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Perspective

Enhanced Rock Weathering for Carbon Removal—Monitoring and Mitigating Potential Environmental Impacts on Agricultural Land

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ABSTRACT: Terrestrial enhanced rock weathering (ERW) is the application of pulverized silicate rock to soils for the purposes of carbon removal and improved soil health. Although a geochemical modeling framework for ERW in soils is emerging, there is a scarcity of experimental and field trial data exploring potential environmental impacts, risks, and monitoring strategies associated with this practice. This paper identifies potential negative consequences and positive cobenefits of ERW scale-up and suggests mitigation and monitoring strategies. To do so, we examined literature on not only ERW but also industry, agriculture, ecosystem science, water chemistry, and human health. From this work, we develop recommendations for future research, infrastructure, and policy needs. We also recommend target metrics, risk mitigation strategies, and best practices for monitoring that will permit early detection and prevention of negative environmental impacts.

KEYWORDS: *carbon dioxide removal, negative emission technology, monitoring, reporting, verification, environmental impacts, silicate weathering*

INTRODUCTION

Terrestrial weathering of silicate minerals, operating on geologic time scales,[1,2] consumes and fixes atmospheric carbon dioxide,[3] alkalizes soils,[4] and provides a range of macro- and micronutrients to soils and waters.[5] This weathering process, and provision of its associated benefits, may be accelerated by pulverizing rock to finer, high-surface-area particles, and dispersing them in a reactive medium, such as the soils of a farm field where roots, microbes, and a high soil pCO_2 promote weathering.[6,7] This process has become known as enhanced rock weathering (ERW).

The geochemistry of ERW and its theoretical potential for carbon removal have been well-described in a series of reports and studies.[7,8] However, the relative novelty of the field means that there is a shortage of experimental and field data,[9] and that existing research has largely focused on theoretical modeling of ERW outcomes for carbon removal, with few studies addressing impacts beyond the carbon cycle.[5,10]

Only recently has research begun to emerge that directly addresses fundamental questions about how ERW practices will affect land, water, and lifeforms.[11] Recently, Vandeginste et al. outlined environmental risks of ERW to ecosystems, water, and air,[12] while Taylor et al. detailed impacts on soil respiration and pH on streamwater organisms.[3] While instructive, these papers also highlight the uncertainties and distributed nature of ERW environmental impacts—there continues to be a need for robust monitoring and mitigation guidance that can assist practitioners and policymakers in implementing ERW.

In this paper, we explore the potential environmental impacts of ERW of silicate minerals on agricultural cropland for the purpose of carbon sequestration. Rangelands, roads, waterways, and oceans are also candidates for the application of pulverized minerals, which may represent their own unique environmental questions that need to be examined. Carbonate minerals may also be used in ERW, and the wealth of research into their application to agriculture has been used here to inform outcomes for silicate weathering where relevant, as discussed in the supplement.

We provide a detailed exploration of ERW environmental risks, from point of application to final storage (Table S1). We conclude by tabulating clear monitoring and mitigation recommendations (Table 1). We suggest key thresholds, safe

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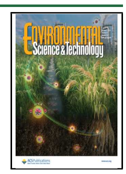

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ranges for geochemical indicators, and best practice for monitoring metrics (Tables S2 and S3).

TERRESTRIAL IMPACTS

Direct addition of powdered rock to soils affects the composition, chemistry, and physical properties of both the soil itself, and the microbiota, macrobiota, and crops onsite.

Accumulation of Trace and Major Elements. Pulverized rocks may contain trace elements that can accumulate to hazardous concentrations in the soil.[13] In natural soils developed on ultramafic[14] and basaltic[15] bedrock, parent rock composition is the primary determinant of soil contamination.

