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Methods for determining the CO_2 removal capacity of enhanced weathering in agronomic settings

Maya Almaraz[1]*, Nina L. Bingham[1], Iris O. Holzer[2], Emily K. Geoghegan[2], Heath Goertzen[1], Jaeeun Sohng[2] and Benjamin Z. Houlton[3]

[1]Institute of the Environment, University of California, Davis, Davis, CA, United States, [2]Department of Land, Air and Water Resources, University of California, Davis, Davis, CA, United States, [3]Department of Global Development and Department of Ecology and Evolutionary Biology, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, United States

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EDITED BY
Sara Vicca,
University of Antwerp, Belgium

REVIEWED BY
Patrick Frings,
GFZ German Research Centre for Geosciences, Germany
Jonathan Sanderman,
Woodwell Climate Research Center, United States

*CORRESPONDENCE
Maya Almaraz
almaraz@ucdavis.edu

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Recent analysis by the IPCC suggests that, across an array of scenarios, both GHG emissions reductions and various degrees of carbon removal will be required to achieve climate stabilization at a level that avoids the most dangerous climate changes in the future. Among a large number of options in the realm of natural climate solutions, atmospheric carbon dioxide removal (CDR) *via* enhanced silicate weathering (EW) in global working lands could, in theory, achieve billions of tons of CO_2 removal each year. Despite such potential, however, scientific verification and field testing of this technology are still in need of significant advancement. Increasing the number of EW field trials can be aided by formal presentation of effective study designs and methodological approaches to quantifying CO_2 removal. In particular, EW studies in working lands require interdisciplinary "convergence" research that links low temperature geochemistry and agronomy. Here, drawing on geologic and agronomic literature, as well as demonstration-scale research on quantifying EW, we provide an overview of (1) existing literature on EW experimentation as a CO_2 removal technique, (2) agronomic and geologic approaches to studying EW in field settings, (3) the scientific bases and tradeoffs behind various techniques for quantifying CO_2 removal and other relevant methodologies, and (4) the attributes of effective stakeholder engagement for translating scientific research in action. In doing so, we provide a guide for establishing interdisciplinary EW field trials, thereby advancing the verification of atmospheric CO_2 in working lands through the convergence of geochemistry and agronomy.

KEYWORDS
enhanced weathering, field study, methods, soil carbon sequestration, agriculture, working lands

Introduction

Natural climate solutions (NCS) center on improved land management techniques to remove carbon (C) from the atmosphere in the near-term and, depending on the approach, can retain C for decades to millennia. Enhanced weathering (EW; the application of pulverized silicate rock to soils) is an NCS that has been proposed to capture 1–2 billion metric tons of CO_2 from the atmosphere per year by 2100, storing it as either as calcium carbonate in soil or bicarbonate in soil pore water, which can eventually leach to the ocean through groundwater and rivers (Beerling et al., 2018). Enhanced weathering has been suggested across a wide variety of land systems, including forests, coasts, and working lands (i.e., croplands and rangelands; Schuiling and Krijgsman, 2006; Meysman and Montserrat, 2017; Beerling et al., 2018). Working lands are particularly appealing for EW applications because they are already highly managed, widely distributed across the globe, and may experience co-benefits for crop production from EW (Beerling et al., 2018). Applying novel technologies like EW to agricultural systems requires a blending of scientific knowledge from geology and agronomy, two disciplines which do not interact strongly in many field studies. While EW in working lands has garnered much attention in the literature, few field studies of EW efficacy exist; rather, most of our existing knowledge on EW and carbon dioxide removal (CDR) is sourced from examinations of natural silicate weathering coupled with small scale laboratory or mesocosm studies, which are then scaled into global models. Verification of CDR rates and other co-benefits of EW across climates, crop types, soil types, and management practices will require a dramatic increase in field studies to understand and optimize this NCS (e.g., Haque et al., 2020).

Enhanced weathering accelerates the natural geologic processes by which water and carbonic acid chemically weather silicate rocks. As part of these reactions, atmospheric CO_2 dissolves into water as carbonic acid, reacts with silicate minerals, and forms bicarbonate, calcium carbonate or other secondary minerals. While silicate weathering helps to stabilize atmospheric CO_2 levels over million-year time scales, it is too slow to reduce the pace of modern climate change. By contrast, the purposeful crushing and shattering of silicate rocks to create high surface areas can be applied to soils to greatly accelerate the natural weathering reaction kinetics and the concomitant CO_2 removal process. The mechanisms by which geologic materials sequester C have been widely studied in laboratory settings and in natural ecosystem field studies (Gaillardet et al., 1999; Dupré et al., 2003; Ibarra et al., 2016); however, the efficacy that smaller rock sizes generated for use in EW have on weathering kinetics and CO_2 removal rates are largely untested at large (acre to multi-acre) scales or in agronomic settings (Beerling et al., 2020). Instead, global models, estimates of EW, weathering kinetics, and reaction products have relied on mesocosm studies, often in greenhouses or growth chambers (Ten Berge et al., 2012; Amann et al., 2020). This is a major barrier to understanding the realized potential for EW as an NCS and deployment of the technology with confidence.

Working lands have the potential to remove CO_2 through the application of rock dust. Given that cropland and pastures span 38% of the global land surface, small management changes may have large impacts on the climate when scaled up (Beerling et al., 2018; Food Agriculture Organization of the United Nations, 2020). Because working lands, particularly croplands, are already highly managed, EW does not pose the same risks to biodiversity as in natural ecosystems. Most industrialized farms already have or use spreading equipment required for silicate rock applications and are familiar with spreading practices, which are similar to applying lime, fertilizer, or other soil amendments. Furthermore, silicate rocks are abundant and globally common–roughly 90% of Earth's crust is made up of silicate minerals–and, while not all are available to mining, such inputs have the potential to be widely available. At present, stockpiles of natural and artificial silicate by-products from mining and other industrial processes exist, however, future demands for EW may require access to unmined material for EW to be effective globally (Beerling et al., 2020). Many working land soils are highly degraded due to years of intensified agriculture that mines soils of C and nutrients, combined with erosion that has resulted in soil loss (Janssens et al., 2022). Since the dawn of agriculture, the top two meters of cultivated soils have lost 133 Gt C globally with dramatic acceleration in the past 200 years (Sanderman et al., 2017). This has resulted in a soil C pool with high potential to be rebuilt through management practices, including the restoration of both organic and inorganic pools. EW has the potential to provide crop and soil health benefits including increases in yield, soil and plant nutrients, and water holding capacity that can provide agronomic and economic benefits to farmers and ranchers (Beerling et al., 2018). Many of the soil, crop, and C benefits of EW are most likely to be observed in highly weathered, low pH, low nutrient systems, but it remains unknown whether such effects will persist across diverse soil conditions. An understanding of factors that influence EW's effectiveness will require field tests across an array of crop, climate, and soil types. Furthermore, potential negative impacts of EW (e.g., heavy metal accumulation, dust inhalation, etc.) remain largely untested under large scale or long-term field conditions. As EW in working lands is under discussion as a globally relevant approach for CO_2 removal, it is incumbent upon researchers to develop, test, verify, and scale this technology for maximum impact.

A principal barrier to EW deployment lies in scientific verification of CO_2 removal under field conditions, which, through testing and refinement of approaches, can help to advance the technological readiness of EW in agronomic settings. Here we provide an overview of geologic and agronomic methods that can be used to assess mechanisms by which EW effectively sequesters C at field scales. This guide is intended for geologists, agronomists, hydrologists, and natural systems soil scientists, among others, who are interested in conducting EW field research in working lands for the first time. In this paper, we examine gaps in the literature related to EW field trials and describe methods to measure CO_2 removal that bridge the fields of geology and agronomy, such that EW can be deployed with less uncertainty and greater assurance in terms of C benefits. In particular, we discuss relevant geologic concepts and methodological options related to measuring geologic, agronomic, and climate relevant processes, namely CDR, factors that influence weathering kinetics, tools to trace weathering products, and soil and crop health outcomes. Finally, we conclude the paper by touching upon applied science considerations such as outreach and engagement.

