Carbon Direct

A BUYER'S GUIDE TO

Enhanced Rock Weathering in Croplands

July 2024

Contents

Executive summary

This report explores the current state of enhanced rock weathering (ERW) in croplands, its scientific uncertainties and risks, and technological readiness for scaled deployment as a carbon dioxide removal (CDR) solution. It also assesses the current market trajectory for ERW, proposed strategies for mitigating uncertainties and risks, and the projected pathway for global scaling. It concludes with a discussion of how buyers and stakeholders can make informed decisions about ERW with the help of current registries, project developers, and other entities in the space. Based on this analysis, buyer involvement at this stage may be most appropriately focused on investment and market scaling to drive the evolution of ERW as a CDR solution. These actions can play a part in the continued development of ERW as a cost-effective option for meeting buyer climate commitments with CDR credit offtakes.

As a CDR pathway, ERW leverages the natural carbon drawdown that occurs during the weathering process of certain alkaline materials. This weathering includes physical breakdown and chemical dissolution. In ERW cropland projects, this natural process is accelerated by applying finely ground alkaline rock over agricultural fields, often using existing equipment designed for spreading agricultural amendments such as lime or fertilizer. As this crushed rock is exposed to rainwater, irrigation, and water held within the soil, the alkaline minerals in the rock dissolve and release positively charged ions (referred to as cations), including calcium cations (Ca^{2+}) and magnesium cations (Mg^{2+}). Some of these may pair with carbon-containing anions in the water derived from atmospheric carbon dioxide (CO_2)—generally a carbon-containing anion called bicarbonate (HCO_3^-). Through the hydrologic cycle, most of this stable form of dissolved carbon (bicarbonate) leaves agricultural fields and travels through surface water systems to the ocean, where it may remain stored for millennia.

In the voluntary carbon market, excitement is building around ERW cropland projects as potential sources of durable, cost-competitive, CDR credits with numerous co-benefits. Over the coming decades, ERW has the potential to scale and annually provide gigatonnes (Gt) of CDR. Some projections suggest that ERW could provide 25–100 Gt of CDR over 50 years, which is roughly 10% of the CDR needed to limit global warming to below 2°C of pre-industrial temperatures.[1, 2] In addition to climate mitigation benefits, ERW offers potential co-benefits such as increased crop yields and a reduced need for agricultural amendments. Project developers and carbon credit buyers are anticipating its potential, as evidenced by large offtake agreements announced in 2023.[3] Carbon Direct Inc. ("Carbon Direct") identified 13 CDR purchases from ERW projects between 2021 and 2023, with prices ranging between US$119–500/tonne, and a median price of US$390/tonne (Appendix D, **table 8**).

Despite this exciting potential and building momentum, ERW cropland projects involve multiple types of risk. Some of these risks are general and intrinsic to the approach itself, such as the risk of over crediting because CO_2 removed by ERW is stored in an open system (i.e., distributed environments outside of the boundaries of project fields); the risk of misattributing some mineral reactions to carbon drawdown; or risks related to uncertainties and technical challenges in ERW carbon accounting frameworks, which are numerous, widespread, and challenging to address. Other risks are specific to a given project or methodology. Effective management of some of these risks—such as the risk of harm from applied materials, or the risk of diverting mineral feedstocks from other uses (i.e., leakage)—can be achieved with practical, conservative measures. Other known risks may increase, decrease, or simply become clearer over time as research progresses, models improve, and more field and project data become available. Risks that are inherent to and characteristic of the approach, such as limitations in the ability to directly measure and validate carbon drawdown from cropland ERW, must be acknowledged and accounted for.

Buyers of credits from ERW cropland projects should be informed about the risks involved and aware of opportunities for evaluating uncertainties around the approach. A strengths, weaknesses, opportunities, and threats (SWOT) analysis of ERW cropland projects is summarized in **table 1** and includes key risks, as described above. Depending on the outcome of ongoing research, quantification of these risks and approaches to their management could increase or reduce credit buyer confidence and public trust in ERW.

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1. Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, et al. 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature. 583(7815):242–248. doi:10.1038/s41586-020-2448-9.

2. AR6 Synthesis Report: Climate Change 2023 — IPCC. [accessed 2024 Apr 14]. https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

3. George V. 2023. Frontier Makes Largest Carbon Removal Purchase From Lithos Carbon. Carbon Herald. [accessed 2024 May 31]. https://carbonherald.com/frontier-makes-largest-carbon-removal-purchase-from-lithos-carbon/.

As cropland ERW scales, it is important to establish clear boundaries on what it means for a project to be considered high-quality. High-quality projects demonstrably remove CO_2 from the atmosphere and store it over a long period of time while causing minimal-to-no environmental or human harm.[4] Developing consensus on best practices among regulators, investors, and other actors in the industry is key for establishing high-quality ERW cropland projects, characterizing their risks, and minimizing remaining uncertainties. This report provides a detailed analysis of the challenges ERW cropland projects face in achieving high-quality status. It also includes guidance on what it would take for ERW projects to produce high-quality CDR tonnes that can be leveraged to meet buyer climate commitments.

Table 1. SWOT analysis of CDR from ERW cropland projects

STRENGTHS	WEAKNESSES
• Highly durable storage once bicarbonate reaches the deep ocean • Comparable pricing to other high-durability CDR pathways • Potential significant agricultural and environmental co-benefits • Potential to scale rapidly to provide gigatonnes of annual CDR • Deployable now	• Difficult carbon accounting due to open system and variable carbon residence time in soil, rivers, and the ocean • Uncertain potential for downstream leakage and other inefficiencies • Some sources of uncertainty may never be reduced • Potential harms to people and the environment
OPPORTUNITIES	**THREATS**
• Early commercial investments can drive research that may reduce uncertainties and facilitate scaling • Early actions may encourage broad interest in CDR via ERW, especially in developing nations and in the Global South	• Large sources of accounting uncertainty and potential for harms could lead to a loss of trust from project credit buyers and land managers • Premature low-cost contracts and exaggerated claims could depress interest in other credible forms of CDR

4. Carbon Direct and Microsoft. 2024. Criteria for High-Quality Carbon Dioxide Removal. [accessed 2024 July 11]. https://www.carbon-direct.com/research-and-reports/criteria-for-high-quality-carbon-dioxide-removal.

Enhanced rock weathering as a global climate solution

Based on one global modeling study, applying ERW to croplands at scale has the potential to remove 25–100 Gt of atmospheric CO_2 over 50 years.[5] This represents about 10% of the CO_2 removals needed to limit global warming to less than 2°C above pre-industrial temperatures.[6] Notably, this study found that the countries with the largest fossil fuel emissions—China, the United States, and India—are also the ones with the highest capacity for ERW deployment based on availability of both feedstock and suitable croplands. Similarly, the three European countries with highest potential for carbon removals from ERW deployment—Germany, Spain, and Poland—are also the largest emitters of CO_2 from fossil fuels in Europe. Indonesia and Brazil also offer high potential for ERW use, due to the appropriate climatic conditions and large areas of existing croplands in these countries.

Broadly, ERW is an emerging CDR pathway with a unique combination of risks, uncertainties, and potential co-benefits. However, buyers today may need to focus on investments to advance ERW science, de-risk projects, and scale the market. These actions may drive ERW to reach the development stage where buyers can feel confident in using ERW credits as high-quality CDR toward their climate commitments.

Currently, ERW cropland project investment efforts are characterized by a blend of private actors and suppliers, which are predominantly in the pilot phase, and university research entities (**figure 1** and Appendix B, **table 5**). Some suppliers of ERW projects are projecting the ability to bring as much as one billion tonnes of CDR to the market by 2030 (**figure 2**).

5. Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, et al. 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature. 583(7815):242–248. doi:10.1038/s41586-020-2448-9.

6. AR6 Synthesis Report: Climate Change 2023 — IPCC. [accessed 2024 Apr 14]. https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

Interest and investment in ERW as a climate solution is growing. Private suppliers have secured large offtake agreements, including a 2023 purchase agreement between Frontier and Lithos for 154,240 tonnes of CDR from 2024 to 2028, valued at US$57.1 million.[7] Carbon Direct identified 13 purchases of ERW-based CDR between 2021 and 2023 with prices varying between US$119–500/tonne, and a median price of US$390/tonne (Appendix D, **table 8**). This current average price is significantly higher than projected future costs of credits from ERW cropland projects when implemented at scale, which are predicted to be between US$45–472/tonne (Appendix C, **table 6**); most estimates fall in the range of US$60–220/tonne. These predictions suggest that future market prices could fall significantly.

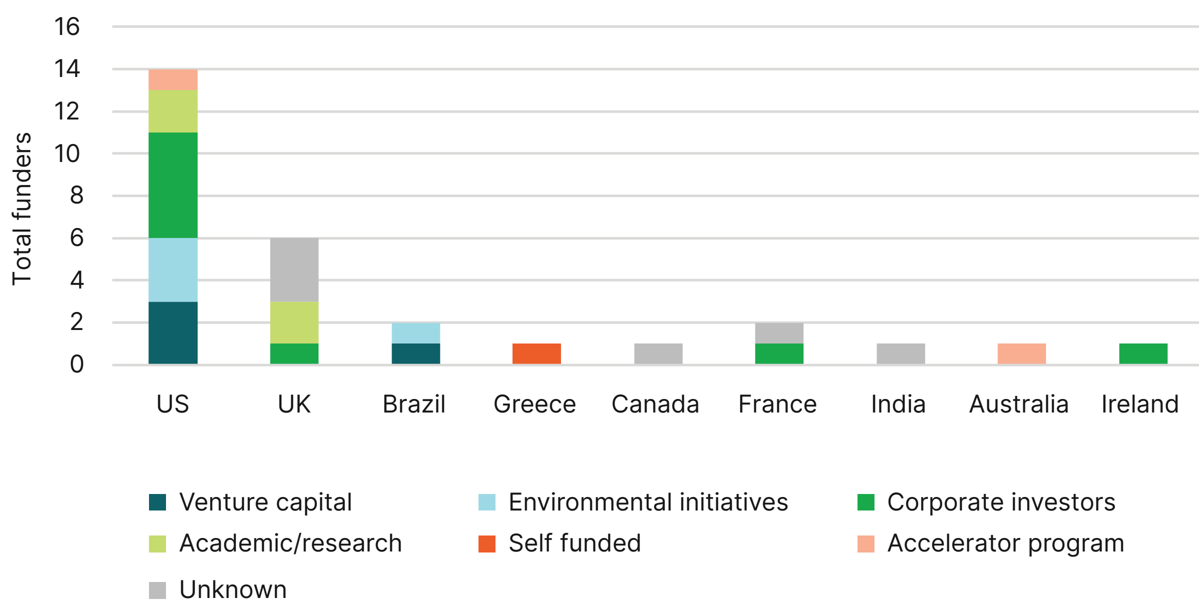

Figure 1. Types of investment in ERW projects by country. Note: Some projects have more than one investor type. Some of the academic and research projects highlighted here received funding from government programs. See Appendix B for additional information on projects included in this analysis.

7. George V. 2023. Frontier Makes Largest Carbon Removal Purchase From Lithos Carbon. Carbon Herald. [accessed 2024 May 31]. https://carbonherald.com/frontier-makes-largest-carbon-removal-purchase-from-lithos-carbon/.

Global enhanced rock weathering offtake commitments by 2030, in metric tonnes

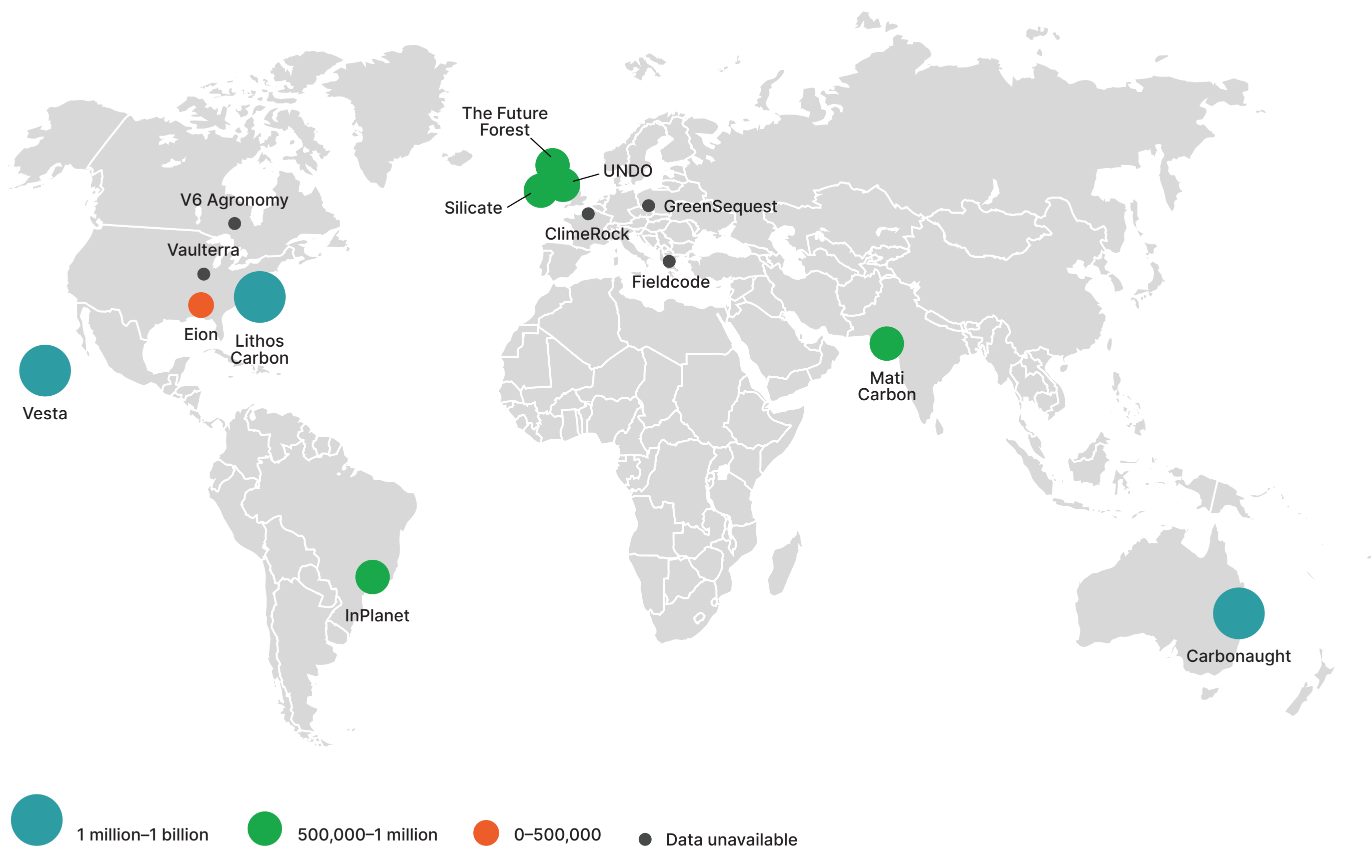

Figure 2. Location and cumulative intended 2030 offtake goals of private suppliers, globally. Note: Vesta is a coastal enhanced rock weathering effort that does not take place on croplands.