Ultramafic feedstocks can also contain significant quantities of chromium, a known carcinogen at relatively low environmental levels if present as chromium VI.[16,17] Chromium, nickel, and copper can also be harmful to soil biota at high abundance.[18−20] Basaltic rocks are expected to contain fewer of these elements than ultramafic rocks, although they react more slowly in soils and may need to be deployed in higher volumes.[21] ERW using basalt as a feedstock also has the potential to release bioavailable phosphorus, dissolved silicon, and other key micronutrients (molybdenum, cobalt, iron).[22]

Many trace elements (such as nickel and chromium) are immobilized in soil through sorption and secondary mineral formation[23,24] under typical field conditions.[25,26] In a five-month mesocosm trial, 99% of nickel and chromium released from olivine weathering was retained in soils.[26] Trace metal accumulation in the edible parts of crop plants cultivated in basalt-amended soils is low, even if soil concentrations are elevated, based on both experimental and field evidence.[22,24,27] In addition, ultramafic feedstocks require screening for asbestos or radionuclides prior to deployment to prevent release into the environment.[11,28]

Suitable ERW feedstocks are usually high in major cation concentrations because they are directly correlated to feedstock CDR potential.[29] Hence, ERW releases large amounts of calcium and magnesium, as well as sodium and potassium which may alter soil physicochemical properties (e.g., porosity and hydraulic conductivity; see also below) and the soil microbiome. Furthermore, feedstocks that are enriched in magnesium but not calcium (e.g., olivine, dunite) may increase soil magnesium/calcium ratios which can cause a decrease in grain yields (e.g., for wheat) and calcium deficiencies in extreme cases when soil water magnesium/(calcium+magnesium) is greater than 90%.[30,31]

Soil Physical Properties. Amending soils with silicate rock dust could alter soil porosity, soil partial pressure of carbon dioxide, and soil moisture, to an extent that depends on application rate, weathering rates and downward transport of applied grains, as well as site water balance. For example, very fine particulates with the granularity of silt or clay[11,28] can reduce soil hydraulic conductivity, oversaturate pore water space, and promote surface runoff.[32] Topsoil exposed to carbonaceous dust can exhibit a lower hydraulic conductivity and higher runoff.[33−35] Marble powder in sandy soils may decrease soil pore size, increase water retention, and decrease hydraulic conductivity.[36] A pedotransfer model suggested that basalt powder, applied at the theoretical quantity needed to supply nutrient demand of phosphorus, would have a minor effect on soil hydraulic conductivity and plant-available water.[37] However, this requires field and laboratory studies to evaluate. Secondary effects on soil properties may follow ERW if cation release of silicate grains changes mineral-organic matter interactions,[37] and dissolution of calcium-rich ERW feedstocks oversaturates pore water calcium carbonate leading to secondary carbonate precipitation.[38−41] However, such effects depend strongly on soil pH and may be reversible if the carbonates undergo seasonal redissolution.[18,38−40]

Soil Chemistry and Environmental Consequences. Weathering of silicate minerals increases soil pH by neutralizing carbonic acid and supplying base cations.[42−46] Increasing pH via weathering tends also to increase cation exchange capacity and cation retention.[47−49] This generally acts to improve soil fertility, although some micronutrients (sulfur, potassium, and boron) become less available at high pH, and realized bioavailability depends on local soil biogeochemistry.[50]

Most agricultural crop species require a soil pH of around 6.5 to 7 to maintain optimum nutrient uptake and avoid toxicity from trace metals.[51] However, 50−60% of agricultural soils are more acidic than this (Figures S2 and S3), indicating a clear potential for ERW to increase pH to a desirable range. About 20% of global cropland has a pH lower than 6.2, indicating that they may lose soil organic carbon if pH is increased.[52] On circumneutral soils, ERW-mediated alkalization may reduce iron, zinc, and manganese bioavailability.[53] About 20% of soils have a pH > 7.5 (5% > pH 8) − these calcareous soils are poorly suited for ERW, and would likely not be further alkalized even if ERW mineral were applied. The liming potential of ERW feedstocks can be estimated based on the stoichiometry of their composition and expected dissolution time frame. Adverse pH effects can therefore be prevented by limiting feedstock application to manage pH within the acceptable range for a given crop type.