Literature survey of enhanced weathering study methodology and context

To better quantify the need for EW field research development, we censused the literature on EW publications to identify the number of existing field studies relative to other methodologies and to identify the contexts in which EW research is being conducted. We used Web of Science to search *"enhanced weathering" AND "carbon" AND "soil"* which resulted in 58 publications. We then further limited our search criteria to only include studies that examined ground silicate rock applications to soils as a method for CDR. After reviewing the papers, we eliminated 17 papers that did not meet this additional criterion, many of which were either paleontological, limnological, or ecological studies that examined rock weathering across natural gradients. We also eliminated 5 papers published in 2022 since data for this year were incomplete at the time of publication. The remaining 36 papers were categorized according to (1) the methodology used (i.e., field, mesocosm, model, or review), and (2) the context in which the study took place (i.e., agriculture, grassland, mining, or non-specific). Mesocosm studies included laboratory and greenhouse pot experiments, microcosms, microplots, soil column, or soil core incubations. Modeling studies included mathematical models and life cycle analyses. Review papers included systematic reviews, meta-analyses, perspective, and opinion pieces. Non-specific contexts included global, regional, or national studies, studies that included multiple locations or settings, or those that did not specify a location/setting, which was most typical of modeling studies. One grassland study also included a forest comparison, which we categorized as a grassland study.

We found that the number of publications on EW applications to soils as a method for CDR has grown in recent years. In the last 4 years, we found 29 publications on EW, whereas a total of only 7 publications had been generated prior to 2018 then (Figure 1). Of the 36 publications our search generated, the majority of papers employed either models (13 publications) to explore the potential of EW as a CDR strategy or synthesized the literature/provided literature-based perspectives in the form of review papers (12 publications; Table 1). Only 5 publications used field-based methods and 4 of those 5 were generated by the same research group, seemingly from a single field study in Ontario, Canada (see Supplementary Data). These data suggest that there have only been data published from two field trials of EW (with a third being published since the time of our literature survey; Larkin et al., 2022). We also found that, while most of the publications included in our dataset were not specific in their context (16 publications), being modeling studies that were broad in scope, the second most common context was agriculture (15 publications; Table 2).

From our findings, it appears that EW is being most rigorously explored in agricultural settings but that such exploration is being predominantly studied using modeling and synthesis approaches and are rarely examined using field trials. In some ways this puts the cart before the horse in that EW is being proposed as a widely scalable CDR technology without adequate field trials to substantiate its effectiveness as such. Such a low frequency of field trials limits our ability to understand the capacity for EW to remove CO_2 from the atmosphere or infer other impacts that such practices may have on ecosystems. Furthermore, published field methods serve a resource for scientists seeking to embark on new field research. Without a wealth of methods to draw on, scientist may struggle to deploy field trials at a rate needed to develop this CDR technology in a timeframe relevant to climate change mitigation.

Recommendations from geology and agronomy for experimental evaluation of enhanced weathering in working lands

The settings under which weathering studies occur shape the approaches that are used to build basic scientific knowledge. A classical distinction involves whether an experimental design is derived from the landscape setting, as is often the case in the geosciences, or if the experimental design is implemented onto the landscape, common to agronomic research. Field research in geology and soil science (particularly sub-fields such as low-temperature geochemistry, geomorphology, hydropedology, and pedology) study how rocks interact with life through an ecosystem process or biogeochemical lens (Dietrich and Lohse, 2014). To address questions within this realm in the field, geological scientists use landscape settings which contain gradients in the factors they hope to study (Pickett,

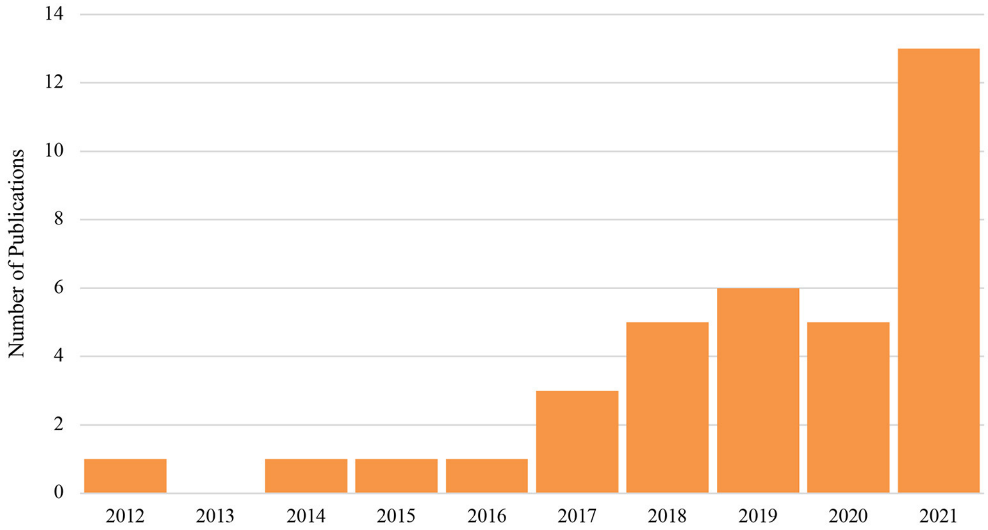

FIGURE 1
Number of publications on enhanced weathering (the application of silicate rock to soils) as a method for carbon dioxide removal in terrestrial ecosystems. Publications were generated using the search *"enhanced weathering" AND "carbon" AND "soil"* and then further refined to meet search criteria (see methods in section Literature survey of enhanced weathering study methodology and context).

TABLE 1 Literature survey results for publications that examined enhanced weathering as a method for carbon dioxide removal, categorized by methodology used in the publication (see methods in section Literature survey of enhanced weathering study methodology and context).

Methods	# of publications
Model	13
Review	12
Mesocosm	6
Field	5
Total	36

TABLE 2 Literature survey results for publications that examined enhanced weathering as a method for carbon dioxide removal, categorized by the context in which this practice was examined (see methods in section Literature survey of enhanced weathering study methodology and context).

Context	# of publications
Non-specific	16
Agriculture	15
Grasslands	3
Mining	2
Total	36

1989; Vitousek, 2004). Conversely, agronomists are principally concerned with identifying and improving issues related to crop production, and thus implement management schemes onto landscapes to test hypotheses. From these two approaches stem various decisions related to site selection, data measurement types, and sampling frequency and timing. To best assess how to study EW, we compare and contrast (Table 3) how two different fields, geoscience and agronomy, typically utilize the landscape to test hypotheses.

Applying geologic approaches to agronomic field studies designs could greatly improve our understanding of EW as a C sequestration technology at shorter time scales. Fortunately, it is likely that many geologic techniques will be more easily deployed in agricultural settings than in natural field settings, where terrain and remoteness pose challenges. At the same time, there may be difficulties (e.g., replication, frequency, etc.) associated with scaling geologic methods to agronomic settings and working around the dynamics of active farms and ranches.

There are tradeoffs associated with translating geologic methods to agronomic contexts. Geologic studies often require considerable care in choosing a study site that controls for the underlying geology, land-use history, paleoclimate influence, aspect, landscape position, and vegetation, among other factors. In contrast, agricultural systems often control for many of these factors, as most farmers select for flat fertile soils and may control for climate through irrigation. At the same time, agronomic studies call for higher replication and sampling frequency than many geologic studies. For instance, geologic measurements of water or sediment may be collected at watershed outlets which provide watershed-averaged measurements. Therefore, the number of samples is limited by the total number of watershed replicates available.

