD

January 2023

Initiative Overview

Precision Development (PxD) and the Institute for Governance & Sustainable Development (IGSD) are partnering on a unique initiative to collaboratively identify opportunities for innovation in climate change mitigation, particularly for the greenhouse gases most problematic in agricultural production, methane and nitrous oxide, as well as carbon dioxide. We are specifically focused on innovations with pertinence to the world's smallholder farmers, who farm most of the world's approximately 570 million farms.[1] The Food and Agriculture Organization of the United Nations defines these smallholder farmers as "small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares… and are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption."[2] The majority of farms in the Global South[3], a term used to denote the regions of Asia, Latin America, Africa, and Oceania, are small and it is within this broad geography and smallholder farming context which we focus our climate change mitigation initiative.

This initiative includes four analytical pieces on the following opportunities for climate change mitigation by smallholder famers:

- carbon dioxide sequestration through enhanced rock weathering,
- carbon dioxide sequestration through conserving (keeping what is already present) or increasing (i.e., sequestering) the organic carbon storage in soils and plant biomass,
- nitrous oxide mitigation through precision nutrient management, and
- methane mitigation in dairy through improved livestock feeding practices.

In our initiative we are guided by the following principles:

Consider the tradeoffs: We aim to determine smallholder farmers' private returns from the adoption of new technologies or agricultural practices, as well as the societal return of such adoption as measured by gauging the impact of these innovations on our main outcome of interest in climate change mitigation, namely, reducing greenhouse gas (GHG) emissions.

Farmer welfare first: Smallholder farmers cannot be expected to pay the price for climate change mitigation. Climate change-related advisory should support livelihoods, especially as sustained adoption cannot occur without realized benefits for farmers. If it is difficult to understand *a priori* how a specific agricultural practice or technology might impact yields or income, we commit to exploring ways to compensate early adopters as payment for promoting the broader social benefit.

Replicate and scale: We aim to deliver impact at scale. We are particularly interested in low-cost climate change mitigation innovations with strong adoption potential, that can be customized to local contexts, and scaled throughout other regions with similar constraints or needs.

Our goal is to identify opportunities in agriculture with potential benefits for smallholder farmers, either directly or through compensation mechanisms for their environmental services, as well as for GHG mitigation. In identifying these opportunities, we will outline the evidence for impact on farmers' outcomes and on GHG-mitigation outcomes as well as address challenges in building that evidence, particularly in outcome measurement methods. We will also address practical next steps to build a pathway to scale for the identified opportunities.

About Precision Development (PxD)

Precision Development (PxD) is a global non-profit organization that harnesses technology, data science, and behavioral economics to build digital services that empower people to change their own lives. We build low-cost information systems at scale to share knowledge with the world's poorest and most disadvantaged people. Our pioneering model of digital development is implemented in collaboration with partner organizations to maximize scale. We continuously experiment, iterate, and gather evidence on our impact to improve service delivery and demonstrate our value. Most of PxD's services deliver customized digital agricultural advisory to smallholder farmers, with more than 6 million users using these services in 2022. Given the many constraints facing these farmers, PxD is investigating the application of our platforms and core competencies to deliver advisory in new informational fields, including climate change adaptation and mitigation, as the effects of global warming ripple through the agriculture sector.

About the Institute for Governance & Sustainable Development (IGSD)

The Institute for Governance & Sustainable Development (IGSD) promotes just and sustainable societies, specifically through building resilience by accelerating fast climate change mitigation actions to slow near-term warming and self-reinforcing climate feedbacks, avoid catastrophic climate and societal tipping points, and limit global temperature increase to 1.5°C—or at least keep this temperature guardrail in sight. IGSD's latest research shows that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5°C or even the more dangerous 2°C guardrail, and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions by decarbonizing the energy system with the sprint to rapidly cut non-CO_2 super climate pollutants, and to protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

Table of Contents

1. Executive Summary

Enhanced rock, or silicate, weathering (ERW) is a developing technology which leverages natural mineral weathering to draw carbon from the atmosphere. Currently it has primarily been studied, developed and implemented in the Global North. For example, Frontier,[4] with its innovative advanced market commitment[5] to accelerate carbon removal strategies, has invested in multiple companies pioneering ERW, but as of this writing it focuses solely on Global North geographies like the United States and the United Kingdom.

In the ERW process, finely ground rocks are applied to soils to drive chemical reactions which capture atmospheric carbon and convert it into stable dissolved forms. These stable forms of carbon then flow out through groundwater into the oceans, where they are stored on the scale of thousands of years. ERW is thus considered a permanent carbon removal strategy, unlike other land-based strategies like agroforestry or agronomic practices that sequester soil organic carbon, as EWR does not require continued implementation to ensure carbon drawdown. Scientific studies also find promising positive impacts from ERW on important farmer outcomes, like crop yields, when applied to agricultural land.

ERW's potential for permanent carbon drawdown and agricultural co-benefits makes it an attractive mitigation strategy, particularly in equator and near-equator geographies like the Global South, where there are ideal soil pH, temperature, and moisture conditions for the technology. However, because ERW is a new technology that is still being tested and has yet to be studied in Global South contexts, there remain critical uncertainties around its safety, carbon sequestration potential, probable benefits to farmers, and feasibility. All of these factors must be addressed in order to move the technology forward. With coordinated efforts by the scientific and international development communities to address these uncertainties, however, ERW could become an important tool to limit global warming to the 1.5 to 2°C targets of the Paris Agreement adopted in 2015 by parties to the United Nations Framework Convention on Climate Change (UNFCCC).

2. The Opportunity of Enhanced Rock Weathering

The agricultural, forestry, and land-use sector is one of the highest greenhouse gas (GHG) emitting sectors worldwide.[6] In the Global South, agriculture and land-use change are the major emitters of carbon dioxide as well as other potent greenhouse gases, such as methane and nitrous oxide. However, producing food and managing land are not exclusively greenhouse gas-emitting practices. Some strategies for managing land and growing food can remove carbon dioxide from the atmosphere (e.g., soil carbon sequestration, afforestation). Reducing net greenhouse gas emissions from agriculture, a key sector for economic development in the Global South, will be a critical goal in the coming century as climate change contributes additional stressors to food security, biodiversity, land management, and resource use. In particular, strategies are needed to concomitantly supply more food in the face of climate stressors, conserve more land for biodiversity, and remove GHGs from the atmosphere.

Enhanced rock weathering is one such strategy that can improve land productivity and food security while also removing carbon dioxide from the atmosphere.[7] ERW is the process of converting carbon dioxide in soil (eq. 1), which would otherwise enter the atmosphere, into stable water-soluble and mineral carbon forms (bicarbonates and carbonates) by applying powdered (20-200 micron grain size) silicate rocks, rich in magnesium and calcium (e.g., basalt), to increase soil pH (eq. 2). These stable carbon forms (eq. 3) are ultimately deposited through groundwater into the oceans for permanent storage for thousands of years.

Enhanced Rock Weathering Equations:

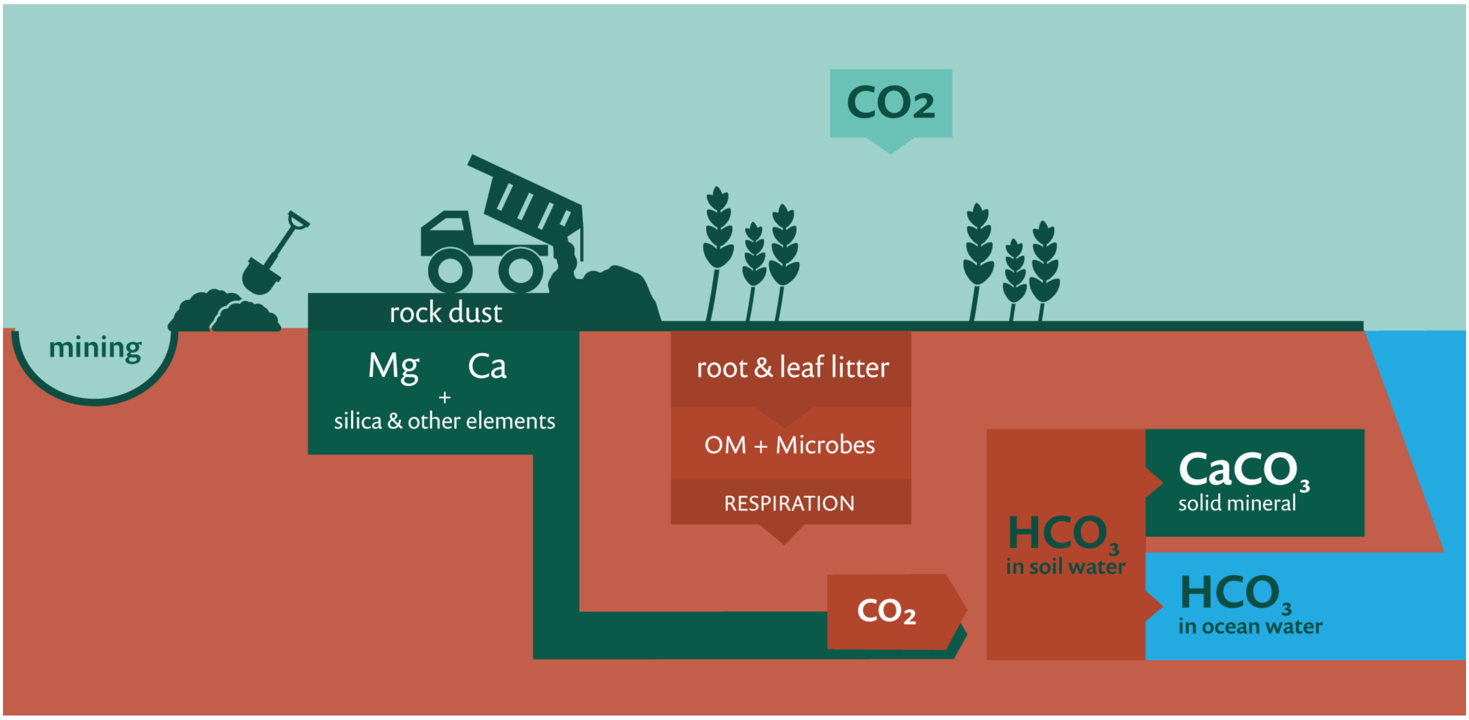
$$4CO_2 + 4H_2O \rightarrow 4H_2CO_3 \text{ (carbonic acid)} \quad (1)$$

$$4H_2CO_3 \text{ (carbonic acid)} + Mg_2SiO_4 \text{ (mineral)} \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4 \quad (2)$$

$$2Mg^{2+} + 4HCO_3^- \rightarrow 2MgCO_3 \text{ (solid)} + 2CO_2 + 2H_2O \quad (3)$$

Carbon dioxide naturally exists in soil water in part as carbonic acid (eq. 1). When in the presence of fresh mineral surfaces, carbonic acid interacts with those minerals (e.g., Mg_2SiO_4, one of the magnesium silicate minerals used in ERW) to form free magnesium ions in soil water solution and results in partition of aqueous CO_2 into bicarbonate, HCO_3^- which increases soil pH, and dissolved silica, H_4SiO_4 (eq. 2). Under certain soil or water conditions, those magnesium and bicarbonate ions can further react to precipitate solid carbonate minerals (e.g., $MgCO_3$), which releases one of the bicarbonate ions back to CO_2 (eq. 3).

Figure 1. The ERW Process



Schematic illustration of the steps involved in sourcing material for ERW and the reactions in the soil that convert carbon dioxide into water-soluble bicarbonate. Once converted, this inorganic carbon can flow with groundwater into streams, rivers, and eventually the ocean, or it can precipitate as carbonate minerals in soils and sediments.

ERW's soil carbon sequestration potential was first mentioned in scientific literature in 1990,[8] but the use of silicate rock soil amendments is not a new agricultural practice. There are examples of farming communities, largely across temperate regions (e.g., North America, Central Europe)[9] and Africa,[10] implementing these types of amendments to provide micronutrients to soils since at least the 19th century. ERW increases the pH of soils, so it can improve nutrient retention of acidic soils (low pH) such as those common in the tropics and Global South.[11] While lime (e.g., $CaCO_3$) is more commonly applied to achieve such pH improvements, its application can generate a net carbon dioxide emission in many, though not all, soils ($CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$).[12] The reduced GHG emissions from the application of silicate rocks thus makes the rocks a desirable alternative to lime, although their rate of dissolution, and thus speed of pH improvement, is slower.

ERW's potential to improve nutrient retention by agricultural soils, thereby improving yields, is an important co-benefit as it not only improves the likelihood of adoption by farmers but can also help address land conversion pressure which leads to deforestation, providing additional benefits to the climate and local biodiversity.[13] Growing economic incentives for carbon dioxide removal through carbon offset markets may also enable more diversified revenue streams for farmers and land managers deploying ERW, which is especially important in the Global South where smallholder farmers are extremely financially constrained.

3. ERW Compared to Other Soil- and Land-based Mitigation Strategies

Enhanced Rock Weathering aims to drawdown carbon dioxide by storing it as inorganic carbon to provide long-term carbon dioxide sequestration.[14] Once carbon dioxide is converted to water-soluble bicarbonate in soil through ERW, it can flow with groundwater into streams, rivers, and eventually the ocean, or it can precipitate as carbonate minerals in soils and sediments.[15] Bicarbonate is generally stable in waters for tens to hundreds of thousands of years,[16] and carbonate minerals can be stable for hundreds of millions to billions of years.[17] Climate change mitigation requires carbon storage to be stable for as long as possible, to reduce the potential for carbon dioxide to be returned to the atmosphere. ERW is thus extremely promising in the permanence of its carbon drawdown.

Current soil- and land-based carbon sequestration strategies mostly focus on converting carbon dioxide into organic carbon (e.g., forest biomass, soil organic carbon), by improving photosynthesis via agroforestry, or increasing soil organic matter through practices like minimum-to-no tillage, intercropping, and increased crop residue retention in soils.[18] However, organic carbon compounds are stable for much shorter timescales than inorganic carbon compounds, and are susceptible to conversion back to carbon dioxide through numerous processes including the resumption of tillage,[19] rising temperature,[20] and wildfire.[21] As a result, organic carbon sequestration is considered a less permanent climate change mitigation strategy, and is valued less than inorganic carbon in most carbon offset markets.[22] Organic carbon buildup in soils is still an important goal to advance sustainability and development, with clear improvements in soil nutrient retention, water retention, and climate resilience[23]—but its utility in climate solutions is lower than strategies like ERW that generate inorganic carbon.