Micronutrient Content for Crop Quality. Initial research suggests it is possible that rock derived micronutrients may help overcome deficiencies in crops - for instance, zinc, copper, manganese, boron, or iron shortfalls.[22,54−56] Silicon release by silicate rock weathering can make crops more resistant to abiotic effects such as wind damage, drought, salinity, and heat.[57,58] Increased silicon release and uptake can also inhibit crop root uptake of heavy metals such as cadmium, arsenic, and lead.[54]

Ecosystems and Organisms. Raising pH via ERW is likely to improve bacterial and earthworm abundance,[59−63] potentially improving nutrient cycling and agricultural soil function.[61] Ground-dwelling invertebrates might be affected by increased dust[64] − past studies have found sensitivity to compost or ground cover application.[65]

AIR AND AEROSOLS

Rock dust from ERW application may be transported beyond target croplands via wind erosion. Wind transport from fields or storage piles can affect local air quality and be redeposited on surrounding croplands and ecosystems. Dust particles from the soil surface can be transported away from the target site by wind on a regional scale. Small, dry particles will be transported further and in larger quantity−transport generally falls off exponentially with distance from the source.[66−69]

Inhalation of Particulate Matter. Potential human health impacts of ERW will be critical to identify before widespread scale-up. A significant concern is the effect of dust generation on human health, during field application and management. The effect of inorganic mineral dust on human health depends on particle size and composition.[70] Basaltic dust in Iceland has

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Table 1. Recommendations for Mitigating and Monitoring Environmental Risk of Enhanced Rock Weathering, As Well As Further Research Needs

Impact	Metric	Monitoring Recommendation	Mitigation Recommendation
Accumulation of trace elements in soils and biomass	Trace element concentration	Assess absolute and bioavailable concentrations of key elements in soils and biomass	Select feedstocks based on low trace element content: low contamination basalts preferred, avoid ultramafic
			Use hyperaccumulating plants to prevent or remediate build up in soils
Magnesium excess in soils	Major element concentration	Assess magnesium concentrations in soil exchangeable extracts and soil pore water or effluent magnesium/(calcium+magnesium) ratios	Use or switch to feedstocks with lower magnesium/calcium ratio
Loss of soil permeability due to carbonate accumulation in soils	Runoff/Ponding	Visual evaluation by farmer or landowner	Increase permeability via aeration and tillage
	Salinity	Assessment of electrical conductivity	Improve soil water holding capacity via organic amendments
	Porosity	Bulk soil and particle density monitoring	Reduce or halt mineral application
Alkalization of soils	Nutrient availability	Filtration and inductively coupled plasma emission spectrometer	Reduce or halt mineral application
	pH	Check soil pH every 2−3 years, ideally sampling should take place in the fall, defer to crop specific guidance	
	Soil microbial activity	Soil respiration test	
Contamination of soils	Radiation	Detection with Geiger counter	Select feedstocks based on low radiation measure
	Asbestos	X-ray Diffraction Analysis and/or microscopy	Select feedstocks based on low asbestos content: avoid serpentinized ultramafics
Respiratory disease from mineral dust inhalation	Pneumoconiosis	Medical research studies to assess exposure risk and outcomes	Comply with health and safety guidance for all workers and operators
	PM 2.5	Air quality sensor	Minimize open rock dust piles
	PM 10		Deploy when windspeeds low
			Reduce number of tractor passes and vehicle speed
			Maintain soil cover via plants and mulching
			Increase soil moisture prior to deployment if water supplies allow
Loss of sensitive ecosystems and organisms	Biodiversity	Annual transect surveys	Avoid sensitive environments with low nutrient inputs and pH, such as bogs or moorlands
	Community composition		
Physical damage to plants	Mortality	Annual transect surveys	Minimize open rock dust piles
	Yield		Deploy when windspeeds low
			Reduce number of tractor passes and vehicle speed
			Maintain soil cover via plants and mulching
			Increase soil moisture prior to deployment if water supplies allow
Alkalization of freshwater systems	pH	Water sampling from weirs along stream length	Deploy on watersheds with a history of acidification from industry and agriculture
			Avoid watersheds with historically high pH and low carbon export
			Manage upstream inputs
Increase in freshwater turbidity	Turbidity	Water sampling from weirs along stream length	Minimize open rock dust piles
			Maintain a barrier between streams and application sites or mineral stockpiles: use bioactive berms, riparian corridors, and hyperaccumulating plants
			Manage upstream inputs
Freshwater bioavailability of trace metals	Concentration	Water sampling from weirs along stream length	Maintain a barrier between streams and application sites or mineral stockpiles: use bioactive berms, riparian corridors, and hyperaccumulating plants
			Manage upstream inputs
Loss of sensitive freshwater ecosystems and organisms	Biodiversity	Tracking of key fisheries, changes in abundance	Develop biological condition gradient responses to changes in ions
	Community composition	Water sampling from weirs along stream length	Monitor changes to water chemistry including pH and trace metals
	Fisheries health		