TABLE 3 Summary of the differences between geology and agronomy studies, and recommendations for geologic experimental designs in working lands.

Consideration for study type	Geologic study	Agronomic study	EW study recommendations in working lands
Timeframe under consideration	1–10^6 years or longer; shorter studies may focus on current or short-term perturbations to an ecosystem Longer studies focus on landscape and ecosystem evolution	Growing season (water-year), single or multiple (1–5+ years)	Growing season (water-year) Multiple years Long-term preferred (∼10 years)
Replication	Limited by availability of appropriate sampling locations within the natural setting	Measurements are typically replicated annually, preferably over multiple years	Replication is dependent on plot size A minimum of 3 replicate plots is acceptable, but 5–9 are highly recommended in larger plots
Sampling Frequency	Studies for short-term effects often involve more frequent sampling (e.g., daily stream water sampling over 1 year) Landscape and ecosystem evolution studies may only sample one time (using space-for-time substitutions)	Multiple times over the growing season (often 3–6 times) More frequently during periods of interest (e.g., fertilization, rain/irrigation events, etc.)	Soils should be sampled annually Other measurements can be taken more frequently (e.g., soil alkalinity multiple times, lysimeters weekly, GHGs continuously, etc.)
Sampling Depth	Sampling depths for soil often extend well below surface soils into deep soil and bedrock	0–10 cm is customary Deeper sampling may occur depending on the research Sampling should consider tillage and crop root depth	0–10 cm minimum Carbon changes have been shown to occur at depth (2 m), so sampling 1–2 m deep every few years is suggested

We limit our scope to that of soil, soil water, plant material, and soil gas emission measurements.

In agronomic settings, sample size of soil and crop materials depends on heterogeneity across the land. Samples could represent land units (such as experimental plots), be divided into similar areas/sections to account for heterogeneity (for instance, drainage or sand content may vary across a site due to the presence of a creek) or represent soil layers that are affected by agronomic practices (e.g., tillage depth, plant root depth, soil horizon depth, etc.). Soil sampling depth is also a major difference between geologic and agronomic studies. For geobiologists, sampling depth is extended to capture the complete picture of how rock interacts with life (Richter and Mobley, 2009), which means sampling depths for soil often extend well below surface soils (0–10 cm) into deep soil and bedrock. In agricultural soils, though C sequestration has been detected as deep as 2 m (Tautges et al., 2019), most sampling efforts remain limited to the surface soil (∼10–30 cm deep).

Sampling frequency is another consideration when translating geologic methods to agronomic settings. For geologists, the spatial and temporal scale of the geological study determines where and what type of samples are taken and how often sampling is conducted. For instance, a geomorphologist focused on landscape and ecosystem evolution may try to measure change over 10^3-10^6 years. Such long timescale-based questions can use space-for-time substitutions which target sites that span a gradient in landscape age to sample (Pickett, 1989) where samples are commonly taken one time (e.g., Long Substrate Age Gradient (LSAG), a long chronosequence sampling design in Hawai'i; Crews et al., 1995). Agronomic field studies typically take place over a growing season (or water-year) and measurements are timed according to management and plant growth (Saville, 1980). Over the course of a growing season, planting, fertilization, irrigation, and harvest are all important events to be considered with agronomic measurements, thus measurements are often taken at multiple time points and may be more intensive at certain times (e.g., rain events, fertilization events, etc.), depending on the measurement. To acquire robust data, is it important that agronomic studies include multiple years of repeated measurements to account for interannual variability (Martin et al., 2004; Smith et al., 2004).

The most critical way in which geology must conform to agriculture is in experimental study design. While geologic studies may consider the landscape as their experimental design, agronomy implements the experiment onto the field. Agronomic field studies commonly use randomized block designs (inclusive of an untreated control) that capture spatial variation within a cropped field (see Chaney, 2017 for some experimental design options). However, within this design, plot size, shape, and arrangement must consider not only the scientific question, but also practicalities related to field equipment used for planting, harvest, irrigation, and amendment spreading. Additionally, experimental designs need to consider factors such as crop lifespan (e.g., annual vs. perennial, short vs. long lived), crop traits (e.g., row crop vs. grass crop, nitrogen fixing or not), irrigation method (e.g., flood vs. drip vs. overhead) as well as other management practices (e.g., tillage, fertilization, liming, etc.) as these may influence weathering rates. Such factors influence the length of study, the method and frequency of rock application, the spatial distribution of sampling, and scientific equipment installation, among other factors. Climatic and soil characteristics should be controlled for in a robust experimental design unless these are being systematically varied to explore their influence on EW. Since agricultural amendment studies are intended for practical application, it is common for researchers to accommodate typical farming practices into experimental designs. If farmers apply manure, use flood irrigation, practice organic farming, and so on, including such practices benefits from land manager knowledge and allows for results that are relevant to real world farming. Lastly, when working on active farms, one must adapt to necessary management changes and be prepared to terminate treatments if they cause issues to crops or aspects of the farm that are vital to production.

Methodological considerations for determining enhanced weathering efficacy

Diverse methods are available for determining the kinetics and products of EW. Many geology methods have been used in natural contexts to approach questions at geologic timescales, so translating those approaches to shorter timescales and agricultural management contexts can pose challenges. While this research is highly necessary, there are few examples of quantifying a geologic process in an agronomic setting. Approaches to quantifying EW products, CDR rates, drivers of CDR, and mechanisms by which C is stabilized are varied, as this is a nascent field. At present, techniques from geochemistry, agronomy, and soil science are being agglomerated depending on specific project objectives, researcher expertise, study system and scale, and financial constraints. In this section, we examine a range of methodological options, both proposed and implemented, for approaching experimental design, measurements of mineral weathering products, and crop and soil health. We conclude this section with a brief list of recommended measurements, acknowledging that a greater quantity of field studies will be necessary to develop best practices for EW monitoring in working lands.

Carbon dioxide removal

Assessing CDR and the mechanisms responsible as a function of EW practices in agricultural settings requires multifaceted approaches to measure different states of C. Different C pools can be targeted to determine the impact of EW technologies in croplands following the application of EW materials, such as measuring total C content of bulk soil, dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) in pore water, plant biomass C, and soil greenhouse gas (GHG) emissions, among others (Figure 2). The goal of quantifying multiple fluxes and pools of C in a system is to generate a total net C budget, which will elucidate if a crop system is a net source or a net sink of C. In this section we discuss a variety of measurement options for characterizing CO_2 removal in response to EW field trials and summarize the strengths and weaknesses of each C measurement in Table 4.

An important first step in budgeting C is to directly quantify the amount of C present in the soils, for which diverse approaches have been studied and reviewed intensively (Smith et al., 2020). To quantify soil C stocks, soil samples should be collected before the initial application of silicate rock materials (to quantify baseline stocks) as well as periodically throughout the experiment. Given that soil C sequestration can take years to observe, annual sampling should be more than adequate for monitoring changes in the soil C pool, however, being a rarely tested mechanism, further field trials will be needed to verify this frequency. Sampled soil can be processed for subsequent analyses; for example, once collected, samples may be air dried, sieved, and ground. After preparation, several approaches can be used to quantify the C present in the soil.

Measuring total (or bulk) soil C is the primary way to quantify CDR in soils. However, there are more advanced approaches measuring different C pools that can help refine C budget estimates or answer specific research questions. Conventionally, total bulk soil C, which consists of both the organic and inorganic fractions (Figure 2), can be determined using Dumas high-temperature combustion (Nelson and Sommers, 1983). Combustion methods can also be used to measure the amount of C in plant biomass such as crop harvest or crop residues. Soil C stocks can be measured using bulk density and depth measurements or by the equivalent soil mass method. Determining soil C *via* equivalent soil mass circumvents potential changes to bulk density that can arise from management practices such as tillage or additions of organic amendments (Von Haden et al., 2020). Robust measurements of soil C are required to quantify CDR rates on a per area basis. However, C stock measurements alone do not indicate the mechanisms controlling changes in C storage.