It should be noted that, theoretically, ERW may also contribute to organic carbon buildup, as it adds nutrients to the soil and thus improves plant growth.[24] However, this process has not been studied or demonstrated previously.[25] Analyses reviewed in this paper exclude these potential biological stores and primarily focus on ERW's inorganic carbon sequestration benefits.[26]

4. Impact on Carbon: Sequestration Potential

ERW scientific research is limited and nascent, with current studies using a wide range of material application rates, different calcium- and magnesium-rich materials (e.g., basalt rocks or calcium- and magnesium-rich minerals like olivine or wollastonite), different soil types, and different, and often incomparable, measurement techniques to estimate the impact of ERW on carbon mitigation. As a result, the estimated efficacy of ERW spans a wide range depending on the literature and study in question, from essentially no impact,[27] to more than 100 tons of carbon dioxide removed per acre.[28] The majority of existing studies are numerical models based on the magnesium and calcium content of the materials added, assuming their complete dissolution through the chemical reactions in the weathering process. The few empirical studies are dominated by small-scale potted plant, mesocosm, experiments. Table 1 shows the range of estimated carbon dioxide removal potential of ERW based on existing studies, and their method of assessment.

The material variability highlighted in Table 1, from basalt (common rock type) to wollastonite and olivine (specific minerals), is a primary control on the overall potential carbon benefits from ERW. These different materials contribute to significantly different practical input requirements and risks to farmers. Basalt, for example, is a common mining by-product, making its availability and input emissions for mining and grinding negligible. Basalt also has a wide range of elements that not only contribute to ERW (e.g., calcium and magnesium), but also supply plant micronutrients (e.g., iron, potassium, boron). However, that variability in mineralogy also makes basalt less efficient by weight for ERW, as it requires the transport and spreading of more material for a given carbon benefit, with associated input energy costs and emissions.[29] Other more specific minerals, like olivine, contain much higher concentrations of ERW elements, but require more specific mining and grinding, which constitute additional energy requirements, and thus carbon emissions, for ERW inputs. The minerals can also contain higher levels of heavy metals (e.g., nickel, chromium) that can be harmful to soil and crop health with accumulation over time.[30]

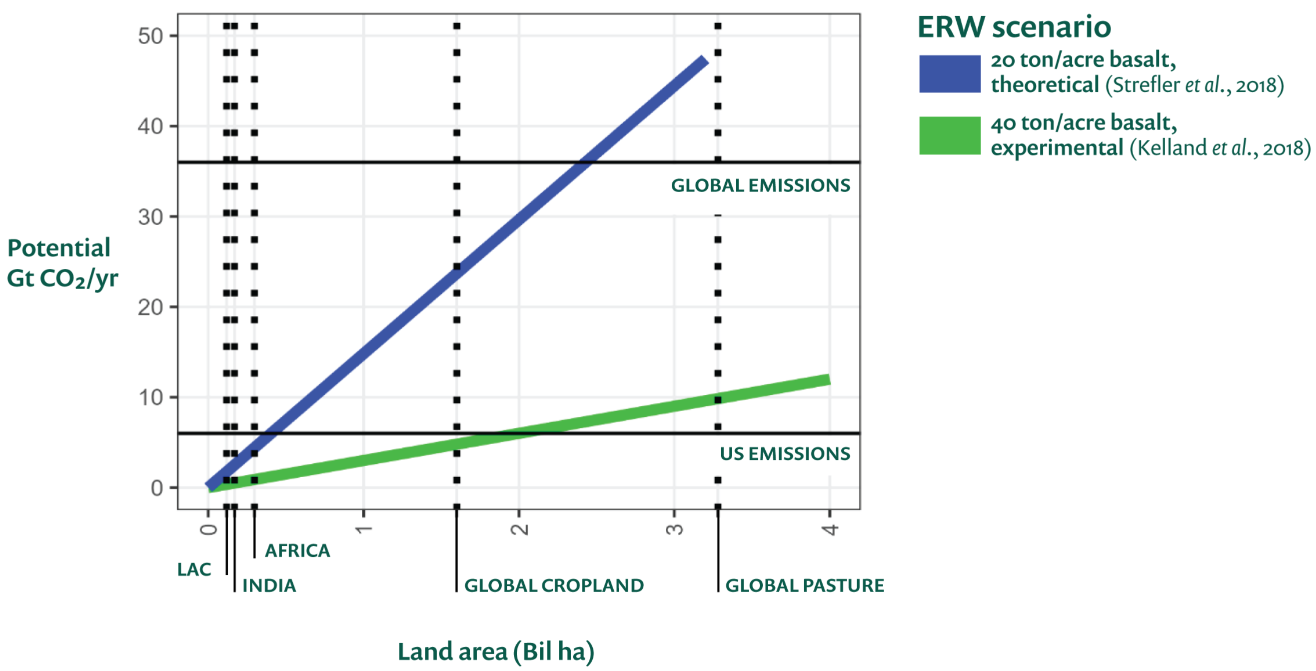
Table 1. Range of estimated CO_2 removal potential of ERW based on existing studies, and their method of assessment.

Rate of CO_2 removed (ton CO_2/ac/yr)	**Rock Rate (metric ton/ acre)**	**Paper**	**Description**
$2.4E^{-7}$	$1.34E^{+2}$	Haque *et al.*, 2020b	Mesocosm, wollastonite
0.009-0.02	97	Amann *et al.*, 2020	Mesocosm, dunite
0.3	20	Taylor *et al.*, 2015	Model, basalt
1.3	5.3	Kohler *et al.*, 2010	Model, olivine
1.3	~1000	Amann *et al.*, 2022	Mesocosm, basalt
1.4	20	Ten Bergie *et al.*, 2012	Mesocosm, olivine
0.8-1.6	40	Kelland *et al.*, 2020	Mesocosm, basalt
2.4	-	Manning *et al.*, 2013	Plot, dolerite + compost
2.5	-	Strefler *et al.*, 2018	Model, basalt
0.4-4	11	Lefebvre *et al.*, 2019	Model, basalt
0.2-4.4	8	Beerling *et al.*, 2018	Model, basalt
4.5	12	Haque *et al.*, 2019a	Model, wollastonite
6	20	Strefler *et al.*, 2018	Model, basalt
7.1	-	Manning *et al.*, 2013	Plot, basalt + compost
22	20	Strefler *et al.*, 2018	Model, dunite
25	20	Kohler *et al.*, 2010	Model, olivine
34	-	Washbourne *et al.*, 2015	Plot, construction waste
49	-	Strefler *et al.*, 2018	Model, dunite
18-56	-	Renforth *et al.*, 2009	Plot, construction waste
118	111	Haque *et al.*, 2019b	Mesocosm, wollastonite

Table of quantitative estimates of the rate of carbon sequestration from ERW. Rock type and study type are described in the Description column, with Mesocosm referring to small scale (e.g., potted plant in greenhouse, soil column in laboratory) experiments, Plot referring to in-field (i.e., outside) trials, and Model referring to non-empirical numerical or geographic modelling. All plot trials were performed in the UK. The wide range of potential carbon benefits stems from the wide range of materials used, material application rates tested, soils in which the materials were applied, and, importantly, variable measurement and estimation practices deployed in the different studies.

While numerical estimates of ERW indicate that upwards of 25 gigatonnes of CO_2 could be removed each year if ERW were deployed across all global croplands (e.g., global scale extrapolation of basalt estimates of Strefler *et al*., 2018), empirical evidence from controlled trials indicate smaller ranges. Research focusing on global croplands estimate removal of up to nine gigatonnes of CO_2 per year (e.g., Kelland *et al*., 2020) or less in other natural settings (e.g., Buckingham *et al*., 2022).[31] Some estimates (Strefler *et al*., 2018; Kelland *et al*., 2020; Figure 2) indicate CO_2 removal rates by ERW that could lead to between 1.7 and 8.5 gigatonnes of CO_2 removed per year if the technology is deployed across all cropland in India, Latin America and the Caribbean (LAC), and Africa (Figure 2).

Figure 2. ERW Carbon Drawdown Potential: Global, India, LAC, and Africa Cropland



The olivine-based estimation model is not used in the Global South potential estimation due to the issues with heavy metal contamination discussed earlier. Indian, LAC, and African cropland data and global cropland and pasture data are from the History Database of the Global Environment (HYDE). US cropland and pasture data are from the U.S. Department of Agriculture's Major Land Uses in the United States report.

5. Impact on Farmers: Costs and Yields

While low application rates (e.g., tens of pounds per acre) of basalt and other silicate rocks are sometimes used in agriculture to add micronutrients to soils, few experiments have tested the crop yield effects of high application rates, such as those required for ERW (e.g., tons to tens of tons per acre). Some modeling studies have considered optimal amendment quantities,[32] and in controlled environments, such as "lab pot" studies, the effects have been further examined.[33] Several studies have shown improvements to soil pH, and thus nutrient retention, in Australian soils.[34] Positive short-term yield responses from basalt have been observed, including for soy and other beans, corn, alfalfa, sorghum, and rice, with many showing improved crop yields with certain silicate rock dust applications (Table 2).[35] Additionally, numerous studies have provided theoretical and empirical evidence for improved crop resistance to stress, including metal toxicity and drought, from silica additions such as crushed basalt.[36] Rice has a particularly long history of amendments, similar to those used in ERW, such as industrial wastes (slag) rich in silica, calcium, and magnesium, as well as heavy metals.

While some initial improvements in yield have been recorded, no long-term research is available for ERW impacts on crop yields. Notably, one study found reduced yield in response to high application rates of wollastonite, a mineral used for ERW, indicating potential long-term reductions in yield with continued application.[37]

Table 2. Demonstrated short-term crop yield increases with various rock weathering materials.

Crop	Reference	Material	Result
Soy	Haque *et al.*, 2020b	Wollastonite	Improved yield up to 5 wt% amendment, with reduced yield at higher application/continued application
Alfalfa	Haque *et al.*, 2020b	Wollastonite	Improved yield to 10 wt%, with reduced yield at higher application/continued application
Bean	Haque *et al.*, 2019b	Wollastonite	Improved biomass at 12.5 wt% amendment (did not reach maturity, bean yield not reported)
Corn	Haque *et al.*, 2019b	Wollastonite	Improved biomass at 12.5 wt% amendment (did not reach maturity, grain yield not reported)
Sorghum	Kelland *et al.*, 2020	Basalt	Increased yield at 40 ton/acre application
Rice	Das *et al.*, 2020	Slag	Improved yield at 2 ton/hectare

All of these studies were carried out in greenhouses, albeit greenhouses in different countries: Haque et al., 2019b and Haque et al., 2020b in Canada, Das et al., 2020 in South Korea, and Kelland et al., 2020 in the UK.

6. Enabling Conditions for ERW and Considerations for the Global South Context

1. Assessment of soil conditions

ERW may be most effective for carbon sequestration in tropical regions, like the Global South, where soil is acidic, and soils have warmer temperatures and higher moisture content than in the Global North. Acidic soils, warmer temperature, and higher moisture all increase the rate of basalt weathering, thereby more quickly releasing the elements in basalt that drive the carbon sequestration reaction. As those elements enter the soil, they in turn increase soil pH, which not only increases nutrient retention but also converts carbon dioxide to bicarbonate.[38] Determining the soil pH can thus help determine the potential efficacy of ERW in a specific location. Other soil characteristics also impact the efficacy of ERW and are thus important to measure, including soil moisture and texture. As weathering is a water-dependent reaction, soil moisture will play a critical role in how fast the basalt can weather, and thus how effective ERW will be.[39] Soil microbial communities, like fungi and bacteria, have also been proposed to either increase or decrease the rate and efficacy of ERW.[40]

Determining soil characteristics like pH, moisture, and biology requires soil testing, a process wherein samples of soil are extracted from the plot(s) of interest and tested in specialized soil testing laboratories. The first step for an effective ERW program is thus to conduct this soil testing, at a sufficient scale, to determine the regions within the considered geography which are most suited for ERW for carbon drawdown potential, and those for which ERW may cause negative impacts, such as for already alkaline soils. Information from this soil testing will not only be useful for advancing ERW but can also be used to better guide precision agriculture in general, from fertilizer usage to water management.

Global South Context: Soil testing is especially important in the Global South as evidence shows there can be significant differences in soil characteristics, and thus responses to agricultural inputs, from plots within the same geographical area.[41] This is partly due to the diverse cropping systems smallholder farmers practice, often in close proximity spatially and temporally[42], and partly to the dramatically different ways farmers can manage their plots, depending on their perceived returns on investment from that plot. PxD's experience with soil testing in Kenya and India reflects this heterogeneity: results of soil tests across various projects showed significantly different soil characteristics across plots in the same geographical area. It is thus difficult to generalize from a single soil test; a high intensity of testing is required to achieve accurate soil data results.

While soil testing is relatively straightforward in high-income countries where the necessary testing infrastructure is readily available (e.g., the network of Cooperative Extension System (CES) across the United States), the process becomes much more challenging when working with smallholder farmers in the Global South. First, while many Global South countries have national soil testing laboratories, these are often operating at or above capacity with long delays in processing. While commercial options are also mostly available, they can be cost prohibitive.[43] Second, with respect to cost, willingness to pay for soil testing information amongst smallholder farmers themselves is quite low and their amount is much below the cost of the test itself.[44] This means any effort to assess soil characteristics probably cannot depend on smallholder farmers themselves initiating the testing. Third, physical infrastructure linking smallholder farmers to urban centers, where testing laboratories are mostly located, can be quite poor. These poor road conditions complicate efficient soil sample extraction and analysis.

There are some low-cost tests which can provide information to guide opportunities for ERW—for example, litmus paper can indicate pH, and hand-held texture tests can indicate moisture retention. However, training is required to use and interpret these tests effectively, and they still require transport and time, which are additional operational costs.