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Table 1. continued

Impact	Metric	Monitoring Recommendation	Mitigation Recommendation
Photosynthetically driven eutrophication of freshwater ecosystems	Dissolved oxygen concentration	Water sampling from weirs along stream length	Manage upstream inputs
Alkalization of marine systems	pH Aragonite saturation	Water sampling from static buoys and coastal monitoring	Manage upstream inputs
Eutrophication of marine systems	Bioavailable nitrogen Plankton ecology	Water sampling from static buoys and coastal monitoring	Manage upstream inputs
Loss of sensitive marine ecosystems and organisms	Biodiversity Community composition Fisheries health	Tracking of key fisheries, changes in abundance Water sampling from static buoys and coastal monitoring	Manage upstream inputs

been found to reduce air quality and increase hospital admissions.[71] Carbonate mineral dust, produced by marble factories in excess of World Health Organization safety guidelines, increased local hospitalizations for breathing problems.[72] Inhalation of silica-containing farm dust can cause pneumoconiosis and lung inflammation in farm workers even in the absence of ERW.[73−75] Health hazards may be magnified in low-income and disadvantaged regions and countries.[76]

Physical Impact on Plants and Ecosystems. Particles finer than 10 μm can coat plant surfaces, reducing photosynthesis and causing die-back or death.[69,77] Lichens, liverworts, and sphagnum may be particularly vulnerable, based on observed impacts of road dust.[69] Crop species have been shown to be vulnerable as well, based on experiments with cement and kiln dust. Saltation of larger particles may physically damage[78] or bury short-stature plants and seedlings.[79] Dust contains micro- and macronutrients as well as metals and other environmental pollutants, which have been found to alter biogeochemical cycling and nutrient availability adjacent to roads, agricultural fields, or even in distant geographies.[80−82]

Alteration of pH in Nontarget Ecosystems. Noncropland ecosystems may be more vulnerable to disturbance as a result of altered pH. Highly acidic soils (pH < 5.5), such as those found in bogs and wetlands, may host unique microbes[83] and provide ecosystem services including soil carbon stabilization.[84] Liming acidic soils can be linked with loss of soil organic carbon due either to increased microbial carbon use efficiency or increased specific respiration, especially at pH below ∼6.2.[52] However, this pH effect is not linear and does not continue to increase with higher lime application rates.[85]

■ FRESHWATER

ERW projects assume the eventual migration of carbonate ions from their farm source to storage in the ocean. However, carbonate and leached elements enter freshwater streams, rivers, lakes and reservoirs. There are a number of potential impacts on inland waters, but it is important to point out that they have seen widespread acidification since industrialization[86,87] − thus it is important to note that the anticipated alkalization from ERW may be viewed in some regions as recovery from past acidification and associated negative consequences.