As EW methods continue to develop, it is also crucial to consider the broader scope of soil C cycling and potential methodological approaches. EW of rock amendments can interact with biogeochemical conditions of the soil matrix by

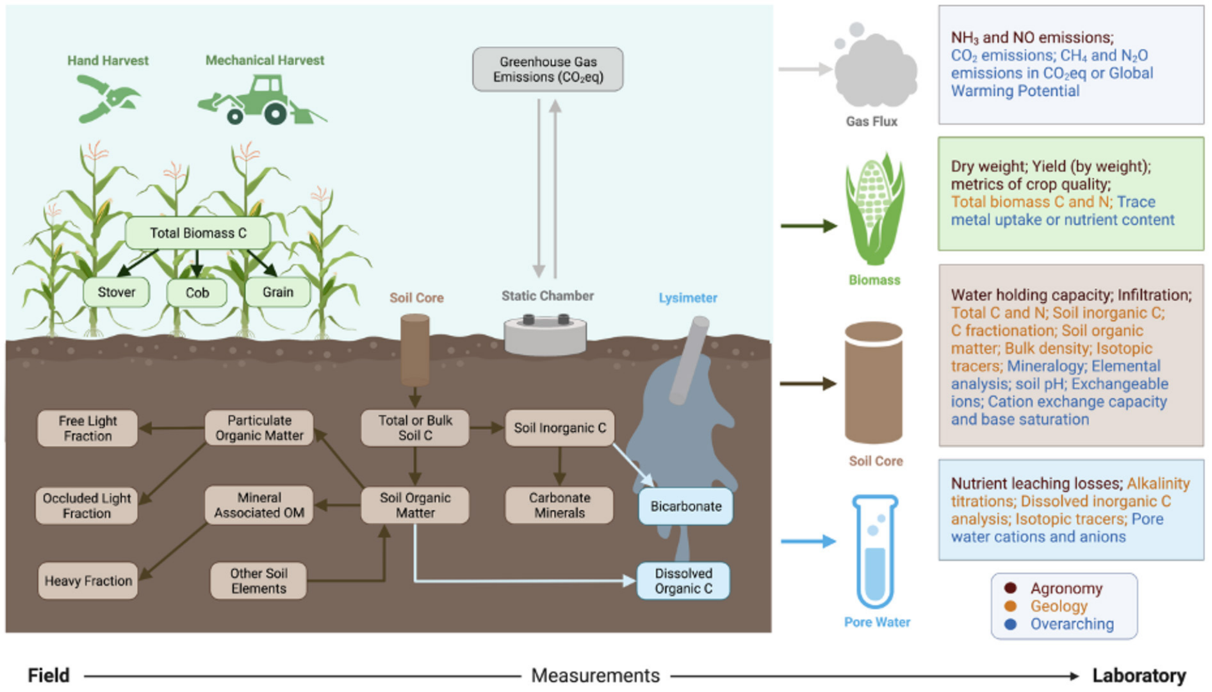

FIGURE 2
Flow chart for field measurements, sample collection, and laboratory analyses from enhanced weathering studies in working land environments.

altering soil pH, base cation pools, and mineral mass in a different range of scales. Such micro or macro environmental changes in the soil matrix can in turn influence microbial vitality, which is a major player in processing SOM into different C pools in soil. SOM is susceptible to decomposition or microbial oxidation and loss back into the atmosphere through microbial respiration.

On one hand, microbial activity can indirectly change SOM pool sizes by decomposing DOC, particulate organic matter (POM) and mineral associated organic matter (MAOM), which are key C pools of SOM (Figure 2; Cotrufo et al., 2019; Kleber et al., 2021). On the other hand, these oxidized C forms, such as organic acids derived from plant root or microbes and respired CO_2 dissolved in soil pore water, are a source of protons that have the potential to drive reactions with minerals, which will directly generate inorganic C products (HCO_3^- and $CaCO_3$; Zaharescu et al., 2020). Moreover, there has been a growing consensus that microbially-derived OM is a key ingredient in formulating stabilized soil C in a form of MAOM (Lavallee et al., 2020). Regarding direct quantification of EW impact on soil C, advanced analytical tools can be utilized to trace biological and microbial processes (stable isotope probing using labeled substrates such as ^{13}C or ^{18}O-H_2O) and to visualize and characterize OM at the sub-micrometer scale (Nano Secondary Ion Mass Spectrometry and Scanning Transmission X-ray Microscopy coupled to Near Edge X-ray Absorption Fine Structure Spectroscopy; Asano et al., 2018; Wang et al., 2019; Wilhelm et al., 2022). While these tools are helpful to identify EW impact on SOC formation and CO_2 removal mechanisms, this approach can be unrealistic for monitoring large scale EW impact in agricultural soils.

Soil inorganic carbon (SIC) pools have traditionally been examined in arid and semi-arid regions where low moisture availability and high average pH lead to carbonate precipitation in the soil (Filippi et al., 2020). In arid soil, inorganic forms of soil C are typically carbonates [$CO_3(2-)$] existing as solid form in carbonate minerals, which are commonly more thermodynamically stable than organic C. Because agricultural soils have highly variable water contents depending on irrigation protocols and seasonal and regional water regimes, EW impact on SIC formation in agriculture could be site specific depending on targeting pools or mechanisms of SIC formation. The major forms of soil inorganic C (SIC) to consider in EW study are not only carbonates, but also bicarbonate ions (HCO_3^-), which is a dominating DIC form in groundwater. Soil pH controls the fraction of EW-derived carbonates that are available as aqueous bicarbonate or precipitated as pedogenic carbonates (Haque et al., 2020; Vienne et al., 2022). The SIC pool can be substantial and thus measurements should be incorporated into EW field studies.

There are several options for quantifying organic and inorganic soil C pools. Combustion methods such as elemental

TABLE 4 Common carbon measurements for determining the CO_2 removal capacity of enhanced weathering in agronomic settings, inclusive of measurement definition, sample type, common methodology, strengths and weakness of each approach, and supplemental measurements best paired with each carbon measurement.

CO_2 removal measurements	Definition	Samples	Laboratory method	Strengths	Weaknesses	Paired measurements
Total carbon (TC)	Total carbon contents (organic and inorganic) of soil	Soils and rock amendments	Combustion (elemental analyzer)	Most common carbon measurement; relatively easy and affordable	Labor intensive collection and processing; does not separate organic and inorganic forms of carbon without additional treatment; difficult to detect changes against background carbon	Bulk density; equivalent soil mass (sample from three depths); dry weight; sample depth
Soil organic carbon (SOC)	Carbon associated with organic compounds	Soils and rock amendments	Loss on ignition; acid digest assay; Walkley-Black (calculated from SOM); LECO elemental analysis	SOC is the dominant carbon pool in most soils	May not differ significantly from TC; methodological inconsistencies exist	Bulk density; equivalent soil mass (sample from three depths); dry weight; sample depth
Total inorganic soil carbon (SIC)	Inorganic (carbonate minerals) forms of carbon in the soil	Soils and rock amendments	Total carbon minus organic carbon; Thermogravimetric analysis (TGA); acidification with pressure calcimeter or infrared analyzer	An important potential fate of EW	SIC pool may be small in many soils; SIC may precipitate at depths >50 cm making sampling more difficult	Bulk density; equivalent soil mass (sample from three depths); dry weight; sample depth
Soil extractable alkalinity	Carbonate alkalinity (buffering capacity) of soil saturated paste extracts, which contribute to bicarbonate and carbonate formation	Soils and rock amendments	Acidimetric titrations of soil saturated paste extract	Direct measurement of initial carbon product of weathering reaction	Scaling from extractable soil samples may miss transient fluxes of high weathering events	pH
Soil carbon pools based on size and density	Labile to recalcitrant soil carbon pools which differ in function and age (particulate organic matter 53-2000 μm in size and mineral-associated organic matter <53 μm in size; or free, occluded, and heavy light fractions)	Soils and rock amendments	Separation using a 53 μm sieve; separation via density fractionation using sodium polytungstate	Can inform about the stability of accumulated carbon	Labor and time intensive; requires specialized equipment to measure density fractionation	Dry weight; carbon contents; 14^C optional to assess age
Soil microbial biomass carbon (SMBC)	Carbon contents of microbial biomass is soils	Soils and rock amendments	Chloroform fumigation; substrate induced respiration	Can indicate the rate of potential microbial carbon transformation processes in the response to amendments	May miss the impact of rock amendments in shifting the microbial functional traits or community composition	Carbon contents