Paths to Overcome Global South Challenges: To address the need for soil data in the Global South, and recognizing the multiple challenges for any one organization attempting to collect such data, there are efforts underway by global scientific and funder communities to create detailed maps of soil characteristics across Global South geographies. For example, the Bill and Melinda Gates Foundation launched a project in 2021 to appraise the national Soil Information Systems (SIS) in multiple countries, including India, Rwanda, Ethiopia, and Tanzania.[45] This project will also assess and identify ways to improve existing soil data initiatives like the World Soil Information Service (WoSIS) soil profile database and the Global Soil Information System (GLOSIS), which coordinate global soil data efforts. There have also been regionally based efforts to gather soil data, especially using spectral soil analysis which assesses soil characteristics with specialized instruments that detect the visible, near-infrared and mid-infrared ranges of the electromagnetic spectrum.[46] For example, the Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF)'s Soil-Plant Spectral Diagnostics Laboratory are working in partnership with the African Soil Information Service to generate direct information on soil properties at a level of accuracy previously unavailable through the Soils 4 Africa initiative.[47]

Advancements have also been made to lower the cost of field-level soil testing technologies. For example, Columbia University's Agriculture and Food Security Center, with support from the Alliance for a Green Revolution in Africa (AGRA), developed a highly accurate, portable soil testing technology, SoilDoc, which costs about $3 per analysis. The results from SoilDoc's soil samples are sent via SMS to a database in the cloud for rapid analysis by a team of soil experts, which could in future be replaced by algorithmic analysis.

In order to address the soil testing challenges for smallholder farmers, there must be continued work both on high level coordination and on technology. Low cost soil testing technology can enable a greater scale of soil data collection, while coordination amongst research and governmental organizations within specific geographies will allow for systematic soil data collection efforts. The ultimate goal is to create regularly updated, accurate soil databases with detailed data from a selection of representative plots at sufficient density across a region.[48] This will allow any organization or company that relies on soil testing data to leapfrog this logistical challenge and focus on innovation, like establishing ERW in a new geography.

2. Access to powdered basalt, potentially as a mining by-product

ERW requires the use of finely ground silicate rocks like basalts, or other minerals like olivine and wollastonite. Of these silicate rocks, basalt is the most prevalent as a material and has other elements to improve micronutrient composition in soils. Basalt is also more likely than the other silicate rocks to exist as an industrial by-product; for many mining operations, finely-ground basalt is a by-product that could be leveraged for ERW to reduce input costs and emissions.[49] Creating a market for basalt and an industry for basalt mining may also support local income generation, and transition local communities from coal mining dependency.[50]

The composition and grain size of the basalt will influence the speed and efficacy of ERW for carbon drawdown. Higher calcium and magnesium content, i.e., Ca^{2+} and Mg^{2+}, in the basalt composition will drive more carbon dioxide sequestration, and a grain size of smaller than 100 microns (μm) is preferable.[51] However, rock grinding contributes to the energy requirement and related carbon dioxide emissions of ERW overall,[52] and transporting and spreading grain sized below 50 μm can contribute to practical and health difficulties because of air-borne dust.[53]

Ground basalt is increasingly available commercially for soil amendments around the world; it was available in Queensland, Australia as early as the 2000s.[54] However, depending on the availability of the source, the cost of the ground basalt will vary widely.[55]

Global South Context: Powdered basalt would be a new agricultural input for almost all smallholder farmers in the Global South. Although there have been a few discussions of obtaining basalt in low- and middle-income countries as a by-product of rock crushing operations and industrial mineral mining operations,[56] there has been no systematic research into developing the needed supply chain, from identifying basalt sources, to developing potential mining operations, to determining the ultimate price of basalt for farmers. This latter point is key as smallholder farmers are extremely risk averse,[57] which can pose large barriers to adoption of new technologies which require investment on their part. Supply chain development for ERW is further complicated because basalt composition varies geographically, so not all basalt will contain the equivalent amount of ERW-driving elements like calcium and magnesium, and will require further site-specific consideration in assessing the efficacy of ERW. Of note, while most Global South countries have not been the focus of existing ERW research, large geological deposits of basalt and other rocks suitable for ERW have been identified in East Africa, and Central America, as well as India, which hosts one of the largest deposits of basalts on the Deccan Plateau.

Paths to Overcome Global South Challenges: Commercial scale basalt distribution for agriculture does exist in the United States, both at small volumes and from mining operations in large volumes. To advance ERW in the Global South, due diligence must be done to create such a market for powdered basalt, from sourcing to distribution to marketing to financing, amongst other market considerations. This process can be especially challenging in emerging economies due to the high level of information asymmetry, as well as transaction costs, between the various stakeholders in the input supply chain. In the smallholder farmer context, one model which has shown promise for increasing the adoption of new technology, i.e., improved seed varieties,[58] is working through the small and medium enterprises (SMEs) which populate the input supply chain. These entities, like agro-dealers, are often the farmer's first point of contact with the market and, in addition to their official business roles, can provide valuable informal services, i.e., credit provision and knowledge sharing.[59] Creating a service economy for basalt, which specifically creates opportunities for these SMEs to participate in, can thus be an impactful lever for its successful distribution. This could involve developing a marketing plan which incorporates an education and outreach component for the agro-dealers who are the primary input suppliers to smallholder farmers and also play an important information-sharing role about the various farm inputs available.[60]

3. Transportation of powdered basalt to agricultural lands

Research in Austria shows that, depending on the distance from the mine to the farm and the mode of transportation used (rail vs. road), transporting <100 μm basalt may cancel out carbon dioxide sequestration benefits.[61] This is partially because the application rate of basalt, if maximizing carbon dioxide removal, for ERW is very high – many tons/acre – so a large volume of basalt delivery is needed. This type of delivery requires specific trucks, personnel trained in driving those trucks, transportation infrastructure (roads and bridges capable of holding 20-ton capacity dump trucks), and fuel. Accordingly, the research suggests basalt powder is best sourced from mining industries near the application sites.[62]

Global South Context: Smallholder farmers often work on small plot sizes, usually less than 10 hectares[63] and sometimes as small as two hectares or below,[64] located in remote areas far from economic and industrial centers. This means the total amount of basalt they might need on their farms for ERW will be much less than on commercial farms. However, the application rate of basalt for ERW is still much higher than for other soil amendments. The corresponding transportation and storage costs required by ERW amendments may be prohibitively expensive for smallholders, and may decrease their likelihood of adopting the technology. However, lowering application rates of basalt would proportionately reduce the efficacy of ERW. Another transportation consideration is the emissions generated to transport basalt to smallholders, i.e., transporting the input from supplier to hub agro-dealer, from hub agro-dealer to retail agro-dealer, and ultimately to the farmer. As mentioned above, depending on the distance from the source and the mode of transportation, those emissions may outweigh the carbon sequestration benefits.

Paths to Overcome Global South Challenges: Access to basalt for Global South farms will require network and infrastructure optimization. Transport of material from mine to farmer must be optimized to avoid emissions, and infrastructure (e.g., roads and bridges) must have the capacity to support the transport of a high volume of geologic material (i.e., many tons of powdered basalt) where this capacity had not previously been necessary. Farms in close proximity to basalt mines should be a priority in testing the adoption of ERW in Global South communities—these early adoptions could be funded as philanthropic grants, accompanied by external scientific partnerships to assess feasibility more broadly. Additionally, the scientific community is still developing frameworks and best practices for performing ERW for carbon benefits, as the environmental and geologic variability of ERW hinders a simple prescriptive methodology for spreading a known volume of basalt for a known carbon sequestration volume.

4. Availability of labor and machinery to apply powdered basalt to land

For carbon benefits, several tons of basalt must be applied per acre, with the exact rate dependent on the concentration of calcium and magnesium in the rock material, as well as the desired carbon dioxide-removal potential. For agronomic applications, i.e., as a micronutrient amendment, applications are as low as 50 pounds per acre.[65] Some researchers have used aircraft to spread the ERW materials over large areas,[66] although, given considerations of moisture availability, runoff potential, water saturation, and safety, most studies have incorporated rock dust into the soil, such as with tillage.[67] The tradeoff between surface application, which accords with recommended practices like no- or reduced-till to improve soil organic matter, versus in-soil incorporation of basalt to increase ERW efficacy is a topic for further scientific investigation.

Global South Context: Labor and access to labor saving technologies, i.e., agricultural machinery, is a major production constraint for smallholder farmers.[68] The labor intensity of basalt application and its dependence on machinery may thus be a significant barrier to ERW adoption, as has been found for fertilizer application in smallholder contexts.[69] Even access to basic tools, like a shovel, cannot be assumed for all smallholders. Women in particular often operate with the least resources and have additional demands on their labor, as they are usually responsible for many household management tasks like cooking and cleaning, as well as childcare. [70]

Paths to Overcome Global South Challenges: Because field trials of ERW in scientific settings are rare and in early stages, there are not yet universally accepted guidelines for practicing ERW. Table 1 shows the wide range of material application rates studied; questions remain around the economic and carbon cost-benefit analysis of rock rates and associated transportation. Most studies incorporate the material into the soil, though depths vary widely. While scientific studies to date have focused on variable maxima for crop and carbon performance in different rock application rates,[71] future studies could instead focus on optimizing for cost in Global South contexts, where available labor, equipment, and crop outcomes are leveraged for maximum carbon and crop benefits using ERW. In addition, for technologies for climate mitigation, if the social and environmental benefits are larger than private benefits to farmers like increased profits, then there is a strong economic case for compensating farmers for their environmental services and covering associated costs of implementation. Emerging evidence shows policy levers like payments for environmental services (PES) can motivate change in farmers' behavior as well as continuation of those behavior changes, for example, in adopting sustainable land-use practices to conserve watershed ecosystems.[72] It is critical to develop the necessary infrastructure for successful

PES program implementation, for example, by determining the appropriate payment amount and securing land tenure, as well as by building the evidence base for this market-based approach in addressing negative environmental externalities of human behavior.[73] Such research and development should be a priority for assessing the viability of ERW in Global South contexts.

5. Measurement and verification of carbon sequestration after ERW application

The current measurement method of carbon sequestration through ERW is direct chemical analysis of soil carbonate minerals and soil water chemistry. This measurement method requires hands-on sampling and complex chemical analyses, but the scientific community recognizes the need to streamline monitoring so the technology can scale, and is thus working on developing other methods to track efficacy. Two of these emerging measurement methods are:

(1) Using *in situ* soil chemistry sensor technology (e.g., electrical conductivity) to measure changes in the chemistry of soil water in response to ERW. Electrical conductivity has been shown to be related to the alkalinity (e.g., from bicarbonate and carbonate ions—the outputs of the ERW chemical process) of water, though more work is needed to leverage this relationship for a straightforward measurement.[74]

(2) Modeling approaches to estimate soil carbon sequestration potential based on local conditions and basalt characteristics.[75]

Both methods are nascent and lack field validation. There is currently no standardized or universally accepted method for verification of the amount of carbon dioxide mitigated, although methods entail some combination of “life-cycle assessment” of the total input carbon dioxide emissions (i.e., from rock grinding, transportation, and spreading) and in-field measurements of carbon sequestration (either of the actual change in carbon dioxide, bicarbonates and carbonates, or in some proxy related to those compounds). Verification of the realized carbon sequestration will probably be required, as offset purchasers increasingly require higher confidence in nature-based carbon removal practices.[76]

Global South Context: There is a significant knowledge gap and lack of consensus on measuring and verifying the efficacy of ERW in general, but especially for the Global South where little to no testing has been done. Technological approaches are needed for reliable verification, but their high cost is a barrier for implementation across smallholder farmer geographies. Lower-cost soil chemistry sensor technology (i.e., electrical conductivity) may provide opportunities for measurement-based verification, though that technology is still being refined and studied. Additional innovations in the measurement field for ERW will be required in order to allow for measurement at scale in the Global South smallholder farmer context.[77]

Paths to Overcome Global South Challenges: Increased field deployment across settings, and advanced technological approaches to in-field measurements, will accelerate the reliability and consensus of ERW verification. In addition, although no carbon offset registry methodology currently exists for ERW, such methodologies are being developed to provide guidance to farmers and land managers in deploying ERW for revenue through carbon offsets, although the validity and appeal of these methodologies for offset purchasers have yet to be demonstrated.[78] Measurement and verification standardization will stimulate more widespread access to carbon market rewards, as well as prioritize the low cost, scalable measurement technologies which will support adoption of ERW in the Global South. Increasingly, carbon offset purchasers are requiring measurement-based verification for carbon removal offset, as other nature-based carbon removal projects verified with models alone are increasingly scrutinized and losing value.[79] Technology innovation and deployment strategies that specifically empower Global South smallholder farmers to take measurements and transmit measurement data, will create a sustainable framework for converting ERW practices into high-quality offsets for high-value trade.

7. Pathways to Scale ERW

Carbon offset payments to farmers for deploying ERW may be an opportunity to scale its use by providing an incentive for its application and would also help to diversify farm revenue streams in the future. Currently, however, carbon offset market opportunities are not widely available for ERW, given the uncertainties around its monitoring, verification, and efficacy. The majority of carbon offsets are through governance bodies, called "registries," that oversee the implementation, verification, and trading of offsets by those performing the carbon dioxide removal practice and those purchasing the offsets. Offset registries require the technology or practice that offsets emissions, or removes carbon dioxide from the atmosphere, to be well understood to ensure it is performed with some regularity across geographies and times, and that the climate benefits accrue. "Methodologies" are the registry-prescribed protocol for implementing offset practices, generally developed and reviewed by some knowledgeable scientific body, although exact practices vary across registries. Currently one registry, Verra, is assembling such a review body for its first receipt of methodology proposals for ERW, and another new registry, Puro.earth, has created a draft methodology. Once approved, there may be an opportunity for farmers and other land managers (termed "project developers") to apply to perform under the new methodology to receive offset payments. Depending on how methodologies develop, farmers and land managers in Global South countries may be able to participate. University and private research is ongoing to generate more data from field-based ERW trials, and could be directed towards testing ERW in Global South countries.

8. ERW Opportunities in the Global South

The science behind ERW is nascent, and the specific outcomes of ERW[80] will depend on rock type, amount of rock applied, soil type, climate, and crop and plant type, as well as the ability to measure and monitor the impacts of EWR on atmospheric carbon dioxide.[81] Furthermore, the geological,[82] infrastructural, material, and technological requirements to facilitate the mining,[83] crushing,[84] transporting,[85] spreading, and tilling of silicate rocks for ERW need significant investments to be realized in Global South geographies. Still, as the global community seeks opportunities for improved food security, climate solutions, and sustainable development, ERW may be an attractive technology with wide ranging benefits and economic opportunities. To advance the positive outcomes of ERW for benefits in the Global South, increased studies of ERW in Global South-specific conditions, robust scientific monitoring, technological innovations, investments, and more stable carbon market incentives will be needed.