Alkalinity and pH in Freshwater Environments. Enhanced weathering has the potential to increase alkalinity and pH and lower dissolved organic carbon.[88] Alkalization and inorganic carbon limitation have been shown to restrict phytoplankton primary productivity.[89] It may also decrease photosynthesis[90−92] improve carbonate shell production in freshwater crustaceans,[93] alter food web community structure,[92] and result in more nutrient-rich phyto- and zooplankton.[91,92,94] Therefore, enhanced rock weathering may alleviate eutrophication in acidified freshwater systems. Carbonate chemistry and pH can also alter the bioavailability of many metals[95,96] and change speciation and complexation.[97−100]

While there has been extensive research on the consequences of aquatic acidification, alkalization is far less studied.[92] However, we can anticipate that past human impacts and natural variability will all play a role in defining outcomes. These changes may be highly beneficial in the large number of water basins globally with naturally low buffering capacity and

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a history of acidification. Restoration work in catchments like these has previously made use of mineral weathering to restore fisheries and ecosystem function to acidified waters.[101−104] ERW will likely be less beneficial to waters that are naturally buffered with high alkalinity and low water throughput.

Erosion and Leaching of Trace Elements. Inorganic nutrients from rock dust may also be blown or leached into adjacent water bodies. Experimental evidence is somewhat divided on leachability of metals from soils. Some studies show elevated nickel concentrations in pore water[24,105] while others find little or none.[22,26,106] Theoretical research on trace metal exposure from ERW used upper bounds for element leaching from an acidic, forest soil, citing leaching to groundwater as high as 17% (nickel) and low as 3% (chromium).[107] However, additional research is required to identify how the assumptions used in this review translate to ERW on agricultural soils.

Nutrients such as phosphorus can contribute to algal blooms, leading to eutrophication and hypoxia in aquatic ecosystems.[108,109] However, silicate from ERW minerals may reduce blooms, as it can theoretically shift freshwater stoichiometry to favor diatoms over algae, dinoflagellates, and cyanobacteria.[54,110]

Where the fine particles from enhanced rock weathering are vulnerable to erosion, they can be washed into streams and contribute to turbidity in the water column.[51] The impact may be to reduce photosynthesis and survival of submerged vegetation, with subsequent impacts on the aquatic food chain.

MARINE

ERW at scale is expected to impact coastal and open marine systems primarily via downstream alterations to ocean carbonate chemistry,[111] as well as through increased presence of silicon and solutes leached upstream from ERW feedstocks.

Ocean Carbonate Chemistry. ERW solutes will generally increase abundance of carbonate ion and calcium carbonate saturation states in the coastal ocean (Figure S4). Simulations of large-scale ERW roll-out show elevation in surface ocean aragonite saturation, particularly near river mouths but also into the open ocean.[3,112] While local, transient extremes in carbonate saturation state may have unintended ecological impacts, increased carbonate saturation states would in many cases be a clear benefit for coastal marine ecosystems.

Trace Elements and Fertility. Additional potential impacts of other solutes released during ERW are less-known and depend on feedstock used and upstream filtering. While filtering and transfer efficiency are not well-studied at present, model simulations have suggested ocean olivine application will have significant ecological impacts on phytoplankton communities via introduction of silicon and iron.[113,114] In particular, increased bioavailability of dissolved silicon may cause ecological shifts (e.g., greater diatom abundance in certain regions).[110] Whether terrestrial ERW would have analogous impacts—and whether most silicon and other macro- and micronutrients are removed by upstream filtering before introduction to the coastal ocean—represent important topics for future research.

Lastly, a largely unexplored potential positive impact of ERW is the potential for increased nitrogen use efficiency (NUE) in terrestrial systems due to basalt feedstock. There is a well-documented correlation between increasing soil pH and increased NUE in row crops.[115,116] Long-term field trials amending a corn-soy system with basalt indicate the potential for significant increases in NUE.[22] This could have obvious agronomic benefits, but it could also potentially impact marine systems by reducing nutrient fluxes from managed lands into coastal marine settings. This dynamic—in particular a multi-nutrient budget for ERW across a range of feedstocks and deployment scenarios—represents an important topic for additional research.