(Continued)

TABLE 4 (Continued).

CO_2 removal measurements	Definition	Samples	Laboratory method	Strengths	Weaknesses	Paired measurements
Dissolved inorganic carbon (DIC) of soil pore water, leachate, or discharge	The total amount of CO_2, carbonic acid (H_2CO_3), bicarbonate (HCO_3-), and carbonate (CO_3-) in water	Soil pore water, leachate, or discharge	Coulometric and infrared detection methods; acidimetric titrations to measure carbonate alkalinity (carbonate and bicarbonate anions in a solution)	An important potential fate of EW; could be a large pool; develops relatively quickly	Quick development requires a need for frequent sampling; can be difficult to sample at high frequency, especially in drier soils	Water balance, pH
Dissolved organic carbon (DOC) of soil pore water, leachate, or discharge	Organic carbon dissolved in a water that does not include the suspended solids component	Soil pore water or leachate; water or salt extracts	Filtration (operationally defined as the fraction of organic carbon that can pass through a filter with a pore size 0.45 μm)	Reflects the imminent change of labile carbon pool size in soil	Transient pool; typically small pool in terrestrial ecosystems; should be measured with other pools	Water balance, carbon contents
Total biomass carbon	Total carbon contents of biomass	Plants	Combustion (elemental analyzer)	Can inform about carbon losses/the fate of carbon	Biomass weight can also be used as a proxy, assuming 50% of biomass is carbon	Dry weight; carbon contents by plant anatomy (grain vs. stover) optional to get agronomic implications
CO_2 and CH_4 emissions	Gaseous carbon dioxide and methane exchange between soil and the atmosphere	Atmosphere	Laboratory incubations; automatic or manually-operated static flux chambers, measured with syringe sampling and gas chromatography or in situ with a portable gas analyzer; Eddy covariance flux tower; remote sensing	Can inform about carbon losses or CH_4 consumption potential; can improve carbon budgets	Costly and time intensive	Air temperature; soil temperature; soil moisture; bulk density; chamber volume; CH_4 and N2O can be converted to CO_2 equivalents to get GWP
^{13}C	Natural abundance stable isotope	Any	Mass spectrometer elemental analyzer	Can inform about mechanisms of carbon accumulation; often included with TC measurements	Snapshot of the process of natural isotope fractionation; data interpretation can be challenging	Standard and ^{12}C values to get isotope ratios
^{14}C	Trace the fate or age of carbon	Any	Mass spectrometer elemental analyzer	Can use a labeled substrate to trace the fate of accumulated carbon; can estimate the age of carbon stored	Costly; requires specialized expertise; requires a laboratory that is ok with ^{14}C contamination	None necessary

analyzer loss on ignition (LOI) or LECO elemental analysis can be used to measure SIC or calculate the portion of inorganic C (i.e., total C minus organic C). LOI measurements should be used with caution as they are very sensitive to soil texture and moisture and may produce inconsistent results (*Personal communication with Whendee Silver*). Thermogravimetric analysis (TGA) can also be used to measure carbonaceous components in the mineral (clay and oxides) components of soils (after the removal of OM) and rock samples (Pallasser et al., 2013; Kemp et al., 2022). Additionally, soil can be acidified to measure the evolved CO_2 by using a pressure calcimeter (gives bulk equivalent $CaCO_3$ content; Sherrod et al., 2002), or an infrared gas analyzer (Lin et al., 2016). Inorganic C in soil samples can also be measured using acid dissolutions followed by the manometric, titrimetric, or gravimetric determination of CO_2 (Presley, 1975; Wang et al., 2012). Similarly, carbonates can be measured using rapid titrations (soil treated with hydrochloric acid and titrated with sodium hydroxide) to get $CaCO_3$ equivalents (Rayment and Lyons, 2011). By measuring organic and inorganic soil C stocks at the field scale over time, treatment effects and CDR rates following silicate rock applications can be determined.

In addition to measuring soil organic and inorganic C, directly measuring DIC in the soil pore water is critical to quantifying the flux of C that is removed through EW. An important form of soil DIC is aqueous bicarbonate ions (HCO_3^-) present in the soil pore water. HCO_3^- concentrations may also be estimated using total alkalinity, depending on the pH of the system (Olin Neal, 2001). To obtain soil water samples for monitoring solute fluxes in natural soils, *in situ* soil water extraction methods may be used. These include vacuum lysimeters (also referred to as porous cups/tubes or suction cups), suction plate or tension plate lysimeters, pan or zero-tension lysimeters, wick samplers, and resin boxes (Weihermüller et al., 2007). Lysimeters of varied types provide a method for frequent measurement of soil pore water and may be placed at multiple depths to monitor solute movement; however, selection of a suitable sampler material depending on the solutes of interest is imperative (Weihermüller et al., 2007; Vandenbruwane et al., 2008). In agricultural systems, it is likely that lysimeters will have to be removed and reinstalled to accommodate certain machinery. HCO_3^- formed from EW processes may leach deeper into soil profiles and precipitate as carbonate minerals or eventually leach into groundwater; therefore, SIC measurements at deeper soil depth or DIC monitoring in downstream of ground watershed may be appropriate depending on the hydrologic conditions of the system (Sigfusson et al., 2006; Amann and Hartmann, 2022). Once pore water is collected, samples can be measured for pH, total alkalinity using acidimetric titration, DIC, cations and metals by inductively coupled plasma emissions spectrometry (ICP), or other measurements, enhancing understanding of EW processes. Given the central roles of water volume and flow path length in regulating chemical weathering, determining a water balance estimate is critical to scale concentration values into weathering or C fluxes (Maher and Chamberlain, 2014). In the field, this may require monitoring irrigation inputs with a flow meter, obtaining weather station precipitation data, or establishing and monitoring a site-specific weather station, as well as measuring evapotranspiration, soil moisture, infiltration, and hydraulic conductivity.

C isotopic signatures of both SOC and SIC can be useful to infer the mechanisms responsible for CDR within a system (Del Galdo et al., 2003). C isotopic fractionation of SOC and SIC can be measured by quantifying ratios of stable C isotopes (^{12}C and ^{13}C), or by conducting pulse labeling experiments using radioisotope (^{14}C) as a tracer (Smith et al., 2010). The $\delta^{13}C$ composition of SOC is largely determined by the fraction of plant litter originating from C3 or C4 species and by fractionation occurring during microbial decomposition of the resulting organic matter. For SIC, the $\delta^{13}C$ isotopic composition is controlled by the composition of soil CO_2, which is derived largely from root and microbial respiration (Cerling, 1984). The ^{14}C abundance in pedogenic carbonates, a form of SIC, is similarly determined by the relative proportion of CO_2 respired by the rhizosphere and microbially-induced SOM decomposition (Zamanian et al., 2016). The contribution of SOM decomposition determines ^{14}C abundance in pedogenic carbonates, however, is more important in deeper horizons. This is because the age of SOM increases with soil depth (i.e., the older the SOM, the more depleted the ^{14}C abundance; Amundson et al., 1994). Stable isotope data can often accompany total soil C data, however ^{14}C can be more complicated to obtain (i.e., tracers can be expensive and require special labs), and both require specialized expertise to interpret.