9. Research Needs to Ensure ERW is Safe and Effective

As stated, there is little scientific literature supporting ERW-application success in Global South geographies, nor success on farmer outcomes, like yield, for smallholder farmers. One model of the potential climate benefits by country suggests removal of between 0.25 and 1.1 gigatons of carbon dioxide per year if ERW were deployed across all agricultural land in India,[86] but the theoretical estimates used have not been corroborated by field trials there. Aside from climate impact, evidence for short-term crop yield increases in Global South geographies, as have been observed elsewhere, has yet to be obtained.

In existing ERW research, the cost of application also varies depending on the region of interest, the exact rock materials used, and the emphasized purpose of application (for carbon drawdown or agronomic outcomes like soil health and yields). Farmers and land managers thus may choose to find a balance between improved crop yield and carbon benefits. For example, some studies indicate that, at application rates for maximum carbon sequestration, crop yields suffer.[87] From the smallholder farmer perspective, any negative impact on farmer outcomes, like yield, will outweigh any external climate benefits. Additional research is thus needed to accumulate robust evidence on the impact of ERW on farmers in Global South countries, and the most appropriate ways to implement ERW in a smallholder farmer plot, considering the farmer's priorities.

This research should include investigations of:

- Crop level outcomes – What is the effect of ERW on yields, particularly of the crops important to smallholder farmer livelihoods, considering the soils, climate, and geology of Global South farms? What is the precise dosage of basalt needed to maximize the carbon sequestration potential and to minimize any negative effect on the yield of the crops of smallholder farms in Global South countries?

- Application – What is the appropriate application technique for basalt on the types of soils smallholder farmers are likely to work on?

- Labor and machinery requirements – What labor and machinery needs must be met to correctly implement ERW at the plot level?

- Basalt cost – What is the commercially sustainable price of basalt in different geographies, and, at that commercially sustainable price, does ERW increase profit for farmers without entailing additional payments? Are there heterogeneities in who these profit increases or decreases accrue to?

It is important to note that research addressing the above questions should be conducted for each potential region for ERW application in the Global South, as contextual elements like the type of soils, market dynamics, and key value chains will differ significantly across geographies.

Another area of uncertainty in ERW is the potential risk of soil contamination by heavy metal content in many calcium- and magnesium-rich rocks, which are necessary for the ERW process.[88] This risk could be mitigated by the choice of rock material. Many basalts contain lower concentrations of such metals compared to other calcium- and magnesium-rich minerals like olivine, although continued application at high rates may still lead to soil contamination. More work is needed to better understand the relationship between silica, potential heavy metal contamination, long-term impacts of basalt application, and crop yields, in order to appropriately mitigate potential risks to crop nutrient uptake and resulting human consumption. For example, in Puro.earth's draft methodology for enhanced weathering carbon projects, assessing heavy metal contamination is a key step in their environmental and social safeguards.

To understand and mitigate this heavy metal risk, more scientific investigations are needed to:

- Identify the potential basalt sources in each prospective geography and conduct testing of their total elemental composition. Test results will indicate the sources' amounts of ERW elements (e.g., calcium and magnesium) for carbon benefits, plant micronutrients for crop impacts, and heavy metal content for the risk of toxicity.

- Test the effects of the identified basalt in local geographies to understand the impacts on crop yields and soil contamination and crop yields.

- Through the experimentation listed above, create standards for basalt rock to be used in ERW.

These actions will constitute a substantial undertaking by the scientific community, as the high degree of geological heterogeneity means an accompanying high level of testing. Such work, however, is necessary in order to ensure ERW is a safe technology for those who implement it, as well as for all of us who consume agricultural products affected by it.

In summary, a number of fundamental questions must be addressed to assess the safety, efficacy, and feasibility of deploying ERW in the Global South. These questions are related to safety, likely benefits to the farmer, carbon removal efficacy, and economic and logistical feasibility.

Safety: The key considerations regarding safety involve the potential to release metal contaminants into soil, and the potential for inhalation of fine powdered rock, which is dependent on frequency of exposure.[89]

Heavy metal accumulation in soils can lead to uptake by plants and subsequent consumption by people, causing a range of health effects.[90] Global soils are already increasingly contaminated with heavy metals, from both changing agricultural practices and atmospheric deposition. Remediation of soils with excess heavy metal concentrations is itself an ongoing field of science with no clear solutions. Mitigating the risk of heavy metal contamination will require sourcing materials with lower heavy metal content and ensuring that soils used for ERW do not already contain high levels of heavy metals.

Remobilization of powdered rock by wind can cause fine silicate particles to be inhaled during their application for ERW, particularly at high application rates. Wearing cloth masks and eye-wear is common practice for researchers facilitating ERW studies in the USA and Europe, but the availability of safety equipment and adherence to these protocols in the smallholder farming context are much more uncertain. Furthermore, once rock dust is applied to the surface, wind can pick up and transport the dust and create dust clouds that are hazardous to the people exposed to them. Incorporating the material into the soil reduces the risk of wind remobilizing rock dust after application.

Likely benefits to the farmer: Additional research is needed to understand the immediate and long-term impacts of silicate rocks used for ERW, on soil health and plant productivity, and particularly for Global South geographies of interest, as impacts will depend on soil conditions, source material characteristics, and crop types. Improved low-cost methods for assessing soil characteristics, as well as field testing in a range of conditions relevant to Global South communities, will facilitate the optimization of any benefits from ERW for farmers.

Carbon sequestration potential and MRV (measurement, reporting, and verification): Similar to productivity benefits, the efficacy of ERW for carbon sequestration will depend on soil conditions, source material characteristics, and the amount and size of material applied. Scientific and technological developments are also needed for measuring and verifying carbon sequestration through ERW, as well as for the creation of carbon registry methodologies that could enable economic incentives for carbon sequestration through ERW.

Feasibility: Economic and logistical feasibility is a function of access to material (e.g., distance, transportation infrastructure), farm conditions (e.g., equipment availability, soil characteristics, labor), and market incentives (e.g., carbon offset availability for smallholder-scale ERW). To address these parameters, it is necessary to create investments, policies, and market incentives that incorporate the source of ERW materials and the relevant infrastructure needs, from machinery and transport to the knowledge and labor needed for successful ERW application.

10. Pathways to an ERW Future in the Global South

ERW is already being advanced in the Global North, with research trials targeting soil, crops, and climates in the United States, Canada, and Europe. The future economic benefits of ERW for farmers from carbon offsets will then disproportionately go to Global North farms where research and development has been focused. This is despite many tropical and Global South countries in theory having more ideal conditions for ERW—warmer, wetter, and more acidic soils for more rapid rock weathering than the Global North. But the specific risks, potential benefits, and logistics of implementing ERW in Global South communities require concerted study, research, market development, network building, and investment that are specific to the context of those communities. Necessary steps are:

- assessment of geological material availability to support ERW in Global South countries, as well as assessment of each country's environmental suitability for the weathering process,

- assessment of infrastructural capacity and needs to support ERW in Global South countries,

- field trials that monitor soil health, crop nutrient density and productivity, and soil inorganic- and organic-carbon impacts in Global South countries, and

- technological development of field measurement techniques to better understand soil conditions and monitor ERW in Global South countries.

These actions need to be developed in concert with scientists, policymakers, development organizations, as well as ground-level communities and farmers of the Global South. The people who will ultimately be the ones implementing ERW technology in their geographies will have key insight into their specific contextual challenges and ways to overcome those challenges. Including the perspective of local communities at the outset, beginning with the research and design phases, is imperative to assess ERW's potential success in the Global South.

Endnotes

1 Lowder S. K., Skoet J., & Raney T. (2016) *The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide*, World Dev., 87: 16–29, ("This article uses agricultural census data (provided at the country level in Web Appendix) to show that there are more than 570 million farms worldwide, most of which are small and family-operated.").

2 Food and Agriculture Organization (2013) *Smallholders and Family Farmers*, Fact Sheet, 21 ("Smallholders are small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares. Smallholders are small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares. Smallholders are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption.").

3 Lowder S. K., Skoet J., & Raney T. (2016) *The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide*, World Dev., 87: 16–29, ("We now examine regional patterns among the 58 low- and middle-income countries for which agricultural censuses report information on both number of farms and farmland by land size class (Figure 6). In all regions except Latin America and the Caribbean, the majority of farms are in the smallest cohort (smaller than 1 ha).").

4 For more information, *see* Frontier Our Portfolio.

5 Kremer M., Levin J., & Snyder C. M. (2020) Advance Market Commitments: Insights from Theory and Experience, AEA Papers and Proceedings 110, 269–273, 270 ("The model focuses on the holdup problem: firms invest in R&D and capacity before bargaining with purchasers over price and quantity. Purchasers expropriate some investment returns in bargaining, leading the firm to underinvest. The firm may not develop the vaccine at all; if it does, it will underinvest in capacity to serve low-income countries. An AMC that commits to a subsidy policy prior to the firm's investment helps address the inefficiency.").

6 Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R. *et al.* (eds.), SPM-7 ("In 2019, approximately 34% [20 Gtcarbon dioxide-eq] of total net anthropogenic GHG emissions came from the energy supply sector, 24% [14 Gtcarbon dioxide-eq] from industry, 22% [13 Gtcarbon dioxide-eq] from agriculture, forestry and other land use (AFOLU), 15% [8.7 Gtcarbon dioxide-eq] from transport and 6% [3.3 Gtcarbon dioxide-eq] from buildings.").

7 Beerling D. J., Leake J. R., Long S. P., Scholes J. D., Ton J., Nelson P. N., Bird M., Kantzas E., Taylor L. L., Sarkar B., Kelland M., DeLucia E., Kantola I., Müller C., Rau G., & Hansen J. (2018) *Farming with crops and rocks to address global climate, food and soil security*, Nature Plants 4(3): 138–147, 138 ("The magnitude of future climate change could be moderated by immediately reducing the amount of carbon dioxide entering the atmosphere as a result of energy generation and by adopting strategies that actively remove carbon dioxide from it. Biogeochemical improvement of soils by adding crushed, fast-reacting silicate rocks to croplands is one such carbon dioxide-removal strategy. This approach has the potential to improve crop production, increase protection from pests and diseases, and restore soil fertility and structure.").

8 *See generally*, Seifritz W. (1990) *CO_2 disposal by means of silicates*, Nature 345(6275): 486.

9 Van Straaten P. (2006) *Farming with rocks and minerals: challenges and opportunities*, An. Acad. Bras. Ciênc. 78(4): 731–747, 735 ("Over the last few decades there is a small but consistent use of multi-nutrient silicate rock fertilizers in Central Europe, e.g. Germany, and parts of North America, especially in organic farming practices (von Fragstein et al. 1988, Blum et al. 1989a, b). But apart from organic agricultural operations, silicate rock fertilizers are also tested and applied to reverse the declining soil health in Central Europe's forests affected by pollution, especially acid rain.").

10 Van Straaten P. (2006) *Farming with rocks and minerals: challenges and opportunities*, An. Acad. Bras. Ciênc. 78(4): 731–747, 731, 736 ("Examples are provided from two successful nutrient replenishment projects in Africa where locally available rock fertilizers are used on highly leached acid soils."; "While in some countries in temperate climates the use of multi-nutrient rock fertilizers is growing, especially in the organic agriculture market, there are only few published results from the application of rock fertilizers in developing tropical countries. Although many tests have been carried out in tropical environments, e.g. in Brazil, only a few trial results with well characterized rock and mineral fertilizers as well as soils in which they were applied have been reported.").

11 Gillman G. P. (1980) *The Effect of Crushed Basalt Scoria on the Cation Exchange Properties of a Highly Weathered Soil*, Soil Sci. Soc. Am. J. 44(3): 465–468, 465 ("The results suggest that crushed basalt scoria could be successfully used to prevent cation nutrient losses from highly weathered soils of the tropics").

12 In some soils, liming may generate similar carbon sequestration benefits as enhanced silicate weathering, *see for example* Hamilton S. K., Kurzman A. L., Arango C., Jin L., & Robertson G. P. (2007) *Evidence for carbon sequestration by agricultural liming*, Global Biogeochem. Cycles 21(2): 1–12, 1 ("Soil solutions sampled by tension indicated that lime can act as either a source or a sink for carbon dioxide.").

13 Lambin E. F. & Meyfroidt P. (2011) *Global land use change, economic globalization, and the looming land scarcity*, Proc. Nat'l. Acad. Sci. U.S.A. 108(9): 3465–3472, 3468 ("Aggregate global scale data suggest that past agricultural intensification did spare land for nature. If crop yields would have remained constant since 1961, an additional 1,761 Mha of cropland would have been required to achieve the same production level as in 2005 (53). This cropland expansion would have consumed all of the land reserve and caused massive deforestation. Absent agricultural intensification, large food producing countries would have required two to three times more cropland area to meet current food demands.").

14 Beerling D. J., Leake J. R., Long S. P., Scholes J. D., Ton J., Nelson P. N., Bird M., Kantzas E., Taylor L. L., Sarkar B., Kelland M., DeLucia E., Kantola I., Müller C., Rau G., & Hansen J. (2018) *Farming with crops and rocks to address global climate, food and soil security*, Nature Plants 4(3): 138–147, 139 ("The residence time of dissolved inorganic carbon in the global ocean is around 100,000–1,000,000 years, making it essentially a permanent C storage reservoir on human timescales.").

15 Vicca S. *et al.* (2022) *Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes?*, Glob. Change Biol. 28(3): 711–726, 712 ("The principle of ESW is the reaction of silicate grains with carbon dioxide and water to form bicarbonates which can either leach out of the soil into the groundwater, rivers, and eventually the ocean, or precipitate in the soil, forming pedogenic carbonates (Figure **1**). The latter reduces short-term C storage approximately by half, but in both cases, C is stored for hundreds of years and longer (Hartmann et al., 2013; Köhler et al., 2010).").

16 Beerling D. J., Leake J. R., Long S. P., Scholes J. D., Ton J., Nelson P. N., Bird M., Kantzas E., Taylor L. L., Sarkar B., Kelland M., DeLucia E., Kantola I., Müller C., Rau G., & Hansen J. (2018) *Farming with crops and rocks to address global climate, food and soil security*, Nature Plants 4(3): 138–147, 139 ("The residence time of dissolved inorganic carbon in the global ocean is around 100,000–1,000,000 years, making it essentially a permanent C storage reservoir on human timescales.").