DISCUSSION

ERW is an agricultural practice that could exert an environmental influence across terrestrial, atmospheric, freshwater, and marine systems, with potential to significantly impact nontarget ecosystem services at scales from local to global. Here, we have provided a comprehensive hierarchy of monitoring recommendations during deployment.

At the application site, trace element accumulation from contaminated feedstocks poses a high risk to human health and ecosystems. However, monitoring and mitigation technologies are accessible and well-understood (Table 1). We recommend that ERW projects prioritize feedstocks with low harmful metal abundances—e.g., basalt should be selected over ultramafic rocks such as dunite and olivine. At the site-level, project developers should provide landowners with feedstock composition data, including not only the highest risk metals (chromium, nickel) but also trace metals that could accumulate to risky levels in soil on the order of decades (zinc, copper). Finally, there is a need for regulatory policy and/or technical assistance to define thresholds of trace metal accumulation rates and maximum concentrations which protect agriculture and ecosystems in the long term. These thresholds should consider both annual and cumulative trace element concentrations and that some soils may have higher starting baselines of trace element content. Regulatory thresholds for relevant trace elements in soils currently exist in Brazil, Canada, China, Germany, and Russia.[21] Thresholds should be set for other countries where ERW is expected to or is taking place. Monitoring of this risk is expected to be affordable and the technology readily available (Table S2). Low-metal sources for mineral dust can be identified through public data in many countries, however there are significant data gaps in the global south which may slow project development. Testing for trace elements in both mineral dust and soils is a well-developed science—however, there will be a need to streamline monitoring to keep costs low for project developers and landowners.

We considered the risk to soil porosity and hydraulic conductivity from ERW to be medium to low, with the risk largely dictated by the need for additional research. Mitigation strategies are expected to be accessible and depend largely on thoughtful selection of ERW sites. We recommend that ERW projects avoid high-clay soils with poor drainage and arid soils where carbonate formation is highest. Monitoring may be prioritized particularly for pilot and demonstration plots where data can contribute to overall knowledge of the significance of this impact.

Impacts to human health from dust and inhalation were considered the highest risk within air and aerosol systems. Particularly at local scales, fine particulate matter and pneumoconiosis may be potentially high risk. However, there is also high mitigation potential—exposure to dust, including silicate dust, is already well-known in agriculture. At field-scale, dust may be addressed through reducing worker exposure as outlined by current occupational health and safety guidelines. Compliance with safety guidelines will be the responsibility of the project developer or landowner—enforcement of these guidelines will occur at the scale of national and local governments. Regional-scale dust transport can be prevented by applying minerals wet, then trenching or tilling them into the soil profile. In the United States, some regions at high risk for agricultural dust transport already require landowners to follow these protocols. Monitoring is technologically well-developed, however the cost of monitoring may be high and requires investment in infrastructure to capture an impact that tends to be highly seasonal and weather dependent.

In freshwater ecosystems, impacts become less severe but also less mitigatable. Impacts to waterway pH are most significant and must be mitigated via discrimination during site selection. Practitioners should target low-pH and high-carbon-export watersheds.[117] Acute inputs of trace elements can be addressed via siting regulations standard in freshwater protection including keeping mineral stockpiles away from stream edges, supporting riparian corridors or bioactive berms, and using hyperaccumulating plants as appropriate. Chronic leaching must be mitigated by keeping concentrations in soils below described safety thresholds.[15] Monitoring of both pH and trace elements is technologically developed but relatively intensive, requiring either dedicated infrastructure or substantial human effort. It may be possible to reduce costs by placing ERW in watersheds which already require monitoring as part of restoration and fisheries management research.

Marine ecosystems risks are lower but have low mitigation potential as impacts are defined by upstream decisions and extremes in weather and time. The most significant of these risks is a change to carbonate chemistry, although we stress that in many cases this actually represents a cobenefit of ERW deployment rather than an environmental risk. Mitigation might involve reduction of ERW at a regional scale, with large-scale monitoring reliant on new technology development and infrastructure, or development of fine-scale modeling to predict coastal impacts from upstream data.