GHG measurements determine the net flux (gain or loss) of CO_2 and can help inform estimates of CDR rate (Whitehead et al., 2012). GHG emissions are most commonly measured using: (1) static flux chambers where measurements are taken weekly or bi-weekly (with more frequent sampling during rain or fertilization events that can produce pulse emissions), (2) automated flux chambers where measurements are taken multiple times an hour, (3) Eddy covariance flux towers that estimate net CO_2 exchange across the landscape, or (4) remote sensing (Smith et al., 2010). Of these GHG methods discussed here, static flux chambers are on the low tech/cost end of the spectrum and have the advantage of being movable, while automated chambers are most costly but are much better at capturing heterogenous fluxes. Ecosystem-scale GHG measurements (often taken using eddy covariance) account for the initial uptake of C through photosynthesis (gross primary production), and its subsequent partial losses through ecosystem respiration to give net ecosystem exchange. Eddy covariance methods can effectively determine CDR given that there are no lateral or hydrologic soil C fluxes (Arias-Ortiz et al., 2021), but instrumentation are costly, require specialized expertise, and are limited in the number of treatments they can monitor (two). Arias-Ortiz et al. (2021) showed that sediment cores and Eddy covariance CDR estimates agreed in flooded peatlands, however this relationship broke down at the tidal wetland site where lateral C fluxes were large. Gough et al. (2008) found similar results but note that a single year of Eddy covariance data may not be consistent with long-term sediment data, thus multi-year datasets are recommended. Remote sensing is best suited for larger scale observations and also requires specialized training and skills. Eddy flux towers integrate over all C sources and sinks providing real time estimates of net ecosystem exchange (Novick et al., 2022), while static chamber measurements are more typically used to reveal differences in emissions of CO_2, nitrous oxide (N_2O) and methane (CH_4) between experimental treatments. N_2O and CH_4, which have a higher GWP potential than CO_2, can be measured and converted into CO_2 equivalents to assess the total effect of GHG emissions from agronomic systems on global warming. Currently proposed mechanisms for EW mitigation of N_2O emissions include increasing NUE through enhanced P availability or decreasing N_2O:N_2 ratios of denitrification through pH stimulated activity of N_2O reductase (Blanc-Betes et al., 2021). While CH_4 emissions can also be quantified, it is less known how EW may mechanistically influence these emissions. In combination with biomass measurements and other soil C measurements (gains from C inputs and CDR, losses from bicarbonate leaching, respiration, or biomass harvesting), GHG measurements make up one component that can contribute to the development of more accurate calculations of total C budgets in agronomic systems (Smith et al., 2010).

In addition to studying C capture potential from EW at individual field sites, scaling up CDR to regional scales is necessary for understanding the potential for EW technologies to be deployed at a larger scale. Currently, the only available assessments of the large-scale effects of EW on soil C capture are estimates derived from models. These stoichiometric models are parameterized using mass balance equations and interactions between factors such as rock-dissolution reaction rates, climate data, C dynamics, nutrient availability, plant responses, hydrology, and soil physical properties (mineralogy, grain size, soil moisture, bulk density, etc.) (Taylor et al., 2017; Cipolla et al., 2021; Goll et al., 2021). *In situ* field studies and on-the-ground measurements are necessary for both confirming and improving these model estimates across broader scales. Finally, the development of comprehensive life cycle analyses (LCA's) will be necessary to verify the net C benefit of EW, particularly given the energy demands associated with crushing and transporting rock. Existing LCA's report conflicting results regarding EW's net C benefits (Beerling et al., 2020; Taylor et al., 2021; Schlesinger, 2022), results that likely differ as a result of modeled dissolution rate assumptions, C pools incorporated, and transport methodology. In practice, the net C benefit of EW will likely vary regionally based on access to mined materials and soil conditions that support fast CDR rates, thus LCA's will be better informed when coupled with robust field data that elucidates the actualized and regionally specific CDR capacity of this emerging technology.

Influences on weathering kinetics

Terrestrial silicate weathering plays a central role in regulating Earth's atmospheric CO_2 levels. As silicate minerals weather, they react with CO_2 dissolved as carbonic acid (Equations 1 and 2), moving C from the atmosphere into the hydrosphere as bicarbonate (Equation 3), and releasing cations and silicic acid (Mitchell et al., 2010). Subsequently, bicarbonate may react further, yielding carbonate minerals such as calcite or magnesite and resulting in the release of one mole of CO_2 (Equation 4). The CDR benefit of EW may vary based on emissions associated with rock transport (i.e., life cycle emissions; Beerling et al., 2020), chemical composition of the rock, soil characteristics (like pH or texture), management practices (like irrigation or crop type), influences on carbonate formation (i.e., dust inputs of IC, parent material, upward groundwater movement; Zamanian et al., 2016), the form in which CO_2 is sequestered (with bicarbonate sequestering 2 mols and calcium carbonate sequestering 1 mol of CO_2), and whether CO_2 is released back into the atmosphere along surface water flow paths. More field data are needed to better quantify this variation.

Weathering rates and resulting solute concentrations are dictated by tectonic forces and erosion, which control availability of fresh mineral surfaces, and by runoff and water flow path lengths (Maher and Chamberlain, 2014). Additional factors that influence weathering rates include pH and temperature, as well as rock characteristics such as mineralogy and porosity (Isson et al., 2020). For this reason, areas with high rates of erosion, hotter and wetter climates, more acidic soils, or heavily irrigated management practices might expect to see faster rates of CDR in response to EW applications. Dissolution kinetics are key to understanding weathering rates of various lithologies and reaction with atmospheric CO_2 (Yadav and Chakrapani, 2006).

$$CO_2\left(g\right) \leftrightarrow CO_2(aq) \tag{1}$$

$$CO_2\left(aq\right) + H_2O \leftrightarrow H_2CO_3\left(aq\right) \tag{2}$$

$$\begin{aligned} CaSiO_3\,(s) + 2H_2CO_3\left(aq\right) + H_2O \leftrightarrow 2HCO_3^-\left(aq\right) \\ +H_4SiO_4(aq) + Ca^{2+}(aq) \end{aligned} \tag{3}$$

$$\begin{aligned} 2HCO_3^-\left(aq\right) + H_4SiO_4\left(aq\right) + Ca^{2+}\left(aq\right) \leftrightarrow 3H_2O \\ + CO_2\left(g\right) + CaCO_3\,(s) + SiO_2\,(s) \end{aligned} \tag{4}$$

A variety of silicate rocks may be used for EW. The chemical dissolution and subsequent CDR rates vary with silicate rock type, particle size, soil characteristics, climate, and other factors. While particle size is a key determinant in weathering rate (with small higher surface area particles weathering faster than coarse particles), from an applied perspective, extremely fine materials can be difficult to apply and may present a dust inhalation hazard. Furthermore, finely grinding rock materials requires significant energy expenditures (Strefler et al., 2018) that may exceed CDR benefits (Lewis et al., 2021). Most studies suggest that particle sizes of 10–20 microns provide the greatest CDR benefit (Rinder and von Hagke, 2021), but larger particle sizes (~100 microns) have been used in EW research and may be more widely available (Kelland et al., 2020). More recently, researchers have suggested that larger particles may be comparable to finely ground particles in their CDR potential (Kantzas et al., 2022), highlighting the need for critical assessments that compare the efficacy of different grain sizes. Figuring out the largest grain size that is reasonably effective at CDR is critical to minimizing the energy demand of EW as well as health and safety risks associated with handling rock dust.