17 Blättler C. L. *et al*. (2018) *Two-billion-year-old evaporites capture Earth's great oxidation*, Science 360(6386): 320–323, 320, ("This study presents analyses from a remarkably preserved ~2.0-billion-year-old marine evaporite succession bearing carbonates, sulfates, halites, and bittern salts. This succession was discovered during the 2007–2009 drilling of the Onega Parametric Hole (OPH), which intersected 2.9 km of Paleoproterozoic sedimentary and volcanic rocks and 600 m of Archean gneiss in the Onega Basin, Karelia, Russia (*16*, *17*).").

18 Kichamu-Wachira E., Xu Z., Reardon-Smith K., Biggs D., Wachira G., & Omidvar N. (2021) *Effects of climate-smart agricultural practices on crop yields, soil carbon, and nitrogen pools in Africa: a meta-analysis*, J. Soils Sediments 21(4): 1587–1597, 1588 ("Climate-smart agriculture (CSA) has been advanced as an alternative to conventional farmer practices due to its importance in climate change mitigation, food production enhancement, and soil quality improvement (FAO 2013; Lipper et al. 2014). SOC is important in regulating the atmospheric carbon dioxide concentration, improving soil health and increasing yields (Smith et al. 2020; Mtyobile et al. 2020). Agricultural production practices and land use systems could positively or negatively impact ecosystem health and SOC sequestration (Sithole and Magwaza 2019; Mtyobile et al. 2020). The CSA practices such as green manure (GM), crop residue retention (CR), and conservation tillage are recommended to improve soil nutrient levels, increase crop productivity, and enhance soil carbon pools (FAO 2013; Steenwerth et al. 2014; Khatri-Chhetri et al. 2017). The beneficial effects of CSA may enhance climate mitigation and adaptation to current and future climate risks. These practices have been largely adopted in different contexts (climate, altitude, soils, etc.) in Africa with studies reporting diverse observations about their impact on SOC, crop yields, and soil total nitrogen (TN) (Micheni et al. 2016; Masvaya et al. 2017; Sithole and Magwaza 2019; Mtyobile et al. 2020). For instance, conservation tillage (reduced tillage and no-tillage) and CR have been found to increase yields (Thierfelder et al. 2013; Kimaro et al. 2016; Naab et al. 2017) and SOC (Mujuru et al. 2013; Mupangwa et al. 2013)."); *and* Corbeels M., Naudin K., Whitbread A. M., Kühne R., & Letourmy P. (2020) *Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa*, Nature Food 1(7): 447–454, 447 ("Conservation agriculture (CA) is widely proposed as one of the promising pathways to the sustainable intensification of food production[5,6]. The practice of CA is based on three crop management principles: direct seeding of crops with minimal soil disturbance (no/reduced tillage, RT); retention of crop residues as mulch on the soil surface (M); and adoption of crop rotations and/or intercropping (IR). Originally, CA was advocated for its potential to conserve soil and water and to enhance soil fertility by reducing soil erosion, soil organic matter loss and soil structural breakdown[5,7]. More recently, however, CA has been reframed as a technology for increasing crop yields that is able to ensure the food security of smallholder farmers—especially in the African context[8].").

19 Dynarski K. A., Bossio D. A., & Scow K. M. (2020) *Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration*, Front. Environ. Sci. 8 514701, 1–14, 1 ("From a policy perspective, soil C is generally assumed to be a vulnerable pool at risk of being quickly lost via microbial degradation or other avenues of physical loss if soil C building practices are not maintained indefinitely. This assumption has been challenged by recent scientific advances demonstrating that microbial consumption and transformation of plant-derived C actually necessary for the long-term storage of soil organic matter.").

20 Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, Sci. Adv. 7(3): eaay1052, 1–8, 1 ("The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040.").

21 Nave L. E., DeLyser K., Domke G. M., Holub S. M., Janowiak M. K., Kittler B., Ontl T. A., Sprague E., Sucre E. B., Walters B. F., & Swanston C. W. (2022) *Disturbance and management effects on forest soil organic carbon stocks in the Pacific Northwest*, Ecol. Appl. 32(6): 1–21, 1 ("At the ecoregional level, our analysis indicated that fundamental patterns of vegetation, climate, and topography are far more important controls on SOC stocks than land use history, disturbance, or management. However, the same patterns suggested that increased warming, drying, wildland fire, and forest regeneration failure pose significant risks to SOC stocks across the region. Detailed meta-analysis results indicated that wildfires diminished SOC stocks throughout the soil profile, while prescribed fire only influenced surface organic materials and harvesting had no significant overall impact on SOC.").

22 Cullenward D., Hamman J., & Freeman J., (9 Dec 2020) *The Cost of Temporary Carbon Removal* Carbon Plan ("Carbon removal costs are everywhere in climate discussions — this project costs $10, that one costs $200. Policymakers and corporate planners look to metrics to inform their decisions, and cost per ton of carbon dioxide ($/tCO_2$) has become a near-universal unit of measure. But are all tons the same? The answer, unfortunately, is no. Especially when it comes to carbon removal, the duration of carbon storage — what we call a project's "permanence" in our reports — is a critical variable missing from standard $/tCO_2$ metrics.").

23 Palm C., Blanco-Canqui H., DeClerck F., Gatere L., & Grace P. (2014) *Conservation agriculture and ecosystem services: An overview*, Agric. Ecosyst. Environ. 187, 87–105, 94 ("The CA practices of NT and residue retention are key to maintaining or increasing SOM in the topsoil which in turn provides energy and substrate for soil biota activities and their contributions to soil structure and nutrient cycling, as well as many other soil processes and ES.").

24 Kantola I. B., Masters M. D., Beerling D. J., Long S. P., & DeLucia E. H. (2017) *Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering*, Biol. Lett. 13(4): 20160714, 1–7, 3 ("Although EW does not directly sequester organic C from plants, increases in nutrient availability could support greater biomass production, and subsequently lead to increased organic C inputs to the soil system from roots and litter."); Fuss S. *et al.* (2018) *Negative emissions—Part 2: Costs, potentials and side effects*, Environ. Res. Lett. 13, 063002: 1–47, 20 ("Besides being a CDR strategy, EW can ameliorate soil and act as a long-term nutrients source (Leonardos *et al* 1987, Nkouathio *et al* 2008). Many tropical regions have nutrient poor soils, e.g. oxisols and ultisols and due to their high precipitation rates and temperature represent areas of high potential for EW implementation."); *and* Vicca S. *et al.* (2022) *Is the climate change mitigation effect of enhanced silicate*

weathering governed by biological processes?, GLOB. CHANGE BIOL. 28(3): 711–726, 718 ("Hence, similar to liming and fertilization, silicate addition can be expected to impact SOC sequestration by affecting the quantity of plant belowground C inputs, as well as the stabilization of these inputs in soil organic matter (SOM; Paradelo et al., 2015; Van Sundert et al., 2020). ").

25 Vicca S. *et al.* (2022) Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes?, GLOB. CHANGE BIOL. 28(3): 711–726, 718 ("Depending on soil heterogeneity and the magnitude of the effect, it may take several years though before such changes in SOC stocks are detectable (Paradelo et al., 2015)."); *Discussed in* Paradelo R., Virto I., & Chenu C. (2015) Net effect of liming on soil organic carbon stocks: A review, AGRIC., ECOSYST. ENVIRON. 202 98–107, 98 ("In the first 6 months following lime application, they observed significant increases of microbial activity although SOC concentrations did not change with liming. Grieve et al. (2005) did not observe any effect of liming on SOC concentrations on the first two years following a single lime application at 6 Mg ha^{-1} to an Inceptisol. Sapek and Burzyńska (1996) studied the effect of liming on SOC contents of the top 10 cm of mineral soil in three long-term meadow experiments in Poland, on three soils with different properties (Sapek and Barszczewski, 2000). After 15 years, they found that liming at rates bringing the soil pH to neutrality did not modify SOC stocks. Fornara et al. (2011), using data spanning 129 years in the Park Grass Experiment at Rothamsted (UK), showed that the SOC stocks of limed soils were 16.2 Mg C ha^{-1} higher than in unlimed soils, which corresponds to a relative increase of SOC stocks by 21% (Fig. 2A).").

26 Streler J., Amann T., Bauer N., Kriegler E., & Hartmann J. (2018) Potential and costs of carbon dioxide removal by enhanced weathering of rocks, ENVIRON. RES. LETT. 13(3): 034010, 1–9, 2 ("Our study does not include the eventual biological storage of carbon in soils and plants due to mineral fertilization or other un-parameterized feedbacks, which may be particularly relevant for basalt. We also excluded potential hydrological effects, which may affect overall dissolution kinetics due to changes in hydrological flow path and residence time."); *and* Fuss S. *et al.* (2018) Negative emissions—Part 2: Costs, potentials and side effects, ENVIRON. RES. LETT. 13(6): 063002, 1–47, 21 ("Atmospheric carbon can be sequestered via EW in an inorganic or organic form. Inorganic C is sequestered through the production of alkalinity (bicarbonate and carbonate ions) while anions are counterbalanced by the release of cations from the rock products. If the solution is supersaturated with respect to a chemical element, precipitation of secondary minerals can occur, for example, in the form of carbonate minerals (Manning and Renforth 2013, Power *et al* 2013, Washbourne *et al* 2012). Organic C is sequestered when carbon dioxide is reduced and incorporated in biomass and additional carbon sequestration potential can be expected from the release of rock derived geogenic nutrients (i.e. potassium, phosphorus, several micronutrients) enhancing biomass production above previously limiting conditions (Hartmann *et al* 2013).").

27 Haque F., Santos R. M., & Chiang Y. W. (2020b) Optimizing Inorganic Carbon Sequestration and Crop Yield with Wollastonite Soil Amendment in a Microplot Study, FRONT. PLANT SCI. 11(1012) 1–12, 1 ("At all dosages, wollastonite increased the alfalfa growth in terms of height and above-ground biomass dry weight, as well as root biomass. The rate of carbon dioxide sequestration, at optimum wollastonite dosage, reached 0.08 kg carbon dioxide·m^{-2}·month^{-1}.").

28 Haque F., Santos R. M., Dutta A., Thimmanagari M., & Chiang Y. W. (2019b) Co-Benefits of Wollastonite Weathering in Agriculture: CO_2 Sequestration and Promoted Plant Growth, ACS OMEGA 4(1): 1425–1433, 1425 ("Soil amendment with wollastonite promoted enhanced plant growth: beans

showed a 177% greater dry biomass weight and corn showed a 59% greater plant height and a 90% greater dry biomass weight. Wollastonite-amended soil cultivated with beans showed a higher TIC accumulation of 0.606 ± 0.086%, as compared to that with corn (0.124 ± 0.053%). This demonstrates that using wollastonite as a soil amendment, along with legume cultivation, not only buffers the soil against acidification (due to microbial nitrogen fixation) but also sequesters carbon dioxide (12.04 kg of carbon dioxide/tonne soil/month, 9 times higher than the soil without wollastonite amendment).”).

29 Strefler J., Amann T., Bauer N., Kriegler E., & Hartmann J. (2018) *Potential and costs of carbon dioxide removal by enhanced weathering of rocks*, Environ. Res. Lett. 13(3): 034010, 1–9, 6 (“Costs for transportation to and spreading the ground rock on cropland consist of fuel (diesel) costs and specific costs e.g. for labor…, transport costs will increase considerably when more remote fields must be used, forced by the extended deployment of EW. Transport costs may significantly vary by region….Transport may be either by road, rail, or ship. The relative shares will vary over region and time. For an upper estimate of transport costs, we use the cost estimate for transport on road of 0.05 $km−1 t−1 [25] for all transport. Estimates for rail and ship transportation are by a factor of 2 and 50 cheaper, respectively [25, 36], but transfer costs to the road for final transportation would also need to be considered.”).

30 Haque F., Chiang Y. W., & Santos R. M. (2020) *Risk assessment of Ni, Cr, and Si release from alkaline minerals during enhanced weathering*, Open Agric. 5(1): 166–175, 174 (“The main findings of this study indicate the potential release of Ni, Cr, and Si to exceed the SQGE value.”).

31 For more information on carbon removal potentials in practice, *see* Buckingham F., Henderson, G.M., Holdship, P., and Renforth, P. (2022) *Soil core study indicates limited CO2 removal by enhanced weathering in dry croplands in the UK* Appl. Geochemistry (147).

32 Schuiling R. D. & Krijgsman P. (2006) *Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2*, Climatic Change 74(1–3): 349–354, 350 (“Minerals and volcanic glasses display very different rates of weathering. Among the major silicates, olivine weathers fastest, whereas quartz hardly weathers at all. In addition, of course, weathering rates are not only a function of rock-type but also of temperature, rainfall and accessibility of the rock. Crushed olivine in a wet and not too cold climate will weather rather fast. Even so, however, weathering proceeds slowly from the perspective of a technological process. From the experimentally determined rate of weathering it can be calculated that an addition of 1 to 2 tons of crushed olivine (grain size <300 micron) to one ha of soil will last approximately 30 years in a temperate climate. The calculation is as follows. Assumed rainfall 75 cm/yr, pH 4, so each liter of rainwater contains 10^{-4} g of H^+. In 30 years every square meter receives 30 × 7.5 × 100 dm^3 × 10^{-4} g H^+/dm^3 = 2.25 g H^+. To neutralize this with olivine, according to reaction (2) 2.25/4 × 140 g olivine is needed, equivalent to 80 g olivine/m^2, or 800 kg/ha. For every drop or rise of the pH of the rain by 0.3 units, the amount of olivine to be applied must be doubled, respectively halved. If the pH of the rainwater is 5, weathering of the same amount of olivine will take 300 years.”); *and* Köhler P., Hartmann J., & Wolf-Gladrow D. A. (2010) *Geoengineering potential of artificially enhanced silicate weathering of olivine*, Proc. Natl. Aca'd. Sci. 107(47): 20228–20233, 20228 (“We investigate the potential of a specific geoengineering technique, carbon sequestration by artificially enhanced silicate weathering via the dissolution of olivine. This approach would not only operate against rising temperatures but would also oppose ocean acidification, because it influences the global climate via the carbon cycle. If important details of the marine chemistry are taken into consideration, a new mass ratio of carbon dioxide sequestration per olivine dissolution of about 1 is achieved, 20% smaller than previously assumed. We calculate that this approach has the potential to sequestrate up to 1 Pg of C per year directly, if olivine is distributed as fine powder over land areas of the humid tropics, but this

rate is limited by the saturation concentration of silicic acid. In our calculations for the Amazon and Congo river catchments, a maximum annual dissolution of 1.8 and 0.4 Pg of olivine seems possible, corresponding to the sequestration of 0.5 and 0.1 Pg of C per year, but these upper limit sequestration rates come at the environmental cost of *p*H values in the rivers rising to 8.2.”).