Leveraging natural geochemical processes for carbon sequestration

ERW, as a CDR pathway, leverages the natural atmospheric CO_2 drawdown that occurs during the weathering of certain types of minerals. Natural mineral weathering takes place over geologic time scales (>1,000 years), but can be accelerated to timescales relevant to combat climate change. This report focuses on ERW in croplands, where the weathering process is accelerated by spreading crushed alkaline feedstocks across a land area where crops are grown.

The small particle size of the feedstock increases the surface area available for mineral dissolution into water and accelerates the weathering process. As illustrated in **figure 3**, when these minerals dissolve in water in the soil column they release cations, some of which may pair with carbon-containing anions in the water—generally a carbon-containing anion called bicarbonate (HCO_3^-). These cations and dissolved inorganic carbon anions then may make their way through the soil column over time, into streams and rivers, and ultimately into the ocean. Once they reach the ocean, either (a) all the carbon remains dissolved or (b) some of the carbon precipitates to form solid carbonate minerals and, as part of the precipitation reaction, an equal amount is released back into the atmosphere as CO_2. This carbonate mineral precipitation can occur in alkaline solutions that are saturated with cations and dissolved inorganic carbon anions.

Underwater view of a freshwater riverbed. (Source: Adobe Stock).

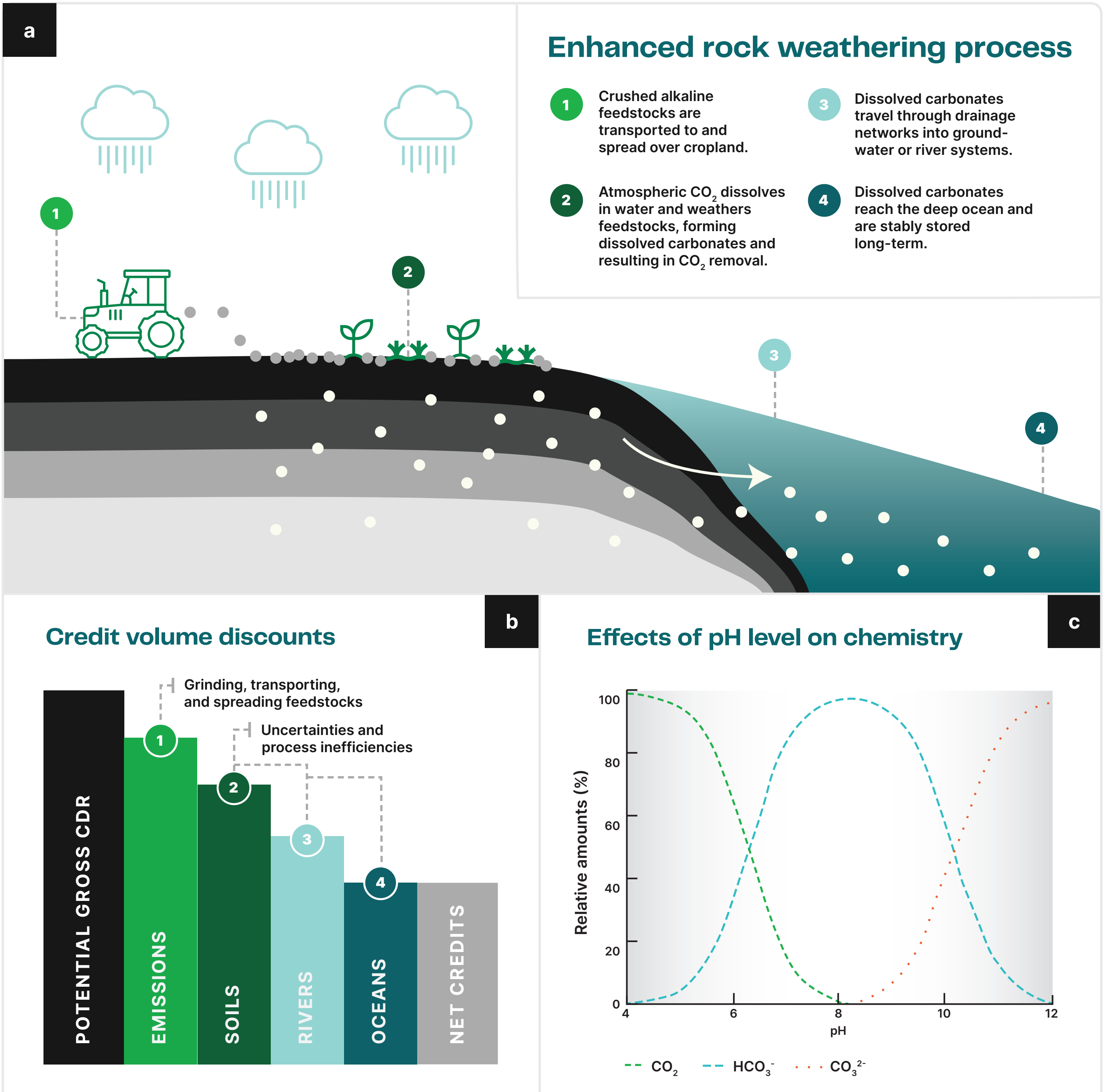

Figure 3. The enhanced rock weathering process (a); qualitative representation of process-based impacts on potential carbon dioxide removal (CDR) credit volumes with gross-to-net discounts made for emissions, uncertainties, and inefficiencies (b); and chemical speciation diagram showing relative amounts of dissolved carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate ions (CO_3^{2-}) at various pH levels (c). Note: The background gradient in panel c indicates the likelihood of CO_2 release back to the atmosphere at various pH levels, with darker tones indicating greater likelihood. At lower pH levels (more acidic conditions) CO_2 may return to the atmosphere; at pH levels closer to neutral, durable carbon storage as bicarbonate ions is likely; and at high pH levels (more alkaline conditions) carbonate minerals may precipitate out of solution, releasing some CO_2.

The scalability and success of ERW in croplands is a function of available mineral feedstock, appropriate soils and climate for application, and rigorous carbon accounting. Appropriate mineral feedstocks for ERW range and can include mined silicate rocks (e.g., basalt, peridotite, serpentinite), mined minerals (e.g., olivine, wollastonite), or waste products from other industries with the right chemistries (e.g., cement kiln dust, fly ash). The ideal mineral feedstocks for ERW have three main characteristics: small particle size, which enables them to rapidly dissolve in water; high concentrations of cations like calcium and magnesium; and low concentrations of heavy metals. Appropriate cropland areas for ERW vary widely, but the CO_2 drawdown process generally happens faster in regions with higher temperatures and precipitation levels (e.g., moist, tropical soils) and lower soil pH (i.e., more acidic soils).[8, 9, 10, 11]

The application of ERW minerals to cropland generally releases cations and increases alkalinity, which can counteract the soil acidification effects of fertilization with nitrogen and help maintain healthy, productive soils. Ideally, feedstocks are located near to the lands where they will be applied, which reduces transport costs and associated greenhouse gas emissions. In some cases, feedstocks with relatively large particle size can be ground to improve their ability to quickly dissolve, but grinding adds to project costs and emissions. The net carbon removal of ERW projects is reduced when grinding or long-distance transport (e.g., by truck, train, or barge) are required. Importantly, any feedstock used in ERW must also be evaluated for the potential to inadvertently introduce harmful contaminants, such as heavy metals, into croplands, food systems, and surrounding ecosystems (**table 2**).

Potential ERW feedstocks

Many different feedstocks exist that could theoretically be used for ERW, including mined materials and mine wastes, manufactured mineral stocks, and industrial waste products. Feedstocks vary in their suitability for ERW based on the efficacy of each material's

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8. Boudinot FG, Dreyfus G, Frederick C, Powers Y. 2023. Enhanced Rock Weathering in the Global South: Exploring Potential for Enhanced Agricultural Productivity and Carbon dioxide Drawdown. [accessed 2024 April 14]. https://precisiondev.org/wp-content/uploads/2023/01/IGSDPxD-ERW-Enhanced-Rock-Weathering-in-the-Global-South-26-02-23.pdf.

9. Gillman GP, Burkett DC, Coventry RJ. 2002. Amending highly weathered soils with finely ground basalt rock. Applied Geochemistry. 17(8):987–1001. doi:10.1016/S0883-2927(02)00078-1.

10. Vicca S, Goll DS, Hagens M, Hartmann J, Janssens IA, Neubeck A, Peñuelas J, Poblador S, Rijnders J, Sardans J, et al. 2022. Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? Global Change Biology. 28(3):711–726. doi:10.1111/gcb.15993.

11. Strefler J, Amann T, Bauer N, Kriegler E, Hartmann J. 2018. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environ Res Lett. 13(3):034010. doi:10.1088/1748-9326/aaa9c4.

weathering reaction in drawing down CO_2, mineral weathering rates, cost and availability of each material at an appropriate particle size (which varies by location), opportunity costs for alternative uses, and potential harms from heavy metals or other components of each material. The major feedstocks under consideration for ERW in cropland projects, along with their risks and benefits, are listed in **table 2**.

Table 2. Comparison of feedstocks with potential for use in ERW cropland projects

Feedstock	Ultramafic rocks (peridotites and serpentines)	Mafic rocks (basalt)	Fly ash	Concrete waste and cement kiln dust
Source	Mined for purpose or for production of nickel, chromium, or diamonds	Mined for purpose or for production of copper	Industrial waste	Industrial waste
Major geographies for production	Global[12]	Global[13]	Global; China responsible for half of annual production with legacy stockpiles available globally[14]	Global[15]
Global availability	Abundant; most-reactive minerals (e.g., brucite) are more rare[16]	Widespread; about 10 times more abundant than ultramafic rocks[17]	About one Gt/yr production; expected to decrease with decline of coal	Widespread; concrete production expected to Increase 12–15% up to 2050[18]

12. Wilcox J, Kolosz B, Freeman J. 2021. Carbon Dioxide Removal Primer. Chapter 3: Global Mapping of CDR Opportunities. Carbon Dioxide Removal Primer. [accessed 2024 Apr 23]. https://cdrprimer.org/read/chapter-3.

13. Pilorgé H, Kolosz B, Wu GC, and Freeman J. 2021. Global Mapping of CDR Opportunities. In: Wilcox J, Kolosz B, Freeman J, editors.CDR Primer. [accessed 2024 May 31]. https://cdrprimer.org/read/chapter-3.

14. Meng J, Liao W, Zhang G. 2021. Emerging CO2-Mineralization Technologies for Co-Utilization of Industrial Solid Waste and Carbon Resources in China. Minerals. 11(3):274. doi:10.3390/min11030274.

15. Pilorgé H, Kolosz B, Wu GC, and Freeman J. 2021. Global Mapping of CDR Opportunities. In: Wilcox J, Kolosz B, Freeman J, editors. CDR Primer. [accessed 2024 May 31]. https://cdrprimer.org/read/chapter-3.

16. Sandalow D, Aines R, Friedmann J, Kelemen P, McCormick C, Power I, Schmidt B, Wilson S. 2021. Carbon Mineralization Roadmap. ICEF Innovation Roadmap Project. https://www.icef.go.jp/wp-content/uploads/2024/02/icef2021_roadmap.pdf.

17. Sandalow D, Aines R, Friedmann J, Kelemen P, McCormick C, Power I, Schmidt B, Wilson S. 2021. Carbon Mineralization Roadmap. ICEF Innovation Roadmap Project. https://www.icef.go.jp/wp-content/uploads/2024/02/icef2021_roadmap.pdf.

18. The International Energy Agency (IEA). 2018. Technology Roadmap—Low-Carbon Transition in the Cement Industry. [accessed 2024 May 31]. https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

Table 2. Comparison of feedstocks with potential for use in ERW cropland projects *(continued)*

Feedstock	Ultramafic rocks (peridotites and serpentines)	Mafic rocks (basalt)	Fly ash	Concrete waste and cement kiln dust
Relative weathering rate	Rapid	Moderate	Variable	Variable
Contaminant concerns	Nickel, chromium	Nickel, chromium, copper, zinc[19]	Sulfur, heavy metals including mercury	Heavy metals
Competing uses	Steel,[20] concrete,[21] mineral wools[22]	General construction aggregate	Building and construction[23]	Pavement[24] and concrete production

Defining an enhanced rock weathering credit

In an open system where CO_2 is removed from the atmosphere far from where it is ultimately stored, what does it mean to assign a CDR credit? When CO_2 is removed from the atmosphere by mineral weathering in the soil column, it may take a long time to travel to its permanent storage destination in the deep ocean. Soils with a high cation exchange capacity may retain the products of mineral weathering for years before they are released into drainage networks. Mineral weathering is also a process that may continue for years to decades after field application, and CO_2 removal does not take place immediately following mineral application to fields. Given these lag times, what does a carbon credit from an ERW cropland project represent?

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19. Dupla X, Möller B, Baveye PC, Grand S. 2023. Potential accumulation of toxic trace elements in soils during enhanced rock weathering. European Journal of Soil Science. 74(1):e13343. doi:10.1111/ejss.13343.

20. Pack A, Hoernes S, Walther T, Bross R. 2003 Feb 18. Behavior of basic refractories at high temperatures in steelmaking processes thermodynamics and implications for the usability of olivine as refractory material. European Journal of Mineralogy.:193–205. doi:10.1127/0935-1221/2003/0015-0193.

21. Traynor B, Mulcahy C, Uvegi H, Aytas T, Chanut N, Olivetti EA. 2020. Dissolution of olivines from steel and copper slags in basic solution. Cement and Concrete Research. 133:106065. doi:10.1016/j.cemconres.2020.106065.

22. Traynor B, et al. 2020. Dissolution of olivines from steel and copper slags in basic solution.

23. Vilakazi AQ, Ndlovu S, Chipise L, Shemi A. 2022. The Recycling of Coal Fly Ash: A Review on Sustainable Developments and Economic Considerations. Sustainability. 14(4):1958. doi:10.3390/su14041958.

24. Pereira PM, Vieira CS. 2022. A Literature Review on the Use of Recycled Construction and Demolition Materials in Unbound Pavement Applications. Sustainability. 14(21):13918. doi:10.3390/su142113918.

Credit buyers should pay attention to the distinction between credits that represent CO_2 that has already been removed from the atmosphere, measured, and verified (referred to as “ex post” credits) and CO_2 that is expected to be removed from the atmosphere in the future (referred to as “ex ante” credits). Credits from ERW projects are sold in either form, though the Puro.earth protocol[25] for ERW specifies that credits should be sold ex post. Though an ex post ERW credit represents a tonne of CO_2 already removed from the atmosphere by weathering, this carbon may remain in the soil for a long period of time before traveling through river systems to the ocean. In fact, some of the removed CO_2 may be returned to the atmosphere, either along the transport path from soil column to ocean or after reaching the ocean. ERW cropland projects may generate credits over several years following a single mineral application, often with credit volumes tapering off over time as applied minerals weather and dissolve. The rate and duration of CDR in an ERW project depends on a wide range of factors, including mineral type, particle size (smaller particles have more surface area and weather faster), and local factors that drive weathering like temperature, rainfall, and soil acidity. While an ex post ERW credit generally represents one tonne of CO_2 that has been removed from the atmosphere in the soil, it is not guaranteed that this same amount of CO_2 has reached durable storage in the deep ocean at the time the credit is awarded.

Coastal waters. (Source: Adobe Stock).

25. Puro.earth. 2022. Enhanced Rock Weathering in Soil. [accessed 2024 April 14]. https://puro.earth/enhanced-rock-weathering.

Risks for enhanced rock weathering projects

Buyers of credits from ERW cropland projects must be prepared to assess both the specific project-level risks and general technological risks associated with the approach. In this section, key risks associated with ERW projects are reviewed and commentary is provided on which of the risks can be mitigated by project-specific safeguard measures, improvements in carbon accounting methods, and anticipated improvements in datasets as ERW matures and benefits from further research.

Key risks and their management

The two key risks associated with ERW projects are: (1) over crediting due to uncertainty in carbon accounting methods, and (2) potential harms to people and the environment from heavy metals (ecotoxicity).

Importantly, some ERW risks can be mitigated today, some may be mitigated with additional research, and some may not be possible to mitigate. Some risks—such as those from heavy metals, asbestos, and silicosis—can be managed with effective, project-specific safeguard measures and sampling. Other risks—such as uncertainties concerning estimates of mineral weathering rates and other soil column processes—may become clearer (whether increased or decreased) as ERW science matures, further research is performed, and more data become available. There are also risks that may be unresolvable due to their scale and distributed nature, such as accounting for potential carbonate precipitation in rivers and oceans and associated CO_2 re-release to the atmosphere or weathering by anions other than bicarbonate.[26]

ERW science is young but developing rapidly. The core idea to use ERW for CDR first appeared in the scientific literature in the 1990s.[27] Experiments began to test the theory using specific minerals in the 2010s. The idea has exploded in popularity and interest in the last 5–10 years. The first private companies using ERW for CDR were founded

26. The stability and durability of bicarbonates in ocean systems is currently a matter of scientific debate. This is described in more detail in the "Measurement, monitoring, reporting, and verification" section of this report.

27. Seifritz W. 1990. CO_2 disposal by means of silicates. Nature. 345(6275):486–486. doi:10.1038/345486b0.

beginning in 2020,[28] and the first registry protocol for generating carbon credits from ERW (there are currently only two) was published in 2022.[29]

Given the recent and rapid development of ERW as a CDR pathway, it does not have a long history of research, development, and testing. Because of this relative immaturity, there are risks associated with ERW that are not scientifically constrained by laboratory experiments, field tests, simulation, or collective experience with real ERW projects. Many of these risks will likely grow or diminish over time as the science improves (**box 1**). However, at present, many questions remain unanswered about whether ERW today can generate high levels of confidence in the volume of carbon removed from the atmosphere while avoiding potential harms to people or the environment.

Box 1. Buyers can reduce risk with market signaling

ERW is a nascent CDR pathway with the potential to scale rapidly and provide cost-effective and durable climate impact. Given the current risks and uncertainties around ERW, buyer involvement in ERW cropland projects may be more appropriate from a market scaling and investment perspective than it is for meeting buyer climate commitments with ERW carbon credit offtakes. Even so, buyers do have a very real opportunity to learn, de-risk, and scale climate technologies through investment and targeted diligence. There are examples of this investment approach in the CDR space for other technologies. For example, Kinnevik's investment in the Carbon Lockdown Project (a project focused on wood harvesting and storage) will support furthering sustainable carbon sequestration technologies.[30] The nature of many of the current uncertainties and risks involved with ERW make it a good candidate for this type of catalytic funding.

28. Watson E. 2023 Oct 18. Enhanced rock weathering startup Eion predicts dramatic growth as DOE pumps $35m into CO_2 removal. AgFunderNews. [accessed 2024 Apr 14]. https://agfundernews.com/enhanced-rock-weathering-startup-eion-predicts-dramatic-growth-as-doe-pumps-35m-into-c02-removal.

29. Puro.earth. 2022. Enhanced Rock Weathering in Soil. [accessed 2024 April 14]. https://puro.earth/enhanced-rock-weathering.

30. The Carbon Lockdown Project | Kinnevik. [accessed 2024 Apr 14]. https://www.kinnevik.com/newsroom/stories/carbon-lockdown-project/.

So, what does all of this mean? What does "good enough" look like for an ERW project? What would it take to increase buyer confidence to the level at which tonnes purchased are not simply an investment in a promising approach, but have the potential to be realized as high-quality CDR tonnes that can be leveraged to meet buyer climate commitments? The major unknowns in ERW boil down to two risk categories: (1) over crediting due to uncertainty in carbon accounting methods, and (2) potential harms to people and the environment from heavy metals (ecotoxicity). These are detailed, along with opportunities for their mitigation, in **table 3** and discussed further below.

Given appropriate levels of finance, some of the risks currently associated with ERW cropland projects are likely to be resolved within the timeframe needed to meet 2030 and 2050 global climate goals. However, this is not true for all risks associated with ERW. Unresolved questions will need to be addressed through not only research but also through developing scientific and investment consensus on what magnitude of uncertainty and risk is acceptable.

Waterways flowing through cropland in the UK. (Source: Adobe Stock).

Table 3. Key risks associated with ERW cropland projects with opportunities for mitigation*

Risk area	Risk description	Project-specific mitigation strategies	Broad research-based mitigation measures	Risk rating	Mitigation potential
Carbon accounting	Over crediting due to uncertainty in models of soil column processes	Increased sampling of variables to test models, such as data from pore water lysimeters and soil samples	Evaluation and iterative improvement of models against data from long-term, well-sampled experiments, including whole-watershed experiments and experiments in tile-drained systems where carbon in soil effluent can be measured directly	Yellow	Red
	Over crediting due to uncertainty in models of river systems or ocean processes	Project- and location-specific applications of river and ocean models to address location-specific risks of reversal	Broad improvements in river system models, ocean models, and the global datasets used to constrain these	Yellow	Yellow
	Financial non-additionality	Clear documentation of all revenue streams and costs/benefits sharing between project proponents	n/a	Yellow	Green
	Leakage due to diversion of mineral feedstocks from other uses	Documentation of alternative uses of mineral feedstocks and demonstration that ERW activities are not increasing the need for mining elsewhere	Analyses in peer-reviewed literature documenting the global availability and potential alternative uses of mineral feedstocks	Green	Yellow
Harms, benefits, and environmental justice	Harm from heavy metals or health-related inhalation risks (e.g., asbestos or crystalline silica)	Safety measures (such as personal protective equipment), elemental/mineralogical analysis of feedstocks, monitoring of soil chemistry	Long-term experiments to measure and characterize the impact of applying specific minerals (e.g., olivine) on the level of heavy metals in soil, nearby waterways, or crops	Red	Green

* Risks and mitigation potentials are scored as red, yellow, or green. Red = high risk/low mitigation potential with additional research; yellow = moderate risk/moderate potential to mitigate with additional research; green = low risk/high potential for mitigation with existing solutions or additional research.

Risk of overestimating carbon removal

A large area of potential risk for ERW is that carbon accounting methods will overestimate atmospheric CO_2 removal, underestimate downstream leakages, underestimate accounting uncertainty, and ultimately generate carbon credits that do not represent real, permanently stored carbon. This risk stems from the complex accounting methods that ERW requires. Carbon accounting for ERW projects is generally done with a combination of life cycle assessments (LCAs) of emissions associated with mineral feedstock sourcing, transportation, and application; estimates of atmospheric CO_2 removal at the soil interface (generally using proxy measurements of mineral weathering rates and assumptions about weathering reaction chemistry); and estimates of the efficiency with which drawn down carbon reaches the ocean based on simulations with models of river systems and the ocean.

Each of these components of an ERW carbon accounting framework has associated uncertainties, which vary in how easily they might be resolved by near-term scientific research and development (**table 3**). While the LCAs are fairly straightforward, uncertainty arises because the carbon drawdown resulting from applying minerals to croplands exists in an open system which is not easily constrained by today's monitoring, reporting, and verification (MRV) methodologies. A combination of remote sensing, direct measurement, and modeling will likely be required for robust carbon accounting, but the presence of these components is not necessarily sufficient to build confidence in ERW carbon accounting methods. Please see the section below on "Measurement, monitoring, reporting, and verification" for more details on the issues and research priorities associated with specific carbon accounting approaches.

Risk of human or environmental harms

There are some concerns around heavy metals or other contaminants in ERW feedstocks. Such contaminants could negatively affect human health and the safety of applicators or have negative downstream implications for people and the environment through the uptake of metals into food crops or the contamination of soils and waterways. While these concerns are real and significant, they are largely addressable using approaches that are available today and are applicable to other climate solutions such as biochar (see the "Environmental harms and benefits" section of this report). These approaches include stringent policies for appropriate feedstock collection and preparation, quality assurance and quality control (QA/QC) of feedstock, environmental health and safety mitigation measures, and community consultation and notification. For additional discussion of concerns around human or environmental harm associated with ERW projects, see Appendix E.

Current guidance on high-quality enhanced rock weathering projects

As ERW rapidly scales as a climate solution and credits from ERW cropland projects become more widely available in the voluntary carbon market, registries and other watchdog groups must be prepared to evaluate the quality of these projects based on holistic criteria. However, given the current early stage of this approach and its rapid development, guidance on how to evaluate the quality of ERW projects is still scarce, with only two active protocols—from Puro.earth and Isometric. Several organizations have recently led major efforts to set protocols and standards for ERW projects, aiming to guide the sustainable scaling of ERW, encourage buyer confidence, and preserve public trust in this CDR pathway. These protocols and standards are detailed below along with an analysis of the current state of guidance on ensuring high-quality ERW projects.

Protocols

The first protocol for generating verified carbon credits from ERW projects was released in 2022 by Puro.earth.[31] This protocol places important constraints upon ERW projects to be considered high-quality. These constraints cover important considerations such as additionality, harms and benefits, and carbon accounting:

1. Project eligibility is limited, based on financial and regulatory additionality and on avoidance of double-counting.
2. Guidance is provided on how to protect against environmental or human harms from applied minerals.
3. Guidance is provided on the underlying principles and techniques that should underlie any ERW project's carbon accounting approach.
    a. Guidance on robust LCAs is outlined, following ISO 14040/44 to account for emissions associated with the sourcing, transportation, and application of mineral materials.
    b. Guidance is provided on the robust quantification of weathering rates using models, including recommendations for model structure, parameters, inputs, and validation techniques.
    c. Guidance is provided at a high level on approaches to simulation validation and uncertainty quantification using empirical measurements.

31. Puro.earth. 2022. Enhanced Rock Weathering in Soil. [accessed 2024 April 14]. https://puro.earth/enhanced-rock-weathering.

The guidance laid out in the Puro.earth protocol is largely in line with Carbon Direct and Microsoft's *Criteria for High-Quality Carbon Dioxide Removal*.[32] Some of the current guidance in the Puro.earth protocol is broad and will likely evolve to be more specific over time as ERW science matures and more ERW projects make credits available for purchase on the voluntary carbon market. For example, the Puro.earth protocol specifies that the models used for carbon removal quantification should be validated and provides high-level commentary on how this should be performed, but lacks detail on what specific data or statistical techniques should be used. By comparison, guidance on model use in credit quantification for other types of CDR (e.g., Verra's VMD0053 Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management, v2.0)[33] provides more specific constraints on the data used for model validation and the statistical methods used to address carbon accounting uncertainty. The Puro.earth protocol also specifically includes both mined minerals and industrial wastes like fly ash or cement kiln dust in the list of eligible land amendments for ERW cropland projects, though industrial wastes may run a higher risk of contamination with heavy metals.

Isometric published the only other ERW protocol in 2024,[34] outlining procedures such as sampling soil and groundwater for nickel and chromium accumulation, reporting uncertainties in removal estimates, and considering losses to the ocean. They note that new carbonate production could reduce CO_2 removal efficiency by as much as 50% in aqueous phase export and advocate for analyzing cation concentration statistics to identify significant changes. Additionally, greenhouse gas emissions from project initiation to post-spreading can be deducted upfront, spread over the project's first half, or allocated per unit of product output to ensure complete accounting by halfway through weathering potential realization. Isometric's protocol also includes a Rock and Mineral Feedstock Characterization protocol that applies broadly to CDR technologies which use mineral feedstocks.[35]

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32. Carbon Direct and Microsoft. 2024. Criteria for High-Quality Carbon Dioxide Removal. [accessed 2024 July 11]. https://www.carbon-direct.com/research-and-reports/criteria-for-high-quality-carbon-dioxide-removal.

33. VMD0053 Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management, v2.0. Verra. [accessed 2024 May 31]. https://verra.org/methodologies/vmd0053-model-calibration-validation-and-uncertainty-guidance-for-the-methodology-for-improved-agricultural-land-management-v2-0/.

34. Enhanced Weathering in Agriculture, v1.0 — Isometric. [accessed 2024 Apr 14]. https://registry.isometric.com/protocol/enhanced-weathering-agriculture.

35. Rock and Mineral Feedstock Characterization — Isometric. [accessed 2024 May 31]. https://registry.isometric.com/protocol/rock-and-mineral-feedstock-characterization.

Other protocols are in development and are likely to be released as the momentum behind ERW as a climate solution grows. For example, Verra, a non-profit leader in the development of standards for carbon credits and one of the largest carbon credit registries in the world, is considering developing its own protocol for the generation of carbon credits from ERW cropland projects.[36] The release date for this protocol has not yet been announced.

Standards

Cascade Climate, a non-profit organization, recently began a concerted effort to develop a set of "community standards" for ERW.[37] Cascade Climate assembled working groups across scientific and business communities, which are dedicated to developing guidance for credit quantification and other challenging aspects of ERW projects in line with the best available science. Cascade Climate plans to regularly publish the findings of these working groups. In December of 2023, Cascade released its "Core Principles on Quantifying Net Carbon Removal Via Enhanced Rock Weathering"[38] as an early indication of the goals and direction of their community standards development process. Numerous academic researchers, ERW project developers, ERW credit buyers, and industry watchdog organizations were signatories on these core principles.

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36. Methodology for Atmospheric Carbon Removal through use of Volcanic Basalt Soil Treatments. Verra. [accessed 2024 Apr 14]. https://verra.org/methodologies/methodology-for-atmospheric-carbon-removal-through-use-of-volcanic-basalt-soil-treatments/.

37. Sanchez J, Ellis D. 2023. Foundations for a Healthy ERW Market Cycle - Cascade Climate. [accessed 2024 May 31]. https://cascadeclimate.org/blog/foundations-for-a-healthy-erw-market-cycle.

38. Wang H, Mills J, Sanchez J, Ellis D. 2023. Introducing the Core Principles on Quantifying Net Carbon Removal Via Enhanced Rock Weathering. Cascade Climate. [accessed 2024 May 31]. https://cascadeclimate.org/blog/core-principles.

Responsibly scaling enhanced rock weathering

The logistical infrastructure required for ERW feedstock application on croplands is already in place and currently used for applying fertilizer and agricultural lime. The presence of this infrastructure boosts the feasibility of rapid ERW deployment at scale. However, scaling ERW also depends on the availability of alkaline feedstocks, such as ground basalt rock. The impact of ERW is greatly influenced by the weathering kinetics of these feedstocks, which are influenced by specific project characteristics such as feedstock mineralogy, crystallinity, particle size, and climate.

Basalt is one of the most abundant potential feedstocks for ERW. Under ideal circumstances, if all the calcium and magnesium in the rock dissolves and is charge balanced by bicarbonate, then one tonne of basalt can remove 400–600 kg of atmospheric CO_2.[39] Global basalt stores are enormous. The Earth's oceanic crust is composed of a 7 km-thick layer of mafic rocks, rich in calcium and magnesium. About one third of this is basalt lava. Large stores of basalt can be found in geographic regions such as Japan, Hawaii, the Northwestern US, and Iceland.[40] Because access to comprehensive global databases on currently operating mines is limited, due to variations in recording methods and regulations across jurisdictions, it is difficult to quantify the exact amount of the Earth's basaltic resources. Worldwide, many rock properties (e.g., mineral distribution, crystallinity) also vary substantially by locale and statistics derived from the US cannot be universally applied. However, available mining and quarrying data can reveal the magnitude of basalt rock accessed for industrial uses. Some basalt is currently mined for extraction of copper and other base metals, and more is quarried for use as a general aggregate or crushed stone in building materials—though its use in these applications is limited due to its aptitude for rapid weathering. Globally, 50 billion tonnes of crushed stone are produced each year, and only a fraction of this crushed stone is basalt. Other

39. Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, et al. 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature. 583(7815):242–248. doi:10.1038/s41586-020-2448-9.

40. Sandalow D, Aines R, Friedmann J, Kelemen P, McCormick C, Power I, Schmidt B, Wilson S. 2021. Carbon Mineralization Roadmap. ICEF Innovation Roadmap Project. https://www.icef.go.jp/wp-content/uploads/2024/02/icef2021_roadmap.pdf.

diabase rocks are more commonly used in construction applications.[41, 42] Metal mining information can provide further clarity on the amount of basalt which may be available for ERW. The Global Tailings Review[43] estimates that 14.4 billion tonnes of mine tailings are produced annually. Of the most commonly mined metal commodities, copper and nickel are routinely extracted from mafic and ultramafic rocks, but these materials are not exclusively produced from basalts. Copper and nickel comprise less than 1% of total annual metal production, suggesting that less than 110 million tonnes of basaltic tailings are produced each year from metal mining.

Basalt mining. (Source: Adobe Stock).

41. Bendixen M, Iversen LL, Best J, Franks DM, Hackney CR, Latrubesse EM, Tusting LS. 2021. Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. One Earth. 4(8):1095–1111. doi:10.1016/j.oneear.2021.07.008.

42. Crushed Stone Statistics and Information | U.S. Geological Survey. [accessed 2024 Apr 14]. https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information.

43. Global Tailings Review. 2020. Towards Zero Harm: A compendium of papers prepared for the Global Tailings Review. https://globaltailingsreview.org/wp-content/uploads/2020/09/GTR-TZH-compendium.pdf.

The feasibility of ERW may be boosted by the use of industrial byproducts (e.g., fly ash, blast furnace slag), which could be promising feedstocks for ERW cropland projects due to the lower risks of economic leakage associated with them and their lower emissions impacts. In particular, blast furnace slag (a byproduct of steel production) often has key properties that are similar to the mineral amendments used in ERW projects.[44, 45] According to the World Steel Association, 1.95 billion tonnes of steel were produced in 2021, with approximately 500 million tonnes of blast furnace slag and steel slag co-produced.[46] This slag has the potential to be used in producing up to 200 million tonnes of CDR.[47] However, these feedstocks still carry concerns about ecotoxicity risks and transport emissions. Current protocols do not have clear requirements for ongoing QA/QC processes to ensure that feedstocks, crops, soils, and waterways are free of heavy metals and other potentially harmful contaminants. Protocols also do not have clear requirements for cleaning of feedstock if issues are identified. In these instances, cleaning and processing could become a large issue and a potential energy sink. Clear and enforceable frameworks, regulatory or otherwise, for ecotoxicology QA/QC and feedstock processing appear to be the largest barriers to the responsible deployment of industrial byproducts for ERW at scale.

Based on the summary provided above of available mine tailings, crushed rock, and industrial wastes that are currently produced and suitable for ERW, achieving gigatonnes of annual CDR will require an increase in the production of these materials of one-to-two orders of magnitude. This may necessitate quarrying and grinding for the specific purpose of ERW, which may increase the cost of feedstocks compared to using existing waste materials.

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44. Horii K, Kitano Y, Tsutsumi N, Kato T. 2013. Processing and Reusing Technologies for Steelmaking Slag. Nippon Steel Technical Report No. 104. https://www.nipponsteel.com/en/tech/report/nsc/pdf/104-20.pdf.

45. Ndlovu S, Simate GS, Matinde E. 2017. Waste Production and Utilization in the Metal Extraction Industry. Boca Raton: CRC Press. https://doi.org/10.1201/9781315153896.

46. World Steel Association. 2023. Fact sheet: Steel and raw materials. [accessed 2024 Nov 11]. https://worldsteel.org/wp-content/uploads/Fact-sheet-raw-materials-2023.pdf; United States Geological Survey. 2024. Mineral Commodity Summaries. [accessed 2024 Nov 11]. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-iron-steel-slag.pdf.

47. Renforth P. 2019. The negative emission potential of alkaline materials. Nat Commun. 10(1):1401. doi:10.1038/s41467-019-09475-5.

Private and public development of enhanced rock weathering projects

Carbon Direct conducted a comprehensive review of public records, project reports, press releases, and scholarly studies to observe trends among major players in the ERW project space, which are detailed below. The data gathered for this report spanned private suppliers, academic institutions, brokers, and government-led projects, providing a detailed characterization of the current ERW space. Project evaluation criteria encompassed sources of funding, project locations, data on potential supply, and the availability of feedstock.

Key takeaways

- The ERW space is characterized by a mix of private suppliers, predominantly in the pilot phase, and university research institutions contracted by private suppliers with the goal of scaling ERW cropland deployment.
- At the time of this writing, Carbon Direct identified 14 private ERW suppliers and five ERW research projects (see Appendix B).
- Varied offtake targets reflect uncertainty in ERW scalability.
- The concentration of university research in the US and UK likely mirrors the availability of funding and advanced research infrastructure in these regions.
- Significant investor interest in private suppliers underscores a growing confidence in the commercial viability of ERW, signaling a promising future for this innovative approach to carbon sequestration.

Major players, project types, and scale

The supplier landscape for agricultural ERW is vast and multifaceted, reflecting the rapid expansion of the market for this nascent CDR pathway. Projects are distributed globally, with a significant focus in the US and UK (Appendix B). Notably, projects with the most ambitious offtake targets (totalling one billion tonnes by 2030) are based in the US (Lithos) and Australia (Carbonaught). These suppliers are primarily funded through diverse investment channels, like venture capital and corporate backing, and are focused on developing marketable offtakes and CDR. Some suppliers—including Eion, Lithos, and UNDO—have already established brokerage arrangements.

The UK emerges as a hub for smaller, research-focused ERW projects, with a high concentration of initiatives led by academic institutions. These initiatives are focused on understanding the mechanisms underlying ERW rather than on immediate commercial application or scalability. The heavy prevalence of ERW research in the UK is likely a direct result of substantial UK policy development in the ERW sector, exemplified by the government's £31.5 million program under their Strategic Priorities Fund. This program emphasizes a commitment to high-quality, interdisciplinary research, including the assessment of ERW deployment in sectors like UK agriculture. The existing UK policy landscape and UK investment in ERW research suggest that UK-based ERW organizations are likely to receive a more open acceptance in the CDR space compared to those based in other countries.

Development stage

While ERW projects vary in their stage of development, most are in the pilot phase. Even the largest projects, despite their significant offtake goals, are predominantly engaged in research and development. Some have secured pre-purchase agreements, indicating a move toward commercial viability. For example, Lithos has secured a significant, US$57.1 million purchase agreement with Frontier to remove 154,240 tonnes of CO_2 between 2024 and 2028. While this is substantial, Lithos is still in the process of refining their modeling assumptions to increase confidence in their carbon accounting methods.

While smaller suppliers, like InPlanet, have less ambitious goals, they have still received significant investment in the form of pre-purchase agreements. InPlanet adopts a deliberate, experiment-based approach, aiming to start with a single tonne of carbon removal by 2026 before considering larger-scale operations. This gradual ERW approach reflects InPlanet's cautious and methodical strategy.

Most, if not all, of the suppliers analyzed were primarily engaged in some form of research and development. Most of these projects aim to sell credits between 2025 and 2030, with full capacity achieved in 2040. The development of scalable, cost-efficient, and reliable MRV protocols is noted as a major roadblock across these projects. Collaboration between university researchers and private suppliers will likely be key to moving the science of MRV for ERW forward.

Collectively, ERW suppliers estimate a potential generation capacity of over two billion credits by 2030. At face value, this total volume outstrips the expected 2030 market demand for voluntary credits, which is closer to one billion total tonnes.[48] Realistically, ERW credit generation will be significantly smaller, given the existing hurdles to scaling, which include limited ideal mineral feedstocks. However, with a predicted price for ERW credits falling between US$60–220/tonne and the high theoretical limit of potential removal volumes, ERW is positioned well to compete in the growing market for high-durability CDR. Significant investor interest in private suppliers underscores a growing confidence in the commercial viability of ERW, signaling a promising future. Further analysis of the market for ERW is provided in the next section of this report.

Agricultural liming is an application process similar to the one used for enhanced rock weathering in croplands. (Source: Adobe Stock).

48. Long-term carbon offsets outlook 2023 | Insights. 2023 Jul 18. Bloomberg Professional Services. [accessed 2024 May 31]. https://www.bloomberg.com/professional/insights/sustainable-finance/long-term-carbon-offsets-outlook-2023/.

Analysis of enhanced rock weathering markets

Some estimates suggest that ERW could offer the advantage of a lower-cost pathway for CDR, compared to other highly-durable methods, such as direct air capture (DAC) and engineered mineralization pathways. On the other hand, ERW involves a higher level of uncertainty regarding the fate and durability of carbon storage compared to methods like DAC. This section reviews both the theoretical and realized costs associated with ERW and compares these against other CDR pathways. Positioned as a premium option, credits from ERW projects are priced higher than those from projects using nature-based solutions (NbS) due to the potential for ERW to provide long-term durability over centuries. The interplay of these factors highlights the need for a comprehensive understanding of the economic intricacies involved in deploying ERW on agricultural lands. While project costs and credit prices for DAC are anticipated to decrease with scale-up, the material costs of ERW may not follow the same trajectory. Uncertainty regarding the costs of MRV in ERW projects further complicates the overall economic assessment of this approach. The potential co-benefits of ERW for farmers, including increased yields and decreased farmland input requirements, may contribute additional value to ERW projects.

The cost dynamics of ERW cropland projects are influenced by a range of factors. Two primary rock types integral to ERW, peridotite and basalt, face supply challenges stemming from competition with other industries. Olivine, the magnesium silicate mineral that is most abundant in peridotite, is in demand as a finishing sand for steel casting, with prices expected to rise as demand increases. Demand for basalt is driven in part by its use as a building material (aggregate). However, there may be a unique opportunity to pursue a waste removal service business model by utilizing mineral wastes and byproducts of industrial uses of mineral material, such as basalt fines. Transporting these rocks between source locations and agricultural sites introduces logistical complexities, which can substantially impact an ERW project's overall cost structure and its net carbon benefits if efficient transportation infrastructure is not in place.

Key market takeaways

- **Feedstock types:** Silicate minerals are critical feedstocks for ERW cropland projects, but other industries may compete for this material, which affects cost. The range of weathering and reaction rates of various mineral materials strongly affects their commercial viability.
- **Comparative cost analysis:** ERW offers lower known sales prices and similar theoretical costs when compared to other high-durability, engineered CDR solutions like DAC (**figure 4**), but comes with greater levels of uncertainty around carbon accounting and potential for co-benefits. ERW removals are priced higher than NbS removals due to their potential for long-term carbon storage.
- **Scalability through geographic proximity:** Co-locating alkaline feedstocks with agricultural regions enhances the potential to deploy ERW by streamlining access to the necessary materials and resources.

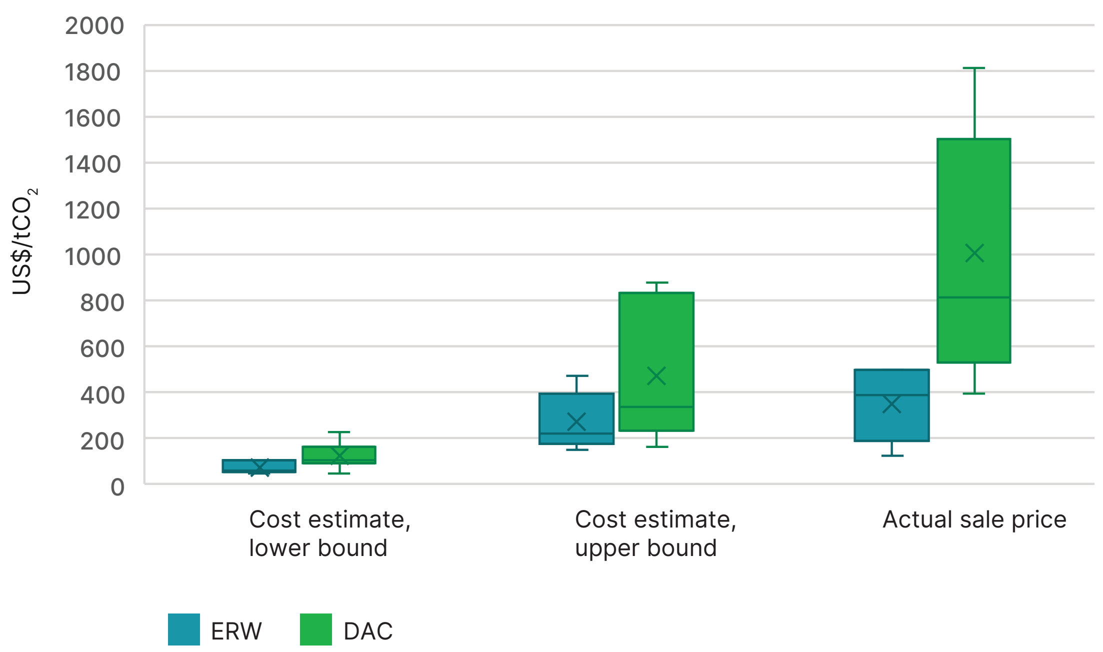


Figure 4. A brief comparison of cost estimates for enhanced rock weathering (ERW) and direct air capture (DAC) pathways, based on theoretical estimates from published literature and actual CDR credit sales data. See Appendices C and D for more information on included data. Note: In this box and whisker chart, the "x" within each box indicates the mean and the horizontal line within each box represents the median.

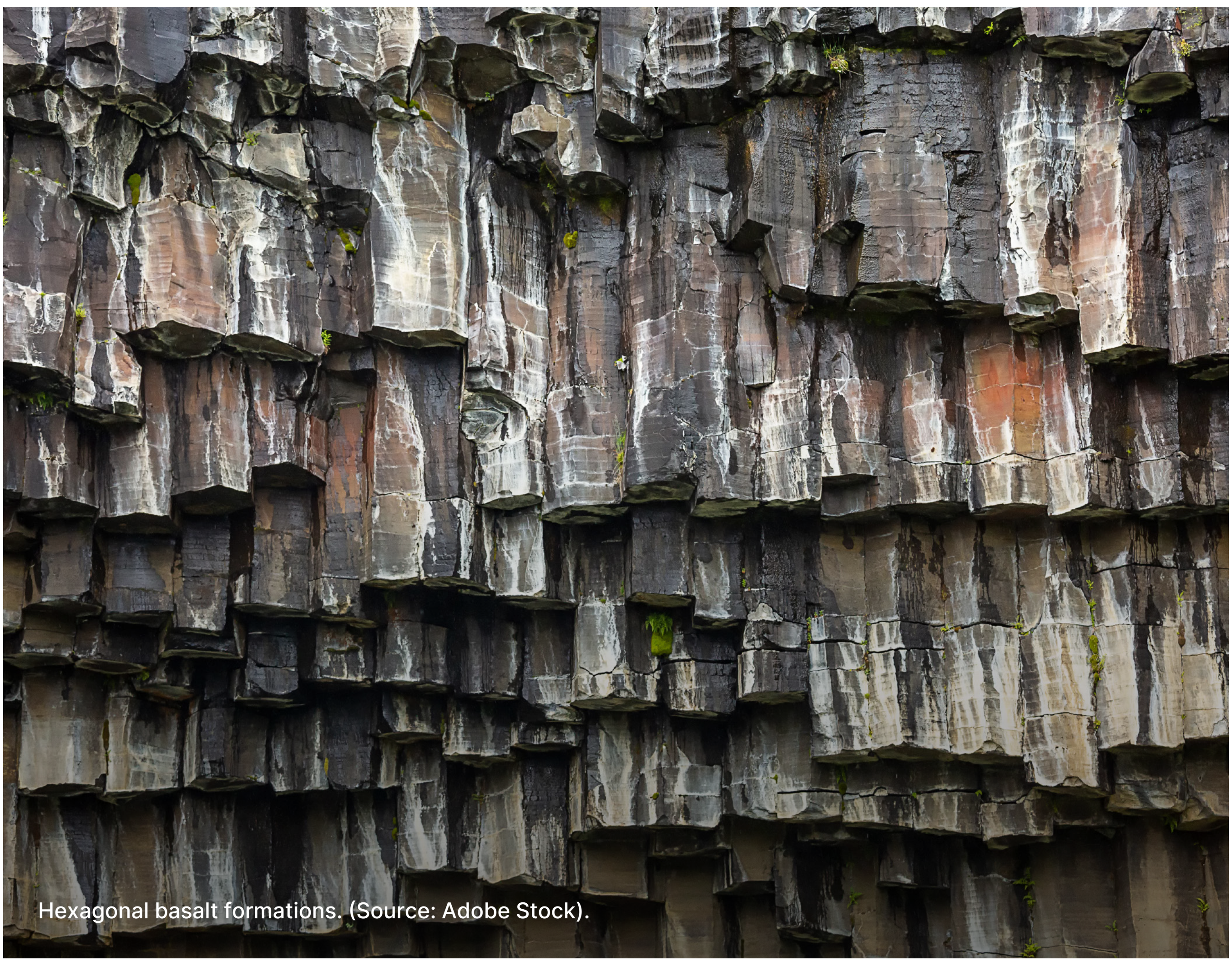
Carbon Direct identified 13 documented sales of DAC (including both ex post and ex ante sales, 11 of which included pricing information) between 2021–2023, ranging from US$394–1,816 and with a median sale price of US$813/tonne.[49] By comparison, Carbon Direct identified 13 documented sales of ERW during the same time period (8 of which included pricing information), ranging from US$119–500/tonne and with a median price of US$390/tonne. See Appendix D for credit sales data. As costs for these technologies decrease with deployment and technological learning in a dynamic landscape, credit prices should fall. However, in comparison to NbS credits that commonly sell in the range of tens of dollars per tonne, ERW solutions sell at prices that are one-to-two orders of magnitude higher on a per-tonne basis. This places ERW in a unique economic position in the voluntary carbon market due to its middle-ground sales prices when compared to current NbS and DAC credit prices.

Peer-reviewed cost estimates for ERW and DAC in the future overlap. The question of whether, and to what extent, costs will fall depends on various factors. Literature values, from techno-economic assessments of ERW at scale, range from US$45–472/tonne, with most estimates falling between US$60–220/tonne (see Appendix C). Comparable cost estimates for DAC at scale range from US$46–877/tonne, with most estimates falling between US$100–335/tonne. For DAC projects, the majority of the cost stack is fixed costs with potential for learning with technology deployment, energy deployment, and facility build out. For ERW projects (and some of the simpler DAC methods involving ambient weathering and calcining to regenerate sorbents), the majority of costs are from the collection and transport of the relevant feedstocks, processes that are already well understood and that have been deployed at scale for centuries. Furthermore, ERW deployment at scale could increase costs as the supply of waste fines of key minerals is limited, necessitating the need for quarrying and grinding to create new supply specifically for ERW. In addition, the cost to perform MRV could either decrease or increase depending on the burden of evidence required for high-quality CDR purchasers. This potential range in MRV costs adds uncertainty to the overall cost structure of ERW projects. Finally, ERW costs could also increase over time if better quantification of leakage and accounting uncertainties necessitates larger deductions from credit volumes.

ERW projects offer a potentially unique cost profile. While they exhibit similar theoretical future cost estimates compared to DAC projects, they offer lower current sales prices and the potential for significant ecosystem co-benefits. These co-benefits are discussed in detail in the next section of this report, “High-quality criteria for enhanced

49. Figures are based on cdr.fyi data available up to December 31, 2023.

rock weathering.” However, compared to DAC systems, the higher level of uncertainty surrounding the fate and durability of carbon storage from ERW (and the MRV approaches required to constrain this uncertainty) may reduce its attractiveness as a verifiable CDR pathway. Compared to credits from projects using NbS, credits from ERW projects are priced higher. This is due to the potential for centuries-long durability via ERW, which typical NbS like reforestation or regenerative agriculture do not offer. Despite their potential, ERW projects face challenges, including competition from other industries for available feedstock, transportation logistics, the evolving landscape of MRV costs, and the possibility of needing to take larger credit volume deductions to account for leakage and accounting uncertainties. Ongoing research and development may reduce current uncertainties, but could ultimately increase the cost of ERW relative to the best-case scenarios used for theoretical future cost estimates. Grappling with these challenges will require a comprehensive understanding of the economic factors influencing ERW cropland projects.



Hexagonal basalt formations. (Source: Adobe Stock).

High-quality criteria for enhanced rock weathering

In this section, common issues in ERW projects are reviewed against Carbon Direct and Microsoft's *Criteria for High-Quality Carbon Dioxide Removal*[50] and likely risks that buyers should consider when evaluating ERW projects are assessed.

Key quality issues

- As described previously, key risks associated with ERW projects include: (1) over crediting due to uncertainty in carbon accounting methods, and (2) potential harms to people and the environment from heavy metals (ecotoxicity).
- ERW projects generally do not directly measure the complete path of CO_2 transfer from the soil column to ocean storage. Most methods use indirect measurement of other variables (e.g., cation weathering products) that are proxies for mineral weathering or alkalinity but not direct proxies or measurements for carbon. Given this trait, carbon accounting and MRV are major challenges for ERW projects that are difficult (and may be impossible) to resolve.
- Other key concerns for ERW projects include financial additionality due to project financial models and selecting an appropriate baseline in cases where ERW replaces other land amendments like agricultural lime.

Overview

Carbon Direct and Microsoft's *Criteria for High-Quality Carbon Removal* include important considerations for assessing carbon project quality across six categories: social harms, benefits, and environmental justice; environmental harms and benefits; additionality and baselines, measurement, monitoring, reporting and verification; durability; and leakage (**figure 5**).

50. Carbon Direct and Microsoft. 2024. Criteria for High-Quality Carbon Dioxide Removal. [accessed 2024 July 11]. https://www.carbon-direct.com/research-and-reports/criteria-for-high-quality-carbon-dioxide-removal.

Social harms, benefits, and environmental justice

Definition: Promotes equitable environmental decision-making.

Analytical considerations: Distributive equity (magnitude and type of benefits sharing) and procedural equity (degree of community consultation).

Environmental harms and benefits

Definition: Safeguards communities against environmental harm.

Analytical considerations: Potential harm to communities; ecosystems and biodiversity; risk mitigation strategies; and transparent reporting.

Additionality and baselines

Definition: Makes a genuine climate impact against a counterfactual.

Analytical considerations: Financial additionality; regulatory additionality; and common practice.

Measurement, monitoring, reporting, and verification

Definition: Accurately represents tonnes of carbon dioxide. Adheres to regulations and protocols with long-term monitoring.

Analytical considerations: Repeatability, verifiability, and conservatism; accurate emissions estimation; and feasibility.

Durability

Definition: Keeps carbon dioxide out of the atmosphere.

Analytical considerations: Likelihood of meeting project durability term and project durability relative to peer technologies.

Leakage

Definition: Avoids causing greenhouse gas emissions elsewhere.

Analytical considerations: Economic leakage (includes activity-shifting leakage and market leakage).

Figure 5. The six criteria for high-quality carbon dioxide removal. Source: Carbon Direct and Microsoft. 2024. Criteria for High-Quality Carbon Dioxide Removal.

Social harms, benefits, and environmental justice

Carbon removal projects, including ERW initiatives, can yield both benefits and harms for communities. High-quality projects must avoid disproportionately harming marginalized communities and vulnerable ecosystems. For instance, it is crucial to ensure equal accessibility and inclusion to ERW projects for minority and low-income farmers and landowners of varying sizes and ownership models (e.g., land ownership or lease). Additionally, proximate communities must be engaged in meaningful procedural equity prior to beginning project activities; be alerted of potential harms, including warnings about air quality impacts during mineral feedstock application; and provided with easy access to monitoring reports of toxicity levels. It is also important to establish a transparent, reachable, two-way communication mechanism for impacted communities to provide feedback and hold project developers and other stakeholders accountable. Project developers can rate their level of meaningful engagement against the Community Engagement Continuum (**figure 6**) from the Center for Disease Control and Prevention's Agency for Toxic Substances and Disease Registry.[51, 52]

Increasing level of community involvement, impact, trust, and communication flow

OUTREACH	CONSULT	INVOLVE	COLLABORATE	SHARED LEADERSHIP
Some Community Involvement Communication flows from one to the other, to inform Provides community with information Entities coexist **Outcomes:** Optimally, establishes communication channels and channels for outreach	***More Community Involvement*** Communication flows to the community and then back, answer seeking Gets information or feedback from the community Entities share information **Outcomes:** Develops connections	***Better Community Involvement*** Communication flows both ways, participatory form of communication Involves more participation with community on issues Entities cooperate with each other **Outcomes:** Visibility of partnership established with increased cooperation	***Community Involvement*** Communication flow is bidirectional Forms partnerships with community on each aspect of project from devlopment to solution Entities form bidirectional communitcation channels **Outcomes:** Partnership building, trust building	***Strong Bidirectional Relationship*** Final decision making is at community level Entities have formed strong partnership structures **Outcomes:** Broader health outcomes affecting broader community, strong bidirectional trust built

Source: Agency for Toxic Substances and Disease Registry, adapted from the International Association for Public Participation.

Figure 6. Community Engagement Continuum showing increasing level of community involvement, impact, trust and communication flow. Source: Agency for Toxic Substances and Disease Registry, adapted from the International Association for Public Participation.

51. Figure 1.1. Community Engagement Continuum | Principles of Community Engagement | ATSDR. 2022 Jul 26. [accessed 2024 Jun 3]. https://www.atsdr.cdc.gov/communityengagement/community-engagement-continuum.html.

52. "Community outreach" is considered the lowest level (i.e., very low-quality) of community engagement here, "community consultation" is low-quality, "community involvement" is moderate-quality, "community collaboration" is good community engagement (i.e., high-quality), and "shared leadership" is ideal community engagement (i.e., very high-quality).

Environmental harms and benefits

Carbon projects have the potential to impact ecosystems and people in ways that extend beyond carbon benefits. In ERW projects, these impacts include the potential for harm to people, crops, or the environment from heavy metals, asbestos, or inhalation of small particles. The risks associated with these harms can be effectively mitigated through appropriate mineral characterization, preparation and handling, monitoring of soil and water chemistry, and safety measures to protect farm workers. ERW projects also have the potential for positive impacts on soil health and productivity, which may benefit the people who depend on croplands where ERW feedstocks are applied. The effects of ERW on downstream environments are expected to be neutral or positive and include increased alkalinity. ERW-driven shifts in pH could also impact the speciation, solubility, and mobility of trace metals. When considering the range of environmental impacts ERW may have, it is useful to look at other effective land amendment regulations that are currently in place, such as those for biochar.

Heavy metals and asbestos

ERW feedstocks can contain elevated concentrations of heavy metals, such as nickel and chromium. When these metals are released during the weathering process, they could potentially cause harm to people or ecosystems. In specific circumstances, these heavy metals could also be absorbed into crops. One novel ERW approach intentionally leverages crop uptake of nickel to create multiple benefits (**box 2**), but generally, such crop uptake could cause harm and should be avoided. To avoid such harms, ERW projects should be required to monitor both the concentration of heavy metals and the presence of asbestos in mineral feedstocks and soil. The concentration of hazardous substances in feedstock and soil should be monitored before, during, and after feedstock application. Guidelines already exist in many jurisdictions (e.g., US and EU) that provide safeguarding limits on agricultural land amendments. In the US, both the Environmental Protection Agency (EPA) and state agencies may regulate soil amendments. Regulatory authority at the federal level may come from the Clean Water Act and the Clean Air Act. However, outside of the EU and US, it is unclear whether such guidelines will be followed by project developers.

Minimizing the impacts of heavy metals to humans and the environment will require a multi-step approach:

- **Baselining:** Operators and developers should begin by characterizing the bulk metals concentrations of both the feedstock and native soil to determine baseline concentrations. These concentrations should be compared to existing guideline and regulatory soil concentration values that are derived to protect ecosystem health and human health.
    - If the heavy metals concentrations of feedstock are below all applicable guidelines and regulations, no additional bulk characterization may be necessary. In projects where feedstocks will be applied multiple times at the same location over time, it may be conservative to set lower allowable threshold concentrations to limit the potential for metals in feedstocks to accumulate in soil over time.
    - If one or more metal concentration exceeds guidelines or regulations, additional tests to evaluate the potential fate and bioavailability of these specific metals could be performed to evaluate risk under site-specific conditions.
    - If the metal concentration of a feedstock falls in between multiple ecosystem and human health guidelines or regulations, then an evaluation of potential receptors and exposure pathways should be performed.
- **Methodology:** Ideally, baseline data collection should also include archiving native soil collected prior to project initiation for future analyses. Baseline data should also be collected from surface water and groundwater that could be potentially impacted by the project.[53] ERW projects should rely on standard methods for assessing bioavailability of trace elements in soil. Bioavailability generally refers to the portion of a substance accessible for uptake by plants, animals, or humans. Bioavailability may also have specific regulatory definitions and requirements depending on site-specific conditions such as crop type (e.g. crops for direct human consumption). Current ERW protocols may not include clear guidance on how existing regulations can and will be applied or enforced. A conservative best practice for projects would be to collect data with defensible methods that could be disclosed in the event that a regulator requests data.

53. This is especially important if the site is above an unconfined aquifer, depending on the depth to groundwater and proximity of nearby wells.

Collection of baseline data is essential to determine whether ERW projects cause harm to humans or ecosystems. Once a project is implemented, ongoing assessment to evaluate its impacts on human and ecosystem health should include an assessment of potential receptors.

Box 2. Metalplant: Nickel refining via crops[54, 55]

Metalplant, a recently launched startup operating a project site in Albania, introduces "carbon-negative nickel farming." Their approach integrates ERW with low-carbon nickel production. Metalplant's ERW process uses magnesium silicate rocks as a feedstock, which are quarried and crushed with hydroelectric power. They apply this material to fields sown with a hyperaccumulator plant species (related to *Odontarrhena chalcidica*, formerly known as *Alyssum murale*) to purposely encourage nickel uptake in biomass, a process known as "phytomining." These fields are located on serpentine soils that are naturally high in metal content and not ideal for food crops. The biomass is then harvested to refine the nickel, producing low-carbon nickel for use in the energy transition. This approach mitigates potential issues regarding nickel uptake in food crops due to the mineral amendments in ERW. However, questions arise regarding potential land use changes associated with the project and the risk of double counting between CDR carbon credits from ERW and statements about low-carbon nickel production. Despite these considerations, Metalplant's approach demonstrates promising potential in addressing both demand for battery metals in the energy transition and carbon drawdown via ERW.

Silicosis

Operators may be at risk of inhalation exposure to small mineral dust particles during application of ERW feedstocks, and inhalation exposure may lead to silicosis. This risk can be mitigated through proper use of personal protective equipment, air filters in broadcasting equipment, and appropriate practices for reducing airborne particles. Some farms may already implement some of these practices when applying agricultural lime

54. Metalplant - Home. Metalplant. [accessed 2024 Jun 3]. https://metalplant.com/.

55. Velev V. 2024. Metalplant Exits Stealth, Announces Novel Technology Combining Nickel Phytomining With Enhanced Rock Weathering To Produce Nickel And CDR. Carbon Herald. [accessed 2024 Jun 3]. https://carbonherald.com/metalplant-exits-stealth-announces-novel-technology-combining-nickel-phytomining-with-enhanced-rock-weathering-to-produce-nickel-and-cdr/.

or other materials. Project developers should clearly document the communication of safety requirements to applicators, specifying the timing and method. Particles of <10 um pose the most severe threat for silicosis, cancer, and other respiratory issues.[56] Project developers must, at minimum, provide evidence that all phases of operation (material grinding, transport, and application) are compliant with local and federal safety regulations. Project developers must clearly outline plans for ongoing monitoring of potential health risks to demonstrate their ability to work safely and protect human health.

Soil health and farm productivity

The impacts of ERW on soil health and crop yields are generally expected to be positive based on experimental evidence.[57] Farmers worldwide already use lime extensively to manage pH,[58] and the silicate minerals used in ERW may partially or fully replace lime for field pH management.[59] In addition, the micronutrients present in many ERW minerals (especially phosphorus and potassium) may support plant growth and reduce the need to apply fertilizer. The pH effects and cation concentrations derived from silicate mineral

Airborn dust resulting from application of minerals. (Source: Adobe Stock).

56. Current intelligence bulletin 36 - silica flour: silicosis (crystalline silica) (with reference package). 2020 Sep 28. doi:10.26616/NIOSHPUB81137. [accessed 2024 Apr 14]. https://www.cdc.gov/niosh/docs/81-137/default.html.

57. Swoboda P, Döring TF, Hamer M. 2022. Remineralizing soils? The agricultural usage of silicate rock powders: A review. Sci Total Environ. 807(Pt 3):150976. doi:10.1016/j.scitotenv.2021.150976.

58. Sumner ME, Noble AD. 2003. Soil Acidification: The World Story. In: Handbook of Soil Acidity. CRC Press. 28 p.

59. Dietzen C, Harrison R, Michelsen-Correa S. 2018. Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment. International Journal of Greenhouse Gas Control. 74:251–258. doi:10.1016/j.ijggc.2018.05.007.

amendments may have positive or negative impacts on soil organic carbon. Some initial ERW field and greenhouse experiments have shown yield increases of more than 10% in crops that receive silicate mineral amendments,[60, 61, 62] though more research is needed to understand if these results are repeatable across broad regions and cropping systems. In some parts of the world (e.g., Africa and Brazil), ground silicate rocks have historically been used as a land amendment for increasing crop yields.[63]

In addition to yield increases, some ERW experiments in fields and mesocosms[64] have shown surprisingly large reductions in the amount of nitrous oxide (N_2O) released following nitrogen fertilizer application on fields that also receive applications of mineral amendments.[65, 66] A potent greenhouse gas, N_2O is a major driver of emissions impacts from agriculture. There are several possible mechanisms behind these observed decreases in N_2O emissions with ERW.[67] The direct effects of soil pH on nitrification and denitrification rates may be responsible. The indirect impact of increased plant productivity on the nitrogen available in soils may also play a role. Because they vary greatly in time and space, N_2O emissions are notoriously difficult to quantify. Therefore, the impacts of ERW on N_2O emissions are not guaranteed to be measurable in a way that could contribute to credit volumes. However, future research should continue to explore the potential for N_2O emissions reduction as a co-benefit of ERW.

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60. Beerling DJ, Epihov DZ, Kantola IB, Masters MD, Reershemius T, Planavsky NJ, Reinhard CT, Jordan JS, Thorne SJ, Weber J, et al. 2023. Enhanced weathering in the U.S. Corn Belt delivers carbon removal with agronomic benefits. doi:10.48550/arXiv.2307.05343. [accessed 2024 Apr 14]. http://arxiv.org/abs/2307.05343.

61. Guo F, Wang Y, Zhu H, Zhang C, Sun H, Fang Z, Yang J, Zhang L, Mu Y, Man YB, et al. 2023. Crop productivity and soil inorganic carbon change mediated by enhanced rock weathering in farmland: A comparative field analysis of multi-agroclimatic regions in central China. Agricultural Systems. 210:103691. doi:10.1016/j.agsy.2023.103691.

62. Kelland ME, Wade PW, Lewis AL, Taylor LL, Sarkar B, Andrews MG, Lomas MR, Cotton TEA, Kemp SJ, James RH, et al. 2020. Increased yield and CO_2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. Global Change Biology. 26(6):3658–3676. doi:10.1111/gcb.15089.

63. Van Straaten P. 2006. Farming with rocks and minerals: challenges and opportunities. An Acad Bras Ciênc. 78:731–747. doi:10.1590/S0001-37652006000400009.

64. Mesocosms are columns of soil contained in tubes under field conditions for which all inputs and outputs can be measured.

65. Beerling DJ, Epihov DZ, Kantola IB, Masters MD, Reershemius T, Planavsky NJ, Reinhard CT, Jordan JS, Thorne SJ, Weber J, et al. 2023. Enhanced weathering in the U.S. Corn Belt delivers carbon removal with agronomic benefits. doi:10.48550/arXiv.2307.05343. [accessed 2024 Apr 14]. http://arxiv.org/abs/2307.05343.

66. Chiaravalloti I, Theunissen N, Zhang S, Wang J, Sun F, Ahmed AA, Pihlap E, Reinhard CT, Planavsky NJ. 2023. Mitigation of soil nitrous oxide emissions during maize production with basalt amendments. Front Clim. 5. doi:10.3389/fclim.2023.1203043. [accessed 2024 Apr 14]. https://www.frontiersin.org/articles/10.3389/fclim.2023.1203043.

67. In part, this may also be a direct result of reactions such as:

$$CaSiO_3 \text{ (rock)} + 2NH_3 \text{ (fertilizer)} + 4O_2 \text{ (air)} = \text{dissolved } Ca^{2+} + 2NO_3^- \text{ (dissolved)} + SiO_2 \text{ (solid)} + 3H_2O$$

where dissolved Ca is charge balanced by nitrate rather than bicarbonate, reducing nitrogen oxidation and N_2O emissions, but also reducing CO_2 drawdown from air.

Environmental impacts

Beyond croplands, ERW is expected to have broadly neutral or positive impacts on downstream ecosystems. In general, ERW will theoretically contribute additional alkalinity downstream from project fields. While some concerns remain about the possible negative impacts of potentially large, sudden shifts in ecosystem pH, to date no such large impacts have been observed that were attributed to alkalinity alone (though this does not mean that they are absent). To understand the potential impacts of large-scale ERW implementation, it is worth noting that alkalinity concentrations have changed dramatically in a number of large US watersheds already.[68, 69, 70] In some cases this is believed to be a result of recovery from acid mine drainage and acid rain,[71] while in others it is due to the effects of agricultural liming.[72] The concentration of alkalinity in the Mississippi has increased from ~20 mg/L to ~27 mg/L in the past 80 years, a remarkable increase for North America's largest river. Any impacts of large-scale ERW implementation would occur against this large background variation in alkalinity.

Shifts in soil, river, or ocean chemistry driven by ERW may have other ecosystem impacts as well. Potential secondary effects are hard to generalize and difficult to measure in situ. For instance, any ERW-driven shifts in pH could impact the speciation, solubility, and mobility of trace metals.

When considering the range of environmental impacts ERW may have, it is useful to look at other effective land amendment regulations that are currently in place, such as those for biochar (see the "Environmental harms and benefits" section of this report).

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68. Raymond PA, Oh N-H, Turner RE, Broussard W. 2008. Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. Nature. 451(7177):449–452. doi:10.1038/nature06505.

69. Raymond PA, Oh N-H. 2009. Long term changes of chemical weathering products in rivers heavily impacted from acid mine drainage: Insights on the impact of coal mining on regional and global carbon and sulfur budgets. Earth and Planetary Science Letters. 284(1):50–56. doi:10.1016/j.epsl.2009.04.006.

70. Stets E, Kelly V, Crawford C. 2014. Long-term trends in alkalinity in large rivers of the conterminous US in relation to acidification, agriculture, and hydrologic modification. The Science of the total environment. 488-489C:280–289. doi:10.1016/j.scitotenv.2014.04.054.

71. Raymond PA, Oh N-H. 2009. Long term changes of chemical weathering products in rivers heavily impacted from acid mine drainage: Insights on the impact of coal mining on regional and global carbon and sulfur budgets. Earth and Planetary Science Letters. 284(1):50–56. doi:10.1016/j.epsl.2009.04.006.

72. Stets E, Kelly V, Crawford C. 2014. Long-term trends in alkalinity in large rivers of the conterminous US in relation to acidification, agriculture, and hydrologic modification. The Science of the total environment. 488-489C:280–289. doi:10.1016/j.scitotenv.2014.04.054.

Biochar as a useful guide to effective land amendment regulations

In exploring potential guidelines for land applications of feedstocks—particularly industrial waste feedstocks—in ERW projects, biochar provides a relevant example for how to address concerns about the constituents of applied materials and their environmental impacts. Biochar is primarily utilized to enhance soil productivity[73] and act as a carbon sequestration agent. Innovative applications of biochar include the use of agricultural, forestry, and other biogenic residues. Commonly, agricultural residues are burned or pyrolyzed in fields to produce char and ash, and the resulting biochar is used as a soil amendment. However, waste materials can also contain potentially harmful and often mobile forms of heavy metals like nickel, lead, cadmium, selenium, aluminum, and others. Existing biochar standards place limits on the material concentration of harmful heavy metals for various biochar applications. These standards may provide guidance to other feedstock applications, particularly where industrial waste feedstocks are concerned.

The European Biochar Certificate (EBC)[74] biochar standards are considered among the best-in-class, setting class-specific limits for various applications. These limits are based on existing regulatory standards in the EU, Switzerland, and Germany, which are backed by decades of data and research. For example, the EBC-Agro category bases its maximum heavy metal content values on the EU-Fertilising Products Regulation and the German Federal Soil Protection Ordinance, while the EBC-AgroOrganic category aligns with EU regulations on organic production and the Swiss Ordinance on Risk Reduction related to Chemical Products (ChemRRV).

These standards primarily focus on material concentration. They do not extensively cover total application rates or cumulative applications, representing a notable gap in biochar standards. This will also be particularly relevant for ERW given the high metal concentration of many feedstocks and the potential for accumulation of heavy metals in soil as a result of repeated application of rock materials. Nascent ERW standards have an opportunity to meet this gap during development. The EPA offers some guidance, but a gap persists in understanding the bioavailability and leachability of ERW feedstocks, which can be influenced by site-specific variables such as soil type and pH. To bridge this gap, there is a need for a comprehensive methodology or evaluation framework that, in addition to material concentration, considers both the application limits (e.g., mass

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73. Schmidt H-P, Kammann C, Hagemann N, Leifeld J, Bucheli TD, Sánchez Monedero MA, Cayuela ML. 2021. Biochar in agriculture – A systematic review of 26 global meta-analyses. GCB Bioenergy. 13(11):1708–1730. doi:10.1111/gcbb.12889.

74. European Biochar Certificate (EBC). 2023. Guidelines for a Sustainable Production of Biochar. Version 10.3. [accessed 2024 April 14]. https://www.european-biochar.org/media/doc/2/version_en_10_3.pdf.

addition rate) and the leachability extent (rate of export of the mobile fraction of specific metals in runoff and groundwater) as well as the resulting accumulation rates of these materials. Existing technical standards for assessing leachability, mainly employed for landfill materials, could be adapted for soil applications. This would involve a thorough consideration of the specific soil context, including soil components and heavy metal presence, to understand how different factors, like pH, impact leachability.

In summary, biochar certifications offer a structured framework and set of standards that can be instrumental in guiding the development of guidelines for ERW. However, their direct application to ERW will require careful consideration and adaptation. Biochar standards have proven effective in setting benchmarks for heavy metal concentrations and rates of material addition, which may be particularly useful in creating standards for industrial waste feedstocks that are commonly targeted for use in ERW projects, such as fly ash. While biochar standards provide a useful template, ERW-specific standards must go beyond the scope of existing biochar guidelines to encompass not only aspects of heavy metal concentrations but also the broader environmental implications of ERW including total application rates, the cumulative impact of applications, and the influence of site-specific factors. One of the existing methodologies for ERW, from Puro.earth, states that ERW projects should follow either local regulations or EU thresholds for potentially toxic elements in inorganic soil improvers, whichever is more stringent.

Although biochar standards are maturing, they also face uncertainties and remain physically, chemically, and biologically distinct from ERW. Biochar standards are an excellent starting point, but not sufficient to address all remaining ERW issues.

Additionality and baselines

High-quality credits from ERW projects must represent a removal of CO_2 from the atmosphere that would not have occurred without project activities and carbon finance. Based on this criterion, to demonstrate quality, a project must show physical, financial, regulatory, and common practice additionality. In addition, a project must select an appropriate baseline, or business-as-usual scenario, to compare project emissions against. In ERW projects, financial additionality and the selection of an appropriate baseline pose the biggest challenges for meeting these quality criteria. Baseline selection is especially important because mineral applications in ERW may replace other cropland amendments like lime, which may be a source or a sink of CO_2 at baseline.

Physical additionality

Projects must demonstrate that they will lead to real atmospheric CO_2 removal in excess of what would have occurred without project activities. ERW projects fulfill this criterion by describing the business-as-usual fate of applied minerals and project fields. Generally, silicate minerals applied in ERW projects would otherwise remain unmined or be stored in piles where they would be subject to much lower rates of mineral weathering than under project conditions. ERW projects should also demonstrate that the application of minerals in ERW will lead to more atmospheric CO_2 removal than any business-as-usual land management practices that may cease following project initiation, such as agricultural liming (see “Selecting an appropriate baseline” below).

Financial additionality

Projects must also demonstrate that project activities and their associated CO_2 removals would not have occurred without project carbon finance. In ERW projects, the demonstration of financial additionality can be complicated by the project’s financial model. Given the numerous potential benefits of silicate mineral amendments for farms, including their usefulness as a replacement for lime for pH management, some ERW project developers may try to supplement carbon finance by having landowners pay for the mineral materials they apply. When this happens, it is unclear if carbon finance results in additional carbon removal. Project developers can avoid such complications surrounding financial additionality by providing clear documentation of all project revenue streams as well as documentation of all costs and benefits sharing between project proponents (e.g., developer, landowner, mineral feedstock supplier).

Regulatory additionality

To satisfy the quality criterion of regulatory additionality, project activities must not be required by any local laws or regulations. This criterion is a straightforward one for ERW projects to meet. Currently, Carbon Direct is not aware of any jurisdictions requiring the application of mineral feedstocks to lands.

Common practice additionality

Finally, to meet the quality criterion of additionality, projects must demonstrate that proposed project activities are not already considered common practice for land managers in the project region. Although the use of agricultural lime for managing soil pH is common practice in many regions, in most places, the use of silicate mineral feedstocks for the same purpose is not. Therefore, ERW project activities generally are considered additional by this criterion.

Selecting an appropriate baseline

Baselines must be established to determine and measure how much CO_2 removal is additional. Projects must demonstrate that credits represent emissions reductions or removals in excess of what would have occurred without project activities. To do this, projects must be able to estimate greenhouse gas emissions under a reasonable baseline scenario (i.e., the emissions that would have occurred without project activities). For ERW projects, an appropriate baseline includes an estimation of the carbon drawdown and mineral weathering occurring naturally in unamended soils (or soils that were previously amended with agricultural lime). This baseline can be broadly estimated based on soil measurements taken prior to the start of project activities, although mineral weathering rates naturally vary according to local climate factors. A more accurate baseline could use modeling based on ongoing measurements or measurements from an adjacent field that remains under business-as-usual management. The historical management of croplands and any changes to management following the initiation of ERW project activities should also be considered. Baseline carbon drawdown and mineral weathering rates are likely to be much lower than rates following ERW mineral amendment. However, depending on the accounting method used, failing to account for baseline carbon drawdown could lead to overestimation of carbon drawdown from project activities.

The widespread use of agricultural lime complicates the selection of an appropriate baseline for ERW projects. Agricultural lime is typically composed of calcium carbonate ground to a small particle size, which weathers quickly in soil and may remove some CO_2 from the atmosphere as it weathers (with approximately half the carbon removal efficacy of most silicate minerals).[75] There has been some confusion in scientific literature

75. To the extent that liming successfully raises the pH of pore water and soils, dissolved Ca^{2+} will be charge balanced by OH- and not by bicarbonate ion. If limestone is used as the liming agent, and dissolved Ca^{2+} is charge balanced only by OH-, then the resulting reaction will release CO_2 to the air:

(1) $CaCO_3$ (limestone) + H_2O = dissolved Ca^{2+} + 2OH- (dissolved) + CO_2 (gas)

If instead some charge balance is via bicarbonate, the process could be CO_2 neutral:

(2) $CaCO_3$ + H_2O = Ca^{2+} + HCO_3^- + OH- (all dissolved)

Finally, the best case for CDR is:

(3) $CaCO_3$ + H_2O + CO_2 (air) = dissolved Ca^{2+} + $2HCO_3^-$ (dissolved)

which removes 1 mole of CO_2 from air per mole of added limestone, but does not achieve the goal of increasing the pH of pore waters and soils.

on whether agricultural lime is a net source or sink of CO_2. One scientific view of liming is biased, based on an incorrect assumption by the IPCC that liming is always a net source of CO_2 because carbonate minerals contain carbon that can be released to the atmosphere if weathered by non-carbonic acids.[76] Subsequent studies have shown that this is not always the case,[77, 78] and that the use of ion ratios and export can be used to constrain the contribution of liming weathered by carbonic acid.[79] If agricultural lime application was part of the historical management practice for a farm and will be discontinued following ERW project initiation, the potential carbon removal associated with calcium carbonate dissolution should be accounted for in estimates of baseline emissions. Future studies will help to constrain the baseline contributions of agricultural lime to atmospheric carbon fluxes across geographies and baseline conditions.

Measurement, monitoring, reporting, and verification

High-quality carbon credit projects must reasonably calculate and monitor emissions reductions or removals using defensible accounting procedures grounded in measured data. ERW projects face carbon accounting challenges due to the difficulty of constraining carbon removal, transport, and fate with direct measurements and the reliance of ERW carbon accounting on models and proxy measurements.

ERW processes take place within an open system. As a CDR pathway, ERW removes CO_2 from the atmosphere, but it is ultimately stored outside of the project boundaries in distributed environments. This makes carbon accounting challenging. Like in other open-system CDR pathways, such as ocean alkalinity enhancement, it would be difficult and prohibitively expensive to directly track CO_2 removed from the atmosphere all the way from its source to its final destination. Leakage during transport and in the ocean is also extremely difficult to monitor and quantify. Even within ERW project bounds (agricultural fields where minerals are applied), carbon drawdown is generally estimated using proxy measurements of weathering products rather than by direct measurements of carbon flux. Such widespread use of indirect measurement methods and a scarcity of studies that

76. Intergovernmental Panel on Climate Change (IPCC). 1997. An introduction to simple climate models used in the IPCC Second Assessment Report. [accessed 2024 April 14]. http://171.67.100.116/courses/2015/ph240/girard1/docs/houghton.pdf.

77. Oh N-H, Raymond PA. 2006. Contribution of agricultural liming to riverine bicarbonate export and CO_2 sequestration in the Ohio River basin. Global Biogeochemical Cycles. 20(3). doi:10.1029/2005GB002565. [accessed 2024 Apr 14]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2005GB002565.

78. Hamilton SK, Kurzman AL, Arango C, Jin L, Robertson GP. 2007. Evidence for carbon sequestration by agricultural liming. Global Biogeochemical Cycles. 21(2):2006GB002738. doi:10.1029/2006GB002738.

79. Raymond PA, Hamilton SK. 2018. Anthropogenic influences on riverine fluxes of dissolved inorganic carbon to the oceans. Limnology and Oceanography Letters. 3(3):143–155. doi:10.1002/lol2.10069.

demonstrate direct carbon mass balance (which might validate indirect methods in some cases) lead to persistent questions regarding the accuracy and precision of measurement and verification of CDR via ERW.

Sources of uncertainty in ERW carbon accounting frameworks are numerous, widespread, and challenging to address. To conservatively estimate credit volumes, projects must demonstrate a reasonable accounting of sources of uncertainty in quantification methods. The open nature of ERW as a CDR pathway means that many natural processes interact with the core desired reaction (carbonic acid weathering) and add uncertainty to carbon removal calculations. Some of these sources of uncertainty, along with opportunities for constraining and decreasing them, are presented in **table 4**, which highlights how challenging each may be to address. Carbon accounting schemes for ERW projects need to evaluate CO_2 removals and greenhouse gas emissions across three core project phases, including: (1) the emissions associated with feedstock preparation (including any mining or grinding), transportation, and application; (2) the rate of atmospheric carbon drawdown within soils due to mineral weathering; and (3) the stability and fate of the drawn down carbon once it leaves the soil column, enters river systems, and eventually enters the ocean. Sources of uncertainty across each of these phases are discussed below, along with their accounting methods.

1. Emissions associated with the preparation, transportation, and application of feedstocks

Project developers must pay careful attention to emissions associated with the preparation, transportation, and application of ERW feedstocks by using LCA to track emissions throughout all key stages of the project. Fortunately, LCA methods capable of handling the requisite level of detail for ERW already exist. When estimating emissions from rock grinding, a thorough assessment must be done that includes an estimate of the energy required for grinding based on the rock's hardness and Bond Work Index; the carbon intensity of all electricity and heat sources; and estimated transport emissions based on mode, fuel type, and distance. Additionally, developers must account for the carbon intensity of the alkaline feedstock, with justification provided if it is zero. If the project does not utilize waste products, the developers should assign appropriate carbon intensities to materials based on the mining or quarrying processes involved. Furthermore, emissions related to the application process should be considered. CDR baselines must be conservative, factoring in both the counterfactual carbon uptake of the alkaline material and the land area involved. Ultimately, accurate LCAs serve as a cornerstone in ensuring the value proposition of ERW as a high-quality CDR solution.

2. Rate of atmospheric carbon drawdown in soils due to mineral weathering

After mineral feedstocks are applied to soils, weathering reactions take place as acids in pore water react with mineral surfaces. The rate and nature of mineral weathering drives the initial rate of carbon drawdown from the atmosphere. Mineral weathering rates are context-dependent and somewhat difficult to predict, but are generally driven by water availability and throughput, concentrations of acids in soil water, temperature, mineral type, and particle size.

Mineral weathering experiments in the lab have provided data to support the development of models for estimating mineral weathering rates in the field. However, exact weathering rates are difficult to extrapolate from laboratory experiments or proxy measurements in the field to in-field rates. Because moisture is an important variable in weathering reactions[80] and soil moisture is highly variable in surface soils[81] (though potentially more controlled in irrigated fields), it is currently difficult to assess field-based dissolution rates from surface soil amendments. Methods used to estimate mineral weathering rates in fields generally rely on proxy measurements of the products of weathering, baseline measurements of these proxies in the absence of applied ERW minerals, and assumptions about how these variables relate to mineral weathering rates. For example, one patented method for ERW carbon accounting[82] measures the accumulation of a specific set of rare earth elements (lanthanides and chromium) to estimate the rate at which minerals are weathering, then uses the measured concentration of magnesium to estimate the quantity of cations that have left the soil column coupled to bicarbonate anions, and finally infers the rate of carbon removal from this value. Both measurement uncertainty (i.e., uncertainty due to lab methods for measuring elements in soil samples) and sampling uncertainty (i.e., uncertainty due to landscape heterogeneity and only sampling a limited number of locations within a field) influence the reliability of weathering rate estimates at this stage.

After estimating initial carbon drawdown rates in the soil column, accounting methods must discount credit volumes to account for uncertainties and inefficiencies in the process at this phase, including the contribution of acids other than carbonic acid to mineral weathering and plant uptake of weathering products. When silicate minerals are weathered

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80. Raymond PA, Hamilton SK. 2018. Anthropogenic influences on riverine fluxes of dissolved inorganic carbon to the oceans. Limnology and Oceanography Letters. 3(3):143–155. doi:10.1002/lol2.10069.

81. Famiglietti JS, Ryu D, Berg AA, Rodell M, Jackson TJ. 2008. Field observations of soil moisture variability across scales. Water Resources Research. 44(1). doi:10.1029/2006WR005804. [accessed 2024 Apr 14]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2006WR005804.

82. Eion Carbon | Carbon removal that checks all the right boxes. 2021. [accessed 2024 Apr 14]. https://eioncarbon.com/.

by acids other than carbonic acid, this does not contribute to the removal of atmospheric CO_2 (although a reasonable argument can be made that non-carbonic soil acids will contribute to weathering regardless of ERW project activities and should therefore not count against the quantification of CDR from ERW, **box 3**). Dissolution by carbonic acid produces one molar equivalent of bicarbonate for each molar equivalent of calcium or magnesium. Dissolution by nitric or sulfuric acid produces calcium and magnesium, but no bicarbonate. Thus, the relative proportion of different acids can be determined by measuring molar equivalents, and ion ratios can be used to partition dissolution between carbonic acid and other acids. This was well demonstrated by a study that presented a conceptual model for determining the fraction of limestone mineral dissolution attributed to carbonic acid versus other strong acids.[83] This study found that, at the study location in southwestern Michigan, most dissolution was from carbonic acid—results which support earlier studies elsewhere.[84, 85] This general approach to estimating the contributions of non-carbonic acids may also be applicable to ERW projects.

Box 3. Questionable impacts of river acidification events on ERW carbon removal efficacy

Dissolved bicarbonate resulting from ERW may be returned to the atmosphere following exposure to a highly acidifying event (e.g., release of acid mine drainage or nitric acid from upstream agricultural activity). However, to quantify the net CDR resulting from an ERW cropland project, it is important to consider the emissions that would have occurred under business-as-usual conditions. In theory, in the absence of ERW project activities, acids in soil or rivers would have driven the bicarbonate buffering system toward release of CO_2 to the atmosphere. Therefore, a reasonable argument can be made that these acid-driven CO_2 emissions should not count against CDR volumes from ERW. Future modeling studies may help to differentiate emissions under project conditions versus business-as-usual conditions to better clarify the net impact of ERW projects.

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83. Hamilton SK, Kurzman AL, Arango C, Jin L, Robertson GP. 2007. Evidence for carbon sequestration by agricultural liming. Global Biogeochemical Cycles. 21(2). doi:10.1029/2006GB002738.

84. Oh N-H, Raymond PA. 2006. Contribution of agricultural liming to riverine bicarbonate export and CO_2 sequestration in the Ohio River basin. Global Biogeochemical Cycles. 20(3). doi:10.1029/2005GB002565. [accessed 2024 Apr 14]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2005GB002565.

85. Semhi K, Amiotte Suchet P, Clauer N, Probst J-L. 2000. Impact of nitrogen fertilizers on the natural weathering-erosion processes and fluvial transport in the Garonne basin. Applied Geochemistry. 15(6):865–878. doi:10.1016/S0883-2927(99)00076-1.

As an example of how such discounts are calculated, in the patented method described above, carbon removal volumes are discounted by about 20% to account for magnesium uptake by plants and the contributions of acids other than carbonic acid (e.g., nitric or sulfuric acid) to weathering. Although the core logic underlying this method is sound and discounts are taken at various stages to account for known sources of uncertainty, there are many built-in assumptions that are not ultimately tested against direct measurements of carbon moving through ecosystems. Numerous ecosystem processes could violate those assumptions and, without detection, they introduce uncertainty. For example, the contribution of strong acids other than carbonic acid to weathering could be higher than anticipated at certain times of the year, especially in agricultural systems where nitrogen-containing fertilizers are applied,[86] and estimates of carbon removal inferred from weathering rates and magnesium transport may be too high.

Overall, uncertainties in estimating rates of carbon drawdown at the soil interface are currently numerous and difficult to constrain. These uncertainties are likely to be better understood in the near term because of scientific development (**box 4**). Intensively-measured sentinel sites and watershed-scale experiments are likely to aid in evaluating models and assumptions related to soil column processes. Significant recent progress has been made in increasing the precision of measurements of weathering products in soil samples (using the TiCAT isotope spike ICP-MS method).[87] Beyond improving measurements and models of processes in the soil column, scientific consensus must be developed on the magnitude of uncertainties that cannot be constrained and how to address these conservatively. For example, fertilizer use introduces strong acids that weather minerals in lieu of carbonic acid. A potentially conservative approach to accounting for this is to assume that all nitrogen that is not taken up by plants becomes nitric acid, and to subsequently discount credit volumes based on the volume of nitrogen-containing fertilizer applied. A similarly conservative approach could account for the addition of sulfur in rock amendments.

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86. Fortner SK, Lyons WB, Carey AE, Shipitalo MJ, Welch SA, Welch KA. 2012. Silicate weathering and CO_2 consumption within agricultural landscapes, the Ohio-Tennessee River Basin, USA. Biogeosciences. 9(3):941–955. doi:10.5194/bg-9-941-2012.

87. Reershemius T, Kelland ME, Jordan JS, Davis IR, D'Ascanio R, Kalderon-Asael B, Asael D, Suhrhoff TJ, Epihov DZ, Beerling DJ, et al. 2023. Initial validation of a soil-based mass-balance approach for empirical monitoring of enhanced rock weathering rates. Environ Sci Technol. 57(48):19497–19507. doi:10.1021/acs.est.3c03609.

Box 4. Research opportunities for constraining unknowns in ERW

Reducing key uncertainties in ERW carbon accounting will require a combination of scientific research, public-private partnerships, collaboration, and data sharing across ERW projects. There are several opportunities for research that may constrain unknowns:

- High-density soil sampling on mineral-amended fields may help assess the impact of landscape heterogeneity on uncertainty in accounting methods.
- Measurements of non-carbonic (i.e., nitric or sulfuric) acid concentrations using pore water lysimeters at multiple depths and time points throughout the growing season, especially in fertilized systems, can be used to assess relationships between strong acids in pore water and fertilizer application rates and timing.
- Model estimates of mineral weathering rates can be compared to actual, measured mineral weathering rates (and other measured soil variables) over time, across multiple geographies, and across soil types.
- Biogeochemical process models of river networks and the ocean can be developed and compared against large-scale datasets of measured variables.
- Monitoring throughout watersheds that contain mineral-amended fields can be used to test assumptions about bicarbonate transportation rates and efficiency through drainage networks.

3. Stability and fate of the drawn down carbon once it leaves the soil column

After atmospheric CO_2 is removed at the soil interface and stabilized as bicarbonate ions following weathering reactions, this bicarbonate may remain in the soil column for years before it travels through river systems to durable storage in the ocean. Between the soil column and the deep ocean, there are a number of ecosystem processes and aqueous reactions that can return some of the dissolved carbon to the atmosphere and reduce the overall carbon removal efficiency of ERW. Quantifying these inefficiencies is challenging, context-dependent, and generally relies on large-scale models of river systems and oceans that are difficult to constrain with direct measurements and contribute large uncertainties despite project monitoring efforts.

Carbon accounting for this phase of ERW projects is a source of disagreement in scientific communities. Some experts believe that carbon losses to the atmosphere after leaving the soil column are negligible, while others point to evidence that these losses can be significant under the right circumstances. Scientists are also working to better understand the impacts of climate change on the efficacy of ocean carbon storage (**box 5**).

Broadly, the scientific discussion about the aqueous processes in rivers and/or the ocean that may result in carbon return to the atmosphere centers on carbonate mineral precipitation and equilibration of the carbonate system downstream. Precipitation of carbonate minerals results in the re-release of some of the CO_2 initially drawn down by silicate mineral weathering. Abiotic carbonate precipitation may occur under circumstances where water exceeds a threshold level of saturation with alkalinity and cations. This process can also be reversed and carbonates can re-dissolve if water chemistry shifts. If ERW introduces new alkalinity and cations to rivers or the shallow ocean in large enough quantities to reach this threshold in specific locations (especially as ERW applications scale and become more extensive across a region), ERW could drive an increase in abiotic carbonate precipitation and re-release of CO_2 into the atmosphere. In addition, biological formation of solid carbonates (in shells, for example) may increase, stimulated by the increased availability of dissolved calcium and carbon. This might begin well below the threshold concentrations for abiotic carbon precipitation events.

Efforts to quantify the potential impact of river and ocean losses on ERW carbon removal efficiency have broadly integrated large-scale biogeochemical models and datasets like the United States Geological Survey's long-term river alkalinity monitoring dataset. The natural world is heterogenous in space and time, so even if threshold events are rare on average, there might be locations or moments where those thresholds are passed. Gradual increases in biological carbonate precipitation occurring in specific ecosystems at specific times of year could be even harder to monitor. Following evidence from model simulations, opinions vary on the size of the discount that is needed to account for all the inefficiencies and unknowns in this phase of carbon accounting for ERW projects. Current estimates using ocean biogeochemistry models suggest that between 9–30% of the carbon initially removed by ERW may return to the atmosphere on decadal timescales, though these estimates are mostly based on theoretical equilibration with ocean carbonate chemistry and not more complex ecosystem processes.[88, 89, 90]

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88. Kanzaki Y, Planavsky NJ, Reinhard CT. 2023. New estimates of the storage permanence and ocean co-benefits of enhanced rock weathering. PNAS Nexus. 2(4):pgad059. doi:10.1093/pnasnexus/pgad059.

89. Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, et al. 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature. 583(7815):242–248. doi:10.1038/s41586-020-2448-9.

90. Kantzas EP, Val Martin M, Lomas MR, Eufrasio RM, Renforth P, Lewis AL, Taylor LL, Mecure J-F, Pollitt H, Vercoulen PV, et al. 2022. Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. Nat Geosci. 15(5):382–389. doi:10.1038/s41561-022-00925-2.

Box 5. Impacts of climate change on the efficacy of ocean carbon storage

Aside from leakage due to carbonate precipitation, storage of bicarbonate from ERW in the ocean is currently thought to be durable for millennia. However, the efficacy of the ocean as a carbon store depends somewhat on future climate conditions. Under current conditions, the ocean takes up about 28% of annual anthropogenic emissions,[91] leading to ocean acidification. Future climate factors like the concentration of CO_2 in the atmosphere and global temperatures impact the ocean's aragonite saturation state (a measure of how readily carbonates precipitate or dissolve in solution), which impacts the ocean's exchange of CO_2 with the atmosphere. Studies on ocean alkalinity enhancement (a CDR pathway related to ERW that involves spreading minerals in the ocean) indicate that carbonate precipitation and other processes that impact the efficiency of ocean carbon storage will vary with future climate conditions[92] and geography-specific factors.[93] The potential impacts of future climate conditions on CDR efficiency in ERW have not yet been constrained by scientific research but may be better constrained by future modeling studies.

Though the potential exists for CO_2 to be re-released to the atmosphere from rivers through carbonate precipitation, some experts suggest that, even in the worst-case scenario, re-release in freshwater drainage networks may have negligible impacts. For instance, despite widespread lime application, there is little empirical evidence from the field of large-scale precipitation and burial of carbonates in watersheds or drainage networks like the Mississippi River.[94] Theoretical models also indicate that river networks have a large capacity for the dissolved products of ERW without exceeding thresholds for abiotic carbonate precipitation.[95] Project-specific factors that might lead to higher carbonate precipitation risks include lower rates of water throughput (e.g., in reservoirs) and underlying geology. Regions that already have high concentrations of calcium, high alkalinity due to low water throughput rates, and high amounts of naturally weatherable

91. ESSD