Mineralogy further impacts weathering rates, with minerals forming at higher temperatures and pressures, such as olivine, weathering more readily at Earth's surface (Goldich, 1938). However, ultramafic minerals that weather faster also pose a higher risk of inducing heavy metal toxicity (Beerling et al., 2018). Monitoring the content of heavy metals such as cadmium, lead, chromium, and zinc in rock and soil before and after application may help mitigate heavy metal toxicity. Moreover, global availability and proximity to mines greatly impacts the scalability of EW (Köhler et al., 2010). Basalt, though less rapidly weathering than olivine-dominated rocks, such as dunite, exists broadly and has lower risk of heavy metal accumulation when applied to soils. Site location will largely determine mine proximity and rock compositions that are accessible (Krevor et al., 2009).

Designing field experiments that not only quantify CDR, but also test the influence of various factors on CDR rates will be vital to deploying highly effective EW strategies. Randomized block designs that test the effect of particle size on CDR rate, multi-site experiments that span gradients of soil pH, or comparisons between tropical and temperate field sites are all examples of ways that field studies can examine the factors that influence weathering kinetics.

Tracing weathering products

A variety of analytical techniques common to pedology, geochemistry, agronomy, and mineralogy may be employed to elucidate the products of EW and track their movement in soil, water, and plant biomass. These products, when quantified alongside ion transport and secondary mineralization, can be used to approximate weathering and dissolution rates, trace nutrient release and movement, and monitor levels of potentially toxic metals released from applied minerals. Markers of weathering (e.g., Mg^{2+} release from olivine dissolution) may also be used to estimate CDR.

Physical and chemical characterization of silicate rock amendments, including grain size, specific surface area, mineralogy, and elemental composition, is a necessary first step in identifying expected weathering products and estimating potential CDR. Both grain size and specific surface area are relevant for estimating dissolution rates and understanding available surfaces for weathering reactions. Numerous approaches are available for characterizing grain size distributions, but a particle size analyzer (PSA) using laser diffraction is common. Additionally, the Brunauer, Emmett, and Teller (BET) method, using gas adsorption to mineral surfaces, is used to measure specific surface area. Mineralogy may be determined using X-ray diffraction (XRD; Silva et al., 2021) or quantitative evaluation of materials by Scanning Electron Microscopy (QEMSCAN), while rock elemental composition is regularly measured using lithium borate fusion coupled with X-ray fluorescence (XRF) or inductively coupled plasma atomic emission spectroscopy or mass spectroscopy (ICP-AES or ICP-MS).

To understand EW dynamics in soil, imaging approaches including scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS; Haque et al., 2020), transmission electron microscopy (TEM; Bonneville et al., 2009), and nanoscale secondary ion mass spectrometry (NanoSIMS) may be relevant. Synchrotron-based x-ray absorption spectroscopy may also help reveal weathering processes and specific mineral phases (Nieva et al., 2019). As noted by Dudhaiya et al. (2019), some of these approaches for tracing weathering products, including thermogravimetric analysis (TGA; discussed in section Carbon dioxide removal), EDS, and XRD may be limited in their application in highly heterogeneous amended soils due to the small sample sizes. However, in-depth examinations of organo-mineral interactions and mineral weathering using SEM, TEM, and other approaches common in natural systems research (e.g., Jongmans et al., 1997; Bonneville et al., 2009) will likely become more common in EW studies as this field of research grows more mechanistic and detailed. Many of the aforementioned non-destructive approaches, as well as infrared spectroscopy and additional forms of x-ray spectroscopy and microanalysis, have been reviewed in detail (Haque et al., 2019a). Approaches used to characterize rock amendment mineralogy and elemental analysis are also relevant to understanding amended soils.

Beyond direct visualization and quantification of weathering products, isotopic tracers are widely used in soils and geology for dating, tracking landscape processes, and interpreting biological influences, among other applications. For example, because strontium (Sr) exhibits limited fractionation (i.e., mass-dependent fractionation is corrected for during data reduction), Sr isotopic ratios ($^{87}Sr/^{86}Sr$) may be used in soil systems as a tracer, provided all input pools (dust, parent material, rain, groundwater) are well-characterized (Capo et al., 1998). Because of this utility, Sr has been proposed as a tracer of EW products, though this would require sufficient distinction between the rock amendment and soil parent material. Refer to the section Carbon dioxide removal for specifics concerning C isotopes in the context of EW.

Because silicate weathering occurs *via* proton-consuming reactions, increasing soil pH is a commonly observed phenomenon (e.g., Haque et al., 2019b; Amann et al., 2020). While not suitable as a direct proxy for dissolution rates, pH is important for nutrient and trace metal mobility, runoff or discharge chemistry, suitability for continued weathering and crop growth, and other ecosystem or soil effects. Tracking pH in soil and water of field experiments can help improve understanding of these dynamics. The desirability of pH shifts largely depends on the system's baseline pH (e.g., increased pH in an acidic system may alleviate some need for liming) (Ten Berge et al., 2012). While increased pH may be highly beneficial in mitigating metal toxicity and low cation exchange capacity (a measure of the soil's ability to hold positively charged ions) in tropical systems, downstream effects of pH changes on aquatic ecosystems may be negative, emphasizing the need for pH monitoring (Edwards et al., 2017).

In addition to pH controls, explicitly measuring exchange complex ions, changes in cation exchange capacity, and macro- and micronutrient pools can help identify ancillary EW effects beyond CDR, allowing for monitoring of both beneficial nutrients and potentially toxic trace metals (Ramos et al., 2022). In agricultural systems, the added step of quantifying trace metal or nutrient content of plant biomass may be relevant for assessing bioavailability of rock-derived ions, whether beneficial or detrimental, and may be quantified using acid digestion of dried plant biomass coupled with ICP-AES, ICP-MS, or AAS for elemental quantification (Ten Berge et al., 2012).

Many of the approaches applied to soil are relevant to the aquatic component of these systems, including the soil pore water, leachate or runoff, and downstream chemistry. Water pH, pore water cations and anions (quantified *via* ICP-AES, ICP-MS or atomic absorption spectroscopy (AAS), among other methods), and C species or other solutes are key metrics for tracing ion movement and export (Ten Berge et al., 2012; Amann et al., 2020; Taylor et al., 2021). A number of these measurements are highly time-sensitive (e.g., pH) and may require particular attention during sample collection (e.g., acidification for metal analysis); however, their wide application in water quality monitoring means standard collection protocols are widely available. As in soils, isotopic tracers may also be used to monitor weathering products in the aquatic component of agronomic systems.

More broadly, the roles of microbial communities, plants, and SOM in mediating mineral weathering are significant (Drever, 1994; Balogh-Brunstad et al., 2008; Bonneville et al., 2009; Taylor et al., 2012); examining these interactions in the context of EW requires a broad suite of additional tools beyond the scope of this paper, though understanding these linkages is essential to completing assessments of EW potential (Cipolla et al., 2021; Verbruggen et al., 2021; Vicca et al., 2022).