33 Kelland M. E. *et al.* (2020) *Increased yield and CO_2 sequestration potential with the C_4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil*, Glob. Change Biol. 26(6): 3658–3676, 3658 (“Here we report that amending a UK clay-loam agricultural soil with a high loading (10 kg/m^2) of relatively coarse-grained crushed basalt significantly increased the yield (21 ± 9.4%, *SE*) of the important C_4 cereal *Sorghum bicolor* under controlled environmental conditions, without accumulation of potentially toxic trace elements in the seeds. Yield increases resulted from the basalt treatment after 120 days without P- and K-fertilizer addition. Shoot silicon concentrations also increased significantly (26 ± 5.4%, *SE*), with potential benefits for crop resistance to biotic and abiotic stress. Elemental budgets indicate substantial release of base cations important for inorganic carbon removal and their accumulation mainly in the soil exchangeable pools.”); Haque F., Santos R. M., & Chiang Y. W. (2020b) *Optimizing Inorganic Carbon Sequestration and Crop Yield With Wollastonite Soil Amendment in a Microplot Study*, Front. Plant Sci. 11(1012): 1–12, 1 (“The plants were grown with different wollastonite dosages (3-20 kg·m^{-2} for soybean and 3-40 kg·m^{-2} for alfalfa), for a duration of 14 weeks in a microplot experiment in Ontario, Canada.”); *and* Amann T., Hartmann J., Struyf E., de Oliveira Garcia W., Fischer E. K., Janssens I., Meire P., & Schoelynck J. (2020) *Enhanced Weathering and related element fluxes – a cropland mesocosm approach*, Biogeosciences 17(1): 103–119, 103 (“In order to evaluate the efficiency and side effects of Enhanced Weathering (EW), a mesocosm experiment was set up and agricultural soil from Belgium was amended with olivine-bearing dunite ground to two different grain sizes, while distinguishing setups with and without crops.”).

34 Gillman G. P. (1980) *The Effect of Crushed Basalt Scoria on the Cation Exchange Properties of a Highly Weathered Soil*, Soil Sci. Soc. Am. J. 44(3): 465–468, 465 (“ The results suggest that crushed basaltic scoria could be successfully used to prevent cation nutrient losses from highly weathered soils of the tropics.”); *and* Gillman G. P., Burkett D. C., & Coventry R. J. (2002) *Amending highly weathered soils with finely ground basalt rock*, Appl. Geochemistry 17(8): 987–1001, 987 (“Surface (0–10 cm) samples of 7 soils from tropical coastal Queensland were incubated at room temperature and at field capacity with finely ground (<150 μ) basalt rock for 3 months. The amendment was applied at 0, 1, 5, 25 and 50 t/ha to cover situations of moderate application rates to that where the amendment might be banded to produce high local concentrations. Having an abrasion pH of about 9, the amendment was able to reduce both active acidity (as estimated by an increase in soil pH) and reserve acidity (reduction in % Al saturation of the CEC). Increases in soil pH resulted in increased CEC, depending on the variable charge nature of each soil, accompanied by increases in exchangeable Ca, Mg, and K supplied by the basalt. The amounts of basic cations converted to exchangeable form constituted only a fraction of the amounts applied. Thus the cations held in reserve ensure that the effect of cation enrichment will be prolonged.”).

35 Haque F., Santos R. M., Dutta A., Thimmanagari M., & Chiang Y. W. (2019b) *Co-Benefits of Wollastonite Weathering in Agriculture: CO_2 Sequestration and Promoted Plant Growth*, ACS Omega 4(1): 1425–1433, 1425 (“This study investigated the role of plants on enhanced weathering of wollastonite ($CaSiO_3$) in soils. Using rooftop pot experiments with leguminous beans (*Phaseolus vulgaris* L.) and nonleguminous corn (*Zea mays* L.), carbon dioxide sequestration was inferred from total inorganic carbon (TIC) accumulation in the soil and thermogravimetric analysis, and mineral weathering rate was

inferred from alkalinity of soil porewater. Soil amendment with wollastonite promoted enhanced plant growth: beans showed a 177% greater dry biomass weight and corn showed a 59% greater plant height and a 90% greater dry biomass weight."); Kelland M. E. *et al*. (2020) *Increased yield and CO_2 sequestration potential with the C_4 cereal* Sorghum bicolor *cultivated in basaltic rock dust-amended agricultural soil*, GLOB. CHANGE BIOL. 26(6): 3658–76, 3658 ("Land-based enhanced rock weathering (ERW) is a biogeochemical carbon dioxide removal (CDR) strategy aiming to accelerate natural geological processes of carbon sequestration through application of crushed silicate rocks, such as basalt, to croplands and forested landscapes. However, the efficacy of the approach when undertaken with basalt, and its potential co-benefits for agriculture, require experimental and field evaluation. Here we report that amending a UK clay-loam agricultural soil with a high loading (10 kg/m^2) of relatively coarse-grained crushed basalt significantly increased the yield (21 ± 9.4%, *SE*) of the important C_4 cereal *Sorghum bicolor* under controlled environmental conditions, without accumulation of potentially toxic trace elements in the seeds. Yield increases resulted from the basalt treatment after 120 days without P- and K-fertilizer addition."); *and* Wang W., Lai D. Y. F., Abid A. A., Neogi S., Xu X., Wang C., (2018) *Effects of Steel Slag and Biochar Incorporation on Active Soil Organic Carbon Pools in a Subtropical Paddy Field*, AGRONOMY 8(8):135, 1–17, 1 ("Our findings suggest that the addition of steel slag and biochar in subtropical paddy fields could decrease active SOC pools and enhance soil C sequestration only in the early crop, but not the late crop.").

36 For more information on theoretical and empirical evidence for improved crop resistance to stress from silica additions such as crushed basalt, *see* Cocker K. M., Evans D. E., & Hodson M. J., (2002) *The amelioration of aluminium toxicity by silicon in higher plants: Solution chemistry or an in planta mechanism?* PHYSIOLOGIA PLANATARUM (104); Guntzer F., Keller C., Meunier J., (2011) *Benefits of plant silicon for crops: a review* AGRON. SUSTAIN. DEV.; Ali S., Farooq M. A., Yasmeen T., Hussain S., Arif M. S., Abbas F., Bharwana S. A., & Zhang G., (2013) *The influence of silicon on barley growth, photosynthesis and ultra-structure under chromium stress*, ECOTOXICOL. ENVIRON. SAF. 89; *and* Adrees M., Ali S., Rizwan M., Zia-ur-Rehman M., Ibrahim M., Abbas F., Farid M., Qayyum M. F., & Irshad M. K., (2015) *Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: A review*, ECOTOXICOL ENVIRON. SAF. 119.

37 Haque F., Santos R. M., & Chiang Y. W. (2020b) *Optimizing Inorganic Carbon Sequestration and Crop Yield with Wollastonite Soil Amendment in a Microplot Study*, FRONT. PLANT SCI. 11(1012): 1–12, 3–5 ("The highest suitable amendment dosage….could be thought of as the cumulative of several applications over multiple crop cycles…for MSA 10 microplot, root biomass was lower by 14.7%, as compared to the control, and poor root biomass density can be responsible for shorter plant height (18.2%) and lower above-ground biomass dry weight (12.7%).").

38 Gillman G. P., Burkett D. C., & Coventry R. J. (2002) *Amending highly weathered soils with finely ground basalt rock*, APPL. GEOCHEM. 17(8): 987–1001, 981 ("Increases in soil pH resulted in increased CEC, depending on the variable charge nature of each soil, accompanied by increases in exchangeable Ca, Mg, and K supplied by the basalt."); *and* Swoboda P., Döring T. F., & Hamer M. (2022) *Remineralizing soils? The agricultural usage of silicate rock powders: A review*, SCI. TOTAL ENVIRON. 807(150976): 1–18, 13 ("Carbonic acids reacts with silicate minerals, which releases base cations (e.g. Ca^{2+}, Mg^{2}) and forms bicarbonate (HCO_3^-), and to a lesser extent carbonate (CO_3^{2-}) anions, depending on the pH (Beerling et al., 2018; Lefebvre et al., 2019).").

39 Vicca S. *et al.* (2022) *Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes?*, GLOB. CHANGE BIOL. 28(3): 711–726, 712 ("Moreover, in the real world, processes such as secondary mineral formation, soil pore water saturation, and low water-sili-

cate contact rates can substantially slow down weathering rates (Zhang et al., 2018)—as was the case in one of the first ESW mesocosm experiments (Amann et al., 2020). In addition, ESW will almost certainly impact primary production, soil organic carbon (SOC) sequestration, and soil GHG emissions. These impacts will affect the climate change mitigation potential of ESW but have not yet been considered in current calculations.").

40 Strefler J., Amann T., Bauer N., Kriegler E., & Hartmann J. (2018) *Potential and costs of carbon dioxide removal by enhanced weathering of rocks*, Environ. Res. Lett. 13(3): 034010, 1–9, 3 ("Biotic soil processes and high soil carbon dioxide concentration exert a strong influence on the weathering rate [24] but need to be better constrained and can only be discussed qualitatively. Taylor *et al* [5] have shown in an exemplary catchment where their model, which includes biotic processes, is able to reproduce rather fast lab-derived weathering rates [15, 22–25], whereas Brantley [16] calculated rates from an abiotic soil column experiment, that are at least two orders of magnitude lower. A larger experiment supports this finding for abiotic field weathering rates [26], which points towards a general underestimation if biotic processes such as soil respiration are disregarded.").

41 Tittonell B. & Giller K. E., (2013) *When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture*, Field Crops Res. 143: 76–90, 83 ("Farmers recognize the existence of soil fertility gradients. They tend to plant crops earlier and more densely, weed earlier and more frequently, and apply nutrients as fertilisers and manure to the plots that are already more fertile (Tittonell et al., 2005b). Thus the resulting differences in yields are due to gradients of management intensity rather than soil fertility alone (Tittonell et al., 2007b).").

42 Tittonell B. & Giller K. E., (2013) *When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture*, Field Crops Res. 143: 76–90, 84 ("An extra source of complexity that contributes to the existence of niches for technologies (and also to explain yield gaps) within smallholder farms is the diversity of cropping systems in space and time.").

43 Pierzynski G. M., Middendorf B. J., Stewart Z. P., & Prasad P. V. V. (2017) Sub-Saharan Africa Soil Fertility Prioritization Report: I. *Survey Results.* Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification, Kansas State University, 22 ("To overcome the identified biophysical barriers, respondents for East Africa recommended the need for regional, well-equipped soil analysis labs and/or mobile testing equipment that can provide affordable, research based, and regionally specific recommendations to farmers.").

44 Fabegas R., Kremer M., Robinson J., & Schilbach F. (2019) *The Value of Local Agricultural Information: Evidence from Kenya*, The Agricultural Technology Adoption Initiative, 1–37, 2 ("Soil tests to determine suitable fertilizer types for a given area are rarely used, and most small-scale farmers have never experimented with inputs using on-farm trials with appropriate comparison plots. While the private benefits arising from such experimentation might be lower than the costs of creating this information, the social benefits may be sufficiently large to outweigh the costs of producing this knowledge if the information is spatially correlated and could be shared among neighbors. Therefore, while soil tests and experimental plots might be too expensive and impractical to be implemented on everyone's farms, testing soils for some farmers in the area and sharing these results with neighboring farmers could be valuable.").

45 Centre for Agriculture and Bioscience International (20 Dec. 2021) *New project aims to review and help strengthen national Soil Information Systems*, CABI News ("CABI has been awarded a $1.07 million contract from the Bill & Melinda Gates Foundation to lead a comprehensive study of national Soil Infor-

mation Systems (SIS) in several countries including India, Rwanda, Ethiopia, Tanzania also capturing learning from the USA, UK, countries within the European Union, Australia, New Zealand, Brazil, and Bangladesh.").

46 McBratney A. B., Minasny B., & Viscarra Rossel R. (2006) *Spectral soil analysis and inference systems: A powerful combination for solving the soil data crisis*, GEODERMA, 136(1–2): 272–278 ("Several physical, chemical, and biological properties can be predicted from the diffuse reflectance spectra of soil. Soil spectroscopy, in the visible, near-infrared and mid-infrared range (Vis–NIR–MIR) of the electromagnetic spectrum, coupled with robust multivariate calibration (e.g. Partial Least Squares Regression, PLSR) have created new opportunities for soil measurement in land resource survey (Janik and Skjemstad, 1995; McCarty et al., 2002; Viscarra Rossel et al., 2006). The method provides another form of PTF whereby latent predictor variables are derived from the spectra.").

47 *See* Sulzberger E., Harris T., & Shepherd K. (6 Oct 2016) *Scientists use technology to shine a light on Africa's farms*, AFRICA SOIL INFORMATION SERVICE.

48 Sanchez P. A., *et al.* (2009) *Digital Soil Map of the World*, SCIENCE, 325(5941): 680–681 ("We call for development of a freely accessible, Webbased digital soil map of the world that will make georeferenced soil information readily available for land-users, scientists, and policy-makers.").

49 Bullock L. A., James R. H., Matter J., Renforth P., & Teagle D. A. H. (2021) *Global Carbon Dioxide Removal Potential of Waste Materials From Metal and Diamond Mining*, FRONT. CLIM. 3 694175, 1–12, 1 ("The global mining industry produces huge volumes of fine wastes that could be utilised as feedstock for enhanced weathering. We have compiled a global database of the enhanced weathering potential of mined metal and diamond commodity tailings from silicate-hosted deposits. Our data indicate that all deposit types, notably mafic and ultramafic rock-hosted operations and high tonnage Cu-hosting deposits, have the potential to capture ~1.1–4.5 Gt carbon dioxide annually, between 31 and 125% of the industry's primary emissions.").