Environmental impacts require large-scale, sector-level monitoring beyond the application site.[115] Counting on suppliers to perform this function may duplicate existing governmental monitoring efforts and lead to lower-quality monitoring by creating conflicting incentives. Alternatively, environmental monitoring could be performed or overseen by public agencies. This may be mandated by overarching frameworks of environmental governance, such as the European Union's environmental impact assessment directive, which may extend to ERW projects. Alternatively, narrower mandates may already support monitoring that can be leveraged to inform ERW implementation. Approaching monitoring through sector-level public policy will reduce the potential for conflicts of interest and more efficiently leverage learnings to reduce costs and requirements for monitoring over time.[118]

Irrespective of the actual implementation path chosen, it is paramount that policy efforts and shaping of the CDR market proactively addresses large-scale environmental monitoring. This is a fundamental aspect of managing environmental impacts of ERW and cannot be left up to supplier discretion or sporadic and uncoordinated investigation of academic actors. Global frameworks and monitoring standards are going to be necessary to prevent ERW outsourcing into countries with more lax environmental regulation and related potential exacerbation of climate justice concerns.[119] It will be essential to create space for public input and involvement, particularly as ERW is currently not well-understood or broadly supported by the public.[118,120−122]

ERW is a relatively novel proposed pathway to carbon removal—as such it is only just developing the research base needed to implement it at scale. We identify that while substantial research gaps remain, parallel research from adjacent fields can supply us with a sense of which potential environmental impacts are anticipated to be most significant, most monitorable, and most mitigable. This can help direct ongoing research effort toward the most significant issues for the field. Additionally, this approach identifies where new policy is needed to ensure adequate monitoring is being conducted and that best practices are being consistently implemented.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c02368.

> Monitoring and mitigation approaches for environmental risks, including geographic scale of the impact, level of concern of the risk from low to high, and political entity potentially responsible for monitoring and mitigation; narrative analysis and figures to show the suitability for enhanced rock weathering of terrestrial geographic regions based on agricultural activity and pH and marine geographic regions based on fisheries activity and aragonite saturation; expansion on lower risk environmental impacts and the rationale behind the assessment of monitoring and mitigation potential; the reasoning for focus on silicate rock weathering and how this paper would apply to carbonate minerals (PDF)

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Notes

The authors declare the following competing financial interest(s): D.J.B. has a minority equity stake in companies (Future Forest/Undo), is a member of the Advisory Board of the Carbon Community, a UK carbon removal charity, and the Scientific Advisory Council of the non-profit Carbon Technology Research Foundation. P.R. is a scientific advisor to CREW Carbon. The remaining authors declare no competing interests.

Biographies

Charlotte Levy, is a Managing Research Advisor at Carbon180, focusing on scaling carbon removal technologies with an emphasis on climate justice. She earned her doctorate from Cornell University in 2019 in Ecology and Evolutionary Biology with a focus on biogeochemistry. In her previous role as an AAAS Executive Fellow at the Department of Energy's Bioenergy Technologies Office she supported the "Roads to Removal" report on local opportunities for carbon dioxide removal, earning the Assistant Secretary's 2022 Outstanding Achievement Award. Dr. Levy's career includes a research fellowship at the School for Environment, UMass Boston, where she integrated satellite data with climate mitigation strategies. A dedicated advocate for community-driven climate policy and environmental justice, she has led the policy team for 500 Women Scientists and chaired the Policy Section of the Ecological Society of America (ESA), which honored her with the Katherine S. McCarter Award for Policy in 2019.