Soil health and crop outcomes

While CDR is often the main goal of EW studies, it is important to evaluate the effects of EW on properties that are important to land managers, such as soil and plant health. Soil health can be defined as the capacity of soil to function optimally within an ecosystem to sustain plants, animals, and humans. Components of soil health that are of interest to land managers due to their influence on plant health include cation exchange capacity, nutrient availability, and soil stability and infiltration. Soil available micro- and macronutrients can contribute positively to crop production and soil health. Cation exchange capacity and base saturation (the percentage of cation exchange capacity occupied) can determine nutrient stock potentials in soils. Silicate rocks typically have tradeoffs related to weathering rate and risk of heavy metal accumulation, with more readily weathered rocks having higher risks. Because heavy metals may be hazardous, potential heavy metal accumulation in soils and crops from EW practices should be assessed. Soil water measurements of interest to land managers include soil water holding capacity, infiltration rates, compaction, evapotranspiration, and salinity, among others (Corwin and Lesch, 2005; Garg et al., 2016; Li et al., 2016). The ability of soils to hold more water can reduce irrigation needs, while poor infiltration rates can lead to flooding, compaction, and increased overland flow. Similarly, increased nutrient contents or increased rates of leaching and runoff can result in contamination of water resources (Daryanto et al., 2017).

Crop yield (biomass) and quality (e.g., nutrient content, forage quality, etc.) are also important factors that should be measured during EW studies in croplands. Yield are most typically measured in the agronomic sciences using industrial methods such as mechanical harvesting instruments, but hand harvest methods that allow for observation of specific changes in biomass can also be useful (Shapiro et al., 1989; Trout and DeJonge, 2017). For instance, if corn biomass increases, but that increase is in stover, that may not be as valuable to farmers as an increase in grain. With certain crops, hand harvest may be necessary if mechanical methods (for instance, hay baling) are not accurate enough or not common (e.g., forage biomass estimates). Remote sensing methods can be employed to estimate yield (e.g., relative crop height using normalized difference vegetation index; NDVI) and crop nutrients (e.g., using near infrared spectroscopy; NIRS). Crop nutrient concentrations can also be determined by subjecting dried, finely-ground plant samples to elemental analysis [using methods such as inductively coupled plasma emissions spectrometry (ICP)]. Crop yield and crop quality analysis may cover total plant biomass or may be divided into relevant sections of the target crop. For example, corn harvests may be divided into grain and stover yields for analysis.

In addition to measurements of GHG emissions to the atmosphere, there are other atmospheric measurements that are relevant to environmental health. For instance, ammonia (NH_3) and nitric oxide (NO) emissions are widely produced from agriculture, which have repercussions for air quality, N deposition, soil acidification, eutrophication of waterways, and adverse effects on human health (Almaraz et al., 2018; Domingo et al., 2021). Dust production from EW practices may create a health hazard for farmworkers and/or nearby residents. Furthermore, dust can have fertilization effects both near and far (Prospero et al., 2020). The degree to which dust from EW practices becomes a hazard will likely depend on grain size and application methods (e.g., tillage, wet vs. dry applications, storage, etc.). The current scarcity of EW field trials means that our understanding of dust and other hazards remains poor and requires more targeted inquiries.

Priority measurements for enhanced weathering field studies in working lands

While further field testing of EW is required to adequately develop best practices for monitoring CDR and other pertinent processes, we provide a brief list of priority measurement recommendations for those seeking to deploy EW field trials in working lands.

The primary set of measurements to include EW field trials will be those to monitor and scale CDR. Measurements of total soil C using combustion methods are the most basic assay for observing soil C sequestration, though it does not capture all pools. Since C sequestration is typically a slow process, soil sampling can occur annually and should include at least three depths (e.g., 0–10, 10–30, and 30–50 cm) so that equivalent soil mass can be used to scale these measurements, as this has been shown to be superior to traditional scaling methods based on bulk density (Von Haden et al., 2020). Deeper depths may be sampled to capture where carbonates precipitate, however, if the soil is predominately organic C, the inorganic C pool may be negligible, precluding the need to sample deeper. EW can produce both carbonates in soil and bicarbonate in soil pore water, thus measurements of soil pore water alkalinity will be critical to observing the CDR removal effect of an experiment. Soil pore water can be monitored using lysimeters sampled daily to weekly and analyzed using acidimetric titration. Lysimeter measurements should be coupled with water balance estimates to scale findings.

Secondary measurements to prioritize would be GHG emissions and yields. GHGs can be measured in a variety of ways but automated chambers are recommended as they can be moved between treatment plots to capture spatially variability, while simultaneously capturing the temporal variability that is critical to understanding the flux of these heterogenous emissions. The effects of EW on yield will be a crucial piece of data for land managers considering this practice. Mechanical yield is preferred from an agronomic perspective; however, hand harvest methods coupled with elemental analysis may better inform C cycling dynamics (i.e., C removed during harvest).

We outline an extensive list of possible measurements to explore rates and mechanisms of CDR and other soil processes that are relevant to EW's influence on the soil environment, however, the above represents a minimal set of analyses that should provide insight with regards to EW's effect on CDR. The best techniques to quantify CDR from EW trials are not yet known because we have few results from field studies across limited soil, rock, and crop types. For instance, lysimetry might pose issues in dry climates or rainfed agriculture where soil pore water is less abundant, and the importance of SIC may vary geographically based on the ratio of SOC:SIC, altering methodological needs. Further field tests will help to build a more robust set of field measurement best practices for EW trials in agronomic settings.

Applied science considerations

As researchers continue to develop robust science generated by EW field studies, the reach of this applied science work can be made more effective by incorporating a variety of stakeholders into the research process. There are numerous constituents who will be vital to developing practices that scale in a responsible and just manner. First, computational modelers can generate emission scenarios regionally or globally using field data, life cycle analyses, and process-based models. Second, sociologists and economists can help to increase an understanding of the barriers to adopting EW practices, assess costs associated with such practices as they scale, and identify potential environmental justice issues. Third, private industry can not only help facilitate EW material sourcing and shipping but have a vested interest in and experiential knowledge of market dynamics as they related to EW. Furthermore, technological industries can help to develop smartphone tools that increase uptake, knowledge, and access to EW practices. Fourth, farmers and ranchers will be vital collaborators in EW research and development, providing land on which to deploy trials, knowledge regarding field maintenance, and feedback/support related to practitioner adoption. Fifth, environmental work has a history of widening environmental injustices, thus is important to consider and incorporate local agricultural and indigenous communities into research projects from their onset; working with non-profit organizations can be a fruitful entry point into community engagement. Lastly, policy is critical for incentivizing climate solutions; thus, partnering with policy advocates and government agencies can help translate science into action. Environmental issues, such as climate change, are highly complex in nature and thus require interdisciplinary approaches to responsible and scalable solution development.

Conclusion

Geoscientists (e.g., geologists, biogeochemists, soil scientists, etc.) are interested in the prospect of EW as a climate mitigation opportunity. While many geoscientists have the unique skill set to explore questions related to EW, few have experience working in contexts where EW is most likely to be applied (e.g., agronomy, rangeland science, forest ecology, coastal ecology, etc.). Geology and agronomy differ in their scientific approach in many ways; thus, we provide a path for incorporating robust geologic measurement techniques into agronomic field trials. While collaborations with interdisciplinary researchers and stakeholders can aid in research project facilitation, we seek to provide a framework by which researchers who are interested in the topic of EW in working lands can gain insight prior to the onset of a new project. As a new and emerging field that urgently requires more field testing across a variety of systems before becoming a viable climate mitigation strategy, we aim to shed light on the experimental design and methodological considerations for geologists and agronomists when establishing new EW field trials.

Author contributions

MA and NB formulated the concept and produced a first draft of the manuscript. EG, HG, IH, and JS contributed sections of text to the manuscript. MA, NB, IH, and EG created tables and figures. BH was the primary investigator, MA was the program manager, and NB was the postdoctoral scholar who led all co-authors in the field research project that informed this manuscript. BH helped formulate concepts on silicate rock weathering methodology and provided general guidance and feedback. MA led the writing and revision of the manuscript with input from all co-authors. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2022.970429/full#supplementary-material

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