50 Goll D. S., Ciais P., Amann T., Buermann W., Chang J., Eker S., Hartmann J., Janssens I., Li W., Obersteiner M., Penuelas J., Tanaka K., & Vicca S. (2021) *Potential carbon dioxide removal from enhanced weathering by ecosystem responses to powdered rock*, NATURE GEOSCI. 14(8): 545–549, 547, ("Third, extracting basalt and applying BD at a large scale would provide a new market for the mining industry currently suffering overcapacity and the accumulating overburden material[18]. Basalt mining could also replace jobs in the declining coal mining sector, facilitating just transitions towards renewable energy[46]. Last, a mix of basalt and waste products such as phosphate gypsum and alkaline industrial waste (for example, steel slag or concrete from demolition[7]) could be used—following the idea of the inevitability of a transition towards a regenerative circular economy (as acknowledged by China, Japan, Canada and the European Union[47]).").

51 Hangx S. J. T. & Spiers C. J. (2009) *Coastal spreading of olivine to control atmospheric carbon dioxide concentrations: A critical analysis of viability*, INT. J. GREENH. GAS CONTROL 3(6): 757–767, 764 ("Similarly, at a grain size of d_0 of 100 μm or 10 μm it would take 230 and 23 years, respectively (see also Section 4). To achieve a steady state emissions rate offset of 30% in 15 years (i.e. by 2024) at 25 °C, Eq. (6) shows a grain size of approximately 6 μm would be required. Since the instantaneous rate of olivine consumption scales linearly with supply rate (Eq. (5)), using olivine grain sizes greater than ~6 μm would require proportionally larger supplies of olivine (>5.0 Gt/year), to achieve the same offset in atmospheric carbon dioxide concentrations in the same time."); Strefler J., Amann T., Bauer N., Kriegler E., & Hartmann J. (2018) *Potential and costs of carbon dioxide removal by enhanced weathering of rocks*,

Environ. Res. Lett. 13(3): 034010, 1–9, 5, Figure 3B; *and* Rinder T. & von Hagke C. (2021) *The influence of particle size on the potential of enhanced basalt weathering for carbon dioxide removal - Insights from a regional assessment*, J. Clean. Prod. 315 128178, 1–13, 1 ("With this in mind, this article reviews of the current state of research and estimates the carbon dioxide drawdown for scenarios using basalt powders of different particle size distribution (<100 μm, <10 μm and <1 μm). Calculated with a modified shrinking core model, the amount of powder dissolved within a timeframe of 10 years is approximately 16% (<100 μm), 55% (<10 μm) and 99.9% (<1 μm). This corresponds to a gross carbon dioxide removal of 0.045 t carbon dioxide t^{-1} of rock (<100 μm) and 0.153 t carbon dioxide t^{-1} of rock, (<10 μm). We evaluate our results on regional scale through a case study for Austria, including emissions from mining, comminution, application and transport. Assuming an average distance of 300 km from mine to field, the net carbon dioxide drawdown decreases to approximately 0.027 t carbon dioxide t^{-1} of rock (<100 μm) or 0.096 t carbon dioxide t^{-1} (<10 μm), when rail transport is used. For truck transport, the numbers are reduced to −0.030 t carbon dioxide t^{-1} of rock (<100 μm) or 0.039 t carbon dioxide t^{-1}(<10 μm), respectively. Accordingly, at the current carbon dioxide intensity, transport related emissions may cancel out any drawdown if grain sizes (<100 μm) are used. Our estimates suggest that enhanced weathering will only significantly contribute to net carbon dioxide drawdown if grain sizes (<10 μm) are used. Under these conditions the large-scale application of particles with a diameter <10 μm may remove about 2% of Austria's annual Greenhouse gas emissions.").

52 Hangx S. J. T. & Spiers C. J. (2009) *Coastal spreading of olivine to control atmospheric carbon dioxide concentrations: A critical analysis of viability*, Int. J. Greenh. Gas Control 3(6): 757–767, 757 ("To accelerate them to rates appropriate for an industrial process, the rock or mineral feedstock must be crushed to a fine grain size (high surface area) (Gerdemann et al., 2002, Gerdemann et al., 2007, Kakizawa et al., 2001, Kojima et al., 1997, O'Connor et al., 2000a) or pre-treated with large quantities of acid (Goff and Lackner, 1998, Haywood et al., 2001, Kakizawa et al., 2001). In addition, temperature and carbon dioxide pressures of 100–185 °C and 4–15 MPa are needed for optimum results (Gerdemann et al., 2007). The associated energy consumption, environmental impact and costs are therefore high and have placed industrial mineralisation low on the list of CCS options (Huijgen et al., 2006)."); *and* Goll D. S., Ciais P., Amann T., Buermann W., Chang J., Eker S., Hartmann J., Janssens I., Li W., Obersteiner M., Penuelas J., Tanaka K., & Vicca S. (2021) *Potential carbon dioxide removal from enhanced weathering by ecosystem responses to powdered rock*, Nature Geosci. 14(8): 545–549, Cost Analysis ("Dust is either mixed with water in a ratio of 1:5 (ref.[32]) or used as free-flowing particles (size > 500 μm)[33]. We calculate the costs based on present-day costs compiled by refs.[7,50,21]. These estimated costs account for uncertainties with respect to energy costs, airborne application and variation between open-pit mines.").

53 Hangx S. J. T. & Spiers C. J. (2009) *Coastal spreading of olivine to control atmospheric carbon dioxide concentrations: A critical analysis of viability*, Int. J. Greenh. Gas Con. 3(6): 757–767, 765 ("Moreover, it should not be forgotten that finely crushed olivine rock might very well pose a (wind-born) health risk, especially if the material contains fibrous serpentine minerals (asbestos), which it often does.").

54 *See* Gillman G. P., Burkett D. C., & Coventry R. J. (2002) *Amending highly weathered soils with finely ground basalt rock*, Appl. Geochem. 17(8): 987–1001.

55 Köhler P., Hartmann J., & Wolf-Gladrow D. A. (2010) *Geoengineering potential of artificially enhanced silicate weathering of olivine*, Proc. Natl. Acad. Sci. 107(47): 20228–20233, 20230, ("In addition, transport decreases the net efficiency by 2.4%, 1.6%, and 11% per 1,000 km of transport for inland and coastal ships, freight trains, and trucks, respectively (22, 35). Fortunately, suitable dunite complexes for mining of olivine are located in the humid tropical regions, to allow relatively short ways for the transport of

olivine powder to application sites (Fig. 2). Thus, the carbon dioxide net efficiency of olivine dissolution for applications within 1,000 km of mines can be 93%. Costs for mining and grinding are estimated (22) to be €10 per tonne of sequestered carbon dioxide (€37 per tonne of C). Taking into account costs for applications (36), total costs might be in the range of €20–40 per tonne of carbon dioxide sequestered (or €70–150 per tonne of C). These costs may be compensated by carbon dioxide-emission–certificate trade (37).”); Taylor L. L., Quirk J., Thorley R. M. S., Kharecha P. A., Hansen J., Ridgwell A., Lomas M. R., Banwart S. A., & Beerling D. J. (2016) *Enhanced weathering strategies for stabilizing climate and averting ocean acidification*, Nature Clim. Change 6(4): 402–406, 406 (“Estimated implementation costs (combined capital and operational) for achieving an initial 50 ppm drawdown of atmospheric carbon dioxide are $60–600 trillion for mining, grinding and transportation, assuming no technological innovation, with similar associated additional costs for distribution (Supplementary Information).”); *and* Fuss S. *et al.* (2018) *Negative emissions—Part 2: Costs, potentials and side effects*, Environ. Res. Lett. 13(6): 063002, 1–47, 33 (“Enhanced weathering is a relatively expensive option due to the high energy requirements for grinding the minerals to sufficiently small size. Hence, carbon prices of US$50 and more are required if larger deployments are to be reached, with prices progressively increasing as proximate mining and deployment locations are exhausted.”).

56 Van Straaten P. (2006) *Farming with rocks and minerals: challenges and opportunities*, An. Acad. Bras. Ciênc. 78(4): 731–747, 738 (“Since peanuts (*Arachis hypogaea*) often show low yields on calcareous soils due to a lack of iron (Fe-chlorosis) Barak et al. (1983) tested the application of ground Fe-rich basaltic rocks and lapilli tuffs, by-products of local quarrying operations, on calcareous soils. The results show significantly improved iron nutrition, chlorophyll production and growth of peanuts upon application of these Fe-rich volcanic rock fertilizers.”).

57 Karlan D., Osei R., Osei-Akoto I., & Udry C. (2014) *Agricultural Decisions after Relaxing Credit and Risk Constraints**, Q. J. Econ. 129(2): 597–652, 600 (“We find strong responses of agricultural investment to the rainfall insurance grant, but relatively small effects of the cash grants. We consider both results striking. Our main result is that uninsured risk is a binding constraint on farmer investment: when provided with insurance against the primary catastrophic risk they face, farmers are able to find resources to increase expenditure on their farms. This result is important in two dimensions. First, it demonstrates the direct importance of risk in hindering investment. Second, the fact that farmers came up with resources to increase investment merely as a consequence of getting rainfall insurance shows that liquidity constraints are not as binding as typically thought.[4]”).

58 Dar M. H., de Janvry A., Emerick K., Sadoulet E., & Wiseman E. (2021) *Private Input Suppliers as Information Agents for Technology Adoption in Agriculture*, UC Berkeley: Center for Effective Global Action, 1–56, 24 (“We find that informing private agrodealers about a new and profitable seed variety, and giving them small amounts of demonstration seeds to test, causes farm-level adoption to increase by over 50 percent, compared to the business-as-usual approach where government workers focus on outreach with selected farmers. Using the private-sector approach increases adoption most among farmers with higher expected benefits from the technology. This improvement in targeting suggests that there is an alignment of incentives between dealers and farmers: dealers benefit in some way from inducing farmers to adopt the right technology. We also found that our treatment triggers a supply response. It causes dealers to be more likely to keep the seed in stock and it increases local production of the seed.”).

59 Liverpool-Tasie L. S. O., Wineman A., Young S., Tambo J., Vargas C., Reardon T., Adjognon G. S., Porciello J., Gathoni N., Bizikova L., Galiè A., & Celestin A. (2020) *A scoping review of market links between value chain actors and small-scale producers in developing regions*, Nat. Sustain 3, 799–808,

801 ("Finding that SME value chain actors provide complementary services shifts the debate on their role in markets. These findings show that SMEs directly improve the market context for small-scale producers and promote inclusion, while such improvements were previously attributed mostly to large companies using contract arrangements. Thus, SMEs (which are more accessible to small-scale producers than are formal contract arrangements) play an important role in facilitating inclusive growth as food systems transform in developing regions.").

60 Sones K. R., Oduor G. I., Watiti J. W., & Romney D. (2015) *Communicating with smallholder farming families - a review with a focus on agro-dealers and youth as intermediaries in sub-Saharan Africa*, CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 1–6, 4 ("Due to the limited number of extension workers in African countries, local agro-dealers are often farmers' primary points of contact for both agro-inputs and technical farming advice.").

61 Rinder T. & von Hagke C. (2021) *The influence of particle size on the potential of enhanced basalt weathering for carbon dioxide removal - Insights from a regional assessment*, J. Clean. Prod. 315 128178, 1–13, 1 ("We evaluate our results on regional scale through a case study for Austria, including emissions from mining, comminution, application and transport. Assuming an average distance of 300 km from mine to field, the net carbon dioxide drawdown decreases to approximately 0.027 t carbon dioxide t^{-1} of rock (<100 μm) or 0.096 t carbon dioxide t^{-1} (<10 μm), when rail transport is used. For truck transport, the numbers are reduced to −0.030 t carbon dioxide t^{-1} of rock (<100 μm) or 0.039 t carbon dioxide t^{-1} (<10 μm), respectively. Accordingly, at the current carbon dioxide intensity, transport related emissions may cancel out any drawdown if grain sizes (<100 μm) are used.)").

62 Swoboda P., Döring T. F., & Hamer M. (2022) *Remineralizing soils? The agricultural usage of silicate rock powders: A review*, Sci. Total Environ. 807 150976, 1–15, 14 ("The current evidence suggests that the agronomic effectiveness is highest when SRPs are obtained as fine-grained mining residues normally low or free of charge and close to the site of application, which could simultaneously resolve a serious disposal challenge of the global mining industry.").

63 Food and Agriculture Organization of the United Nations (2013) *Smallholders and Family Farmers*, Fact Sheet, 21 ("Smallholders are small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares. Smallholders are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption.").

64 Food and Agriculture Organization of the United Nations (23 Apr. 2021) *Small family farmers produce a third of the world's food* ("Five of every six farms in the world consist of less than two hectares, operate only around 12 percent of all agricultural land, and produce roughly 35 percent of the world's food, according to a study published in World Development.").

65 The primary author of this piece, Boudinot F. G., has tested Monty's Plant Food basalt-based amendment at 30 pounds per acre.

66 Peters S. C., Blum J. D., Driscoll C. T., & Likens G. E. (2004) *Dissolution of wollastonite during the experimental manipulation of Hubbard Brook Watershed 1*, Biogeochem. 67(3): 309–329, 310 "…Ca was applied by helicopter to the watershed forest floor in the form of the mineral wollastonite."); *and* Goll D. S., Ciais P., Amann T., Buermann W., Chang J., Eker S., Hartmann J., Janssens I., Li W., Obersteiner M., Penuelas J., Tanaka K., & Vicca S. (2021) *Potential carbon dioxide removal from enhanced weathering by ecosystem responses to powdered rock*, Nature Geosci. 14(8): 545–549, 546 ("Under the conservative

assumption of no technological innovation, we derived a supply cost curve for CDR by BD applied by helicopters or fixed-wing aircraft equipped with agricultural spreaders[31,32,33,34] that are used to spread basalt in the form of free-flowing dust[34] or slurry[33] and have low requirements for ground infrastructure. Modified large aerial tankers such as those currently used for firefighting have >10 times the range and carrying capacities of small aircraft and could provide means to spray dust on large areas.”).

67 Haque F., Santos R. M., & Chiang Y. W., (2020a) *CO_2 Sequestration by wollastonite- amended agricultural soils – An Ontario field study*, Int. J. Greenh. Gas Control 97, 103017, 1–13, 2 (“Wollastonite, with a coarse texture, was added every Fall (August) as an alternate liming agent, and the soil was worked in 6–7 inches.”); *and* Kelland M. E. *et al.* (2020) *Increased yield and CO_2 sequestration potential with the C_4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil*, Glob. Change Biol. 26(6): 3658–3676, 3660 (“Well-characterized crushed basalt (see Section 2.6; total mass of 181.5 ± 0.5 g per column; equivalent to 10 kg/m^2) from a typical volcanic arc mountain in the Cascade Range, Oregon, United States, was mixed with soil in the upper 250 mm of the treated columns (*n* = 6) to simulate plough layer mixing depth.”).

68 Leonardo W. J., van de Ven G. W. J., Udo H., Kanellopoulos A., Sitoe A., & Giller K. E. (2015) *Labour not land constrains agricultural production and food self-sufficiency in maize-based smallholder farming systems in Mozambique*, Food Sec. 7(4): 857–874, 857 (“Our results showed that production can be increased based on current agricultural practices. Farmers did not cultivate all of their land, suggesting that lack of labour constrained intensification by smallholder farmers.”).

69 Freeman H. A. & Omiti, J. M. (2003) *Fertilizer use in semi-arid areas of Kenya: analysis of smallholder farmers’ adoption behavior under liberalized markets*, Nutr. Cycl. Agroecosys. 66(1): 23–31, 23 (“This paper analyzes the factors influencing farm level fertilizer adoption decisions under an era of liberalized markets in Kenya using a Tobit regression model. The level of education of the household head, experience using fertilizer, growing a cash crop, availability of fertilizer in rural retail outlets, availability in small packages, and land pressure positively influenced fertilizer use, while the size of family labor and location in the drier semi-arid zone were negatively associated with fertilizer use.”).

70 Murray U., Gebremedhin Z., Brychkova G., & Spillane C. (2016) *Smallholder Farmers and Climate Smart Agriculture: Technology and Labor-productivity Constraints amongst Women Smallholders in Malawi*, Gend. Technol. Dev. 20(2): 117–148, 119 (“Insufficient labor, poor supervision of labor, and family responsibilities are constraints for smallholder farmers. Women’s labor is also constrained because of their unpaid work in the care economy, which can vary over their life (*e.g.,* prior to childbirth, childcare, or caring for the elderly) (Peterman, Quisumbing, Behrman, & Nkonya, 2010).”).

71 Haque F., Santos R. M., & Chiang Y. W. (2020b) *Optimizing Inorganic Carbon Sequestration and Crop Yield with Wollastonite Soil Amendment in a Microplot Study*, Front. Plant Sci. 11(1012): 1–12, 5 (“The 5 wt.% wollastonite-amended soil showed the highest soybean yield (twofold greater), as seen in Figure 3 and Figure S5. The yield decreased for the 7.5 and 10 wt.% MSA microplots.”).

72 Nyongesa J. M., Bett H. K., Lagat J. K., & Ayuya O. I. (2016) *Estimating farmers’ stated willingness to accept pay for ecosystem services: case of Lake Naivasha watershed Payment for Ecosystem Services scheme-Kenya*, Ecol. Process, 5(1): 15, 1–15, 12 (“Our study results demonstrate that different PES interventions can be applied as alternative sustainable farm practices to mitigate watershed negative externalities. We have shown that most farmers are willing to continue participating in PES scheme and

are willing to accept pay as incentive in monetary form to implement PES farm practices relative to the current flat rate pay of Kshs. 1700 (US$17) to mitigate degradation on their agricultural lands.").

73 International Institute for Environment and Development *Markets and payments for environmental services* ("But the insecure land and resource tenure of many poor people remains a key obstacle to them participating in and benefiting from PES schemes. Other obstacles many PES schemes face are the complex and often bureaucratic project procedures and high project transaction costs.").

74 Amann T. & Hartmann J. (2022) *Carbon Accounting for Enhanced Weathering*, FRONT. CLIM. 4 849948, 1–9, 1 ("The observed strong correlation of alkalinity with electrical conductivity could be harnessed and enable a carbon dioxide uptake monitoring by simple electrical conductivity measurements in soils or any point in the discharge system. For a successful implementation and calibration, data are needed, covering the most likely employment scenarios of soil, climate, hydrology, rock product, application scenario and plant abundance. Incorporated in a growing public database, this could be used as an assessment and benchmark system for future EW deployment.").

75 Kanzaki Y., Zhang S., Planavsky N. J., & Reinhard C. T. (2022) *Soil Cycles of Elements simulator for Predicting TERrestrial regulation of greenhouse gases: SCEPTER v0.9*, GEOSCI. MODEL DEV. 15(12): 4959–4990, 4959 ("Enhanced rock weathering (ERW) on croplands and hinterlands may be one of the most economically and ecologically effective ways to sequester carbon dioxide from the atmosphere, given that these soil environments generally favor mineral dissolution and because amending soils with crushed rock can result in a number of co-benefits to plant growth and crop yield. However, robust quantitative evaluation of carbon dioxide capture by ERW in terrestrial soil systems that can lead to coherent policy implementation will require an ensemble of traceable mechanistic models that are optimized for simulating ERW in managed systems. Here, we present a new 1D reactive transport model – SCEPTER. The model is designed to (1) mechanistically simulate natural weathering, including dissolution/precipitation of minerals along with uplift/erosion of solid phases, advection plus diffusion of aqueous phases and diffusion of gas phases, (2) allow targeted addition of solid phases at the soil–atmosphere interface, including multiple forms of organic matter (OM) and crushed mineral/rock feedstocks, (3) implement a range of soil mixing regimes as catalyzed by soil surface fauna (*e.g.* bioturbation) or humans (*e.g.,* various forms of tilling), and (4) enable calculation of solid mineral surface area based on controlled initial particle size distributions coupled to a shrinking core framework.").

76 Chay F., Klitzke J., Hausfather Z., Martin K., Freeman J., & Cullenward D. (19 Sept 2022) *Verification Confidence Levels for carbon dioxide removal* CARBONPLAN ("The growth and integrity of permanent carbon dioxide removal (CDR) will require developing robust approaches to measurement, reporting, and verification (MRV).[1]1The acronym MRV can also be defined as "monitoring, reporting, and verification." Some also refer to MMRV, "measurement, monitoring, reporting, and verification." High-quality MRV should produce trustworthy, quantitative estimates of real-world outcomes, and communicate those findings and the methods underlying them in a consistent and transparent manner.").

77 Jin Z., Azzari G., Burke M., Aston S., & Lobell D. (2017) *Mapping Smallholder Yield Heterogeneity at Multiple Scales in Eastern Africa*, REMOTE SENSING 9(9): 931, 1–15, 1 ("We identified the prevalence of small field sizes, intercropping management, and cloudy satellite images as major challenges to improve the model performance. Overall, this study suggested that high-resolution satellite imagery can be used to map yields of smallholder farming systems, and the methodology presented in this study could serve as a good foundation for other smallholder farming systems in the world.").

78 For more on developing carbon offset methodologies for ERW application, *see* Verra (20 July 2022) *RFP: Technical Experts on Enhanced Weathering*; *and* Puro.earth (30 Sept 2022) *Enhanced Rock Weathering in Soil Methodology*.

79 Badgley G., Freeman J., Hamman J., Haya B., Trugman A., Anderegg W. R. L., & Cullenward D. (29 Aug 2022) *Systematic over-crediting of forest offsets* CarbonPlan ("Our analysis of crediting errors demonstrates that a large fraction of the credits in the program do not reflect real climate benefits. The scale of the problem is enormous: 29% of the offsets we analyzed are over-credited, totaling 30 million tCO_2e worth approximately $410 million.").

80 Kantola I. B., Masters M. D., Beerling D. J., Long S. P., & DeLucia E. H. (2017) *Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering*, Biol. Lett. 13(4): 20160714, 1–7, 1 ("Uncertainties remain in the long-term effects and global implications of large-scale efforts to directly manipulate Earth's atmospheric carbon dioxide composition, but EW in agricultural lands is an opportunity to employ these soils to sequester atmospheric C while benefitting crop production and the global climate."); *and* Beerling D. J. *et al.* (2018) *Farming with crops and rocks to address global climate, food and soil security*, Nature Plants 4(3): 138–147, 145 ("We conclude that substituting a weatherable silicate rock (such as basalt) or silicate waste for limestone and increasing application rates over those used in conventional liming operations may offer a pragmatic, rapidly deployable global carbon cycle intervention strategy. More broadly, if proven effective, and undertaken carefully to minimize undesirable impacts, enhanced weathering may have untapped potential for addressing the United Nations Sustainable Development Goals (SDGs) adopted by 193 countries in 2015[111]. For example, sequestering carbon dioxide constitutes action on climate change (SDG 13), restoring soils and promoting sustainable agriculture contributes to zero hunger (SDG 2), helping protect the oceans from acidification conserves global resources in life below water (SDG 14), reducing agrochemical usage and recycling wastes helps with sustainable consumption and production (SDG 12) and improving agricultural production and restoring degraded soils contributes to land sparing (SDG 15) (Fig. 4). However, there is an urgent need to address unanswered technical and social questions and develop rigorous audited testing in the field where the full elemental cycles can be closed, the efficacy of carbon dioxide capture quantified and the risks, benefits, socio-economics, techno-economics and ethics assessed (Table 1)."); *and* De Sy V., Herold M., Achard F., Avitabile V., Baccini A., Carter S., Clevers J. G. P. W., Lindquist E., Pereira M., & Verchot L. (2019) *Tropical deforestation drivers and associated carbon emission factors derived from remote sensing data*, Environ. Res. Lett. 14(9): 094022, 1–14, 1 ("In Latin America, pasture was the most common follow-up land use [to deforestation] (72%), with large-scale cropland (11%) a distant second. In Africa deforestation was often followed by small-scale cropping (61%) with a smaller role for pasture (15%). In Asia, small-scale cropland was the dominant agricultural follow-up land use…").

81 Gifford L. (2020) *"You can't value what you can't measure": a critical look at forest carbon accounting*, Climatic Change 161(2): 291–306, 295 ("There are challenges in turning complex, biodiverse forests into simple numerations. For carbon markets to work, multiple forms of carbon must be made commensurate so they can be traded or exchanged…Commensuration poses challenges, and is not a straightforward process.").

82 *See* Amiotte Suchet P., Probst J.-L., & Ludwig W. (2003) *Worldwide distribution of continental rock lithology: Implications for the atmospheric/soil CO_2 uptake by continental weathering and alkalinity river transport to the oceans*, Glob. Biogeochem. Cycl. 17(2): 17-1–17-13.

83 Strefler J., Amann T., Bauer N., Kriegler E., & Hartmann J. (2018) *Potential and costs of carbon dioxide removal by enhanced weathering of rocks*, ENVIRON. RES. LETT. 13(3): 034010, 1–9, 5 ("The main economic cost factors for EW are mining, crushing, and grinding of rocks, and transport to and distribution on crop fields. Only one of these factors, the cost for rock grinding, depends on the required grain size.").

84 Strefler J., Amann T., Bauer N., Kriegler E., & Hartmann J. (2018) *Potential and costs of carbon dioxide removal by enhanced weathering of rocks*, ENVIRON. RES. LETT. 13(3): 034010, 1–9, 5 ("The main economic cost factors for EW are mining, crushing, and grinding of rocks, and transport to and distribution on crop fields. Only one of these factors, the cost for rock grinding, depends on the required grain size.").

85 Hangx S. J. T. & Spiers C. J. (2009) *Coastal spreading of olivine to control atmospheric carbon dioxide concentrations: A critical analysis of viability*, INT. J. GREENH. GAS CON. 3(6): 757–767, 757 ("To obtain useful, steady state carbon dioxide uptake rates within 15–20 years requires grain sizes <10 µm. However, the preparation and movement of the required material poses major economic, infrastructural and public health questions."); *and* Lefebvre D., Goglio P., Williams A., Manning D. A. C., de Azevedo A. C., Bergmann M., Meersmans J., & Smith P. (2019) *Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil*, J. CLEAN PROD. 233, 468–481, 468 ("Our results show that enhanced weathering and carbonation respectively emit around 75 and 135 kg carbon dioxide equivalent per tonne of carbon dioxide equivalent removed (considering a quarry to field distance of 65 km). We underline transportation as the principal process negatively affecting the practice and uncover a limiting road travel distance from the quarry to the field of 540 ± 65 km for carbonation and 990 ± 116 km for enhanced weathering, above which the emissions offset the potential capture.").

86 Beerling D. J. *et al.* (2020) *Potential for large-scale carbon dioxide removal via enhanced rock weathering with croplands*, NATURE 583(7815): 242–248, 243 ("Recognizing the urgent need to assess large-scale options for meeting near-term CDR goals[10], we determine the potential contribution of nations to achieve CDR goals across the 0.5–2 Gt carbon dioxide yr^{-1} range (Table 1; Extended Data Fig. 3). Overall, we find that the three countries with the highest CDR potential are coincidentally the highest fossil fuel carbon dioxide emitters (China, USA and India)[6] (Fig. 1). Indonesia and Brazil, with carbon dioxide emissions 10–20 times lower than the USA and China, have relatively high CDR potential owing to their extensive agricultural lands and warm, seasonally wet climates conducive to high silicate rock weathering efficiency.").

87 Haque F., Santos R. M., & Chiang Y. W. (2020b) *Optimizing Inorganic Carbon Sequestration and Crop Yield with Wollastonite Soil Amendment in a Microplot Study*, FRONT. PLANT SCI. 11(1012): 1–12 ("The 5 wt.% wollastonite-amended soil showed the highest soybean yield (twofold greater), as seen in Figure 3 and Figure S5. The yield decreased for the 7.5 and 10 wt.% MSA microplots.").

88 Haque F., Chiang Y. W., & Santos R. M. (2020) *Risk assessment of Ni, Cr, and Si release from alkaline minerals during enhanced weathering*, OPEN AGRIC. 5(1): 166–175, 165 ("The main findings of this study indicate the potential release of Ni, Cr, and Si to exceed the soil quality guideline value.").

89 Alengebawy A., Abdelkhalek S. T., Qureshi S. R., & Wang M., (2021) *Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications*, TOXICS 9, 42 1–33, 19 ("People working at or around factories that use these metals and their compounds are at

high risk…Recently, the effect of these toxic substances on human health is an intense concern due to ubiquity of exposure.”).

90 Alengebawy A., Abdelkhalek S. T., Qureshi S. R., & Wang M., (2021) *Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications*, Toxics 9, 42 1–33, 23 (“Heavy metals and pesticides cause deleterious implications for human health. Different body organs can be affected along with body systems. Heavy metals toxicity causes serious problems for children and adults by ingestion, inhalation, and dermal adsorption. The harmful health implications of heavy metals can be concluded as neurodegenerative disorders, musculoskeletal diseases, and reproductive hormonal imbalance.”).

PxD PRECISION DEVELOPMENT

IGSD