Maya Almaraz is trained as a biogeochemist, specializing in carbon and nitrogen cycling as they relate to food production, nutrient pollution, and natural climate solutions. She is currently an Associate Research Scientist with the Yale Center for Natural Carbon Capture and the Yale School of the Environment. Maya has worked as an Associate Research Scholar in Sustainable Food Systems at Princeton University, a Carbon Scientist with The Nature Conservancy, and managed the Working Lands Innovation Center out of UC Davis. She was a Postdoctoral Fellow with World Wildlife Fund at UC Santa Barbara's National Center for Ecological Analysis and Synthesis and was a National Science Foundation Postdoctoral Fellow in Biology at UC Davis. Maya earned a B.A. in Public Health and a B.S. in Conservation and Resource Studies from UC Berkeley and received her Ph.D. from Brown University in Ecology and Evolutionary Biology.

David J. Beerling is the founder and Director of the Leverhulme Centre for Climate Change Mitigation, a premier international Centre for carbon dioxide removal, funded through a Leverhulme Research Centre award in 2015 (£10 million) from the Leverhulme Trust. We focus on the biogeochemical improvement of agricultural lands with natural and artificial silicates. A notable early achievement has been our establishment of a network of long-term field sites across three continents assessing carbon capture with diverse agricultural ecosystems and possible cobenefits for soil health and yields, alongside engagement with the public, NGOs and stakeholders.

Peter Raymond's research focuses on the chemistry and ecology of inland waters. This includes research on the exchange of greenhouse gases between inland waters and the atmosphere, controls on the transport of terrestrial elements to inland and coastal waters, the metabolism of aquatic ecosystems, and how storms and droughts impact aquatic ecology. He also uses radiocarbon measurements to explore the age and turnover of carbon in aquatic ecosystems. Raymond was the Editor and Chief of the American Geophysical Union's journal *Global Biogeochemical Cycles*. Raymond received his BS from Marist College and his PhD from the Virginia Institute of Marine Science (College of William and Mary). He is a fellow of the American Association for the Advancement of Science, a member of the Connecticut Academy of Science and Engineering, received the Coastal and Estuarine Research Federations Cronin Award for Young Scientists, and is an ISI highly cited author.

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Christopher. T. Reinhard is a biogeochemist and Earth system modeler, specializing in the global biogeochemical cycles of carbon, oxygen, and phosphorus. He is currently Associate Professor of Biogeochemistry and Georgia Power Chair in the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Previously, Reinhard was an O.K. Earl Postdoctoral Fellow in the Division of Geological and Planetary Sciences at Caltech, having received PhD and MS degrees in Earth Sciences from the University of California, Riverside and a BS in Ecology and Evolutionary Biology from the University of Kansas.

Tim Jesper Suhrhoff is a geochemist and modeler, primarily using interdisciplinary approaches to investigate how to quantify carbon dioxide removal from enhanced weathering. Jesper obtained his PhD from the Swiss Federal Institute of Technology (ETH Zürich) in 2023, where he used sediment records from Lake Baikal to reconstruct how silicate weathering changed as a function of climate during the last glacial cycles. Funded by the Swiss National Science Foundation, Jesper joined Yale University as a Postdoctoral Fellow in April 2023, where he primarily works with the group of Prof. Dr. Noah Planavsky. In his work, he combines modeling and analytical approaches based on both soil and water samples to develop quantification frameworks for carbon dioxide removal from enhanced rock weathering experiments and field trials. In addition, in his work he focuses on questions of additionality of carbon dioxide removal, how existing natural records can be used to constrain transfer time lags of weathering products from weathering sites to the ocean, as well as how environmental risks of enhanced weathering may be mitigated.

Lyla Taylor is an interdisciplinary process modeller of vegetation and weathering geochemistry. With previous experience in astronomy, geophysics, geology, palaeontology and botany, her PhD on the effect of plants and fungi on the long-term carbon cycle was conferred in 2012 by the University of Sheffield. At present, she is a senior research fellow within the Leverhulme Centre for Climate Change Mitigation at the University of Sheffield, where she aims to quantify carbon capture and greenhouse-gas balances associated with silicate mineral treatments on managed land and in laboratory experiments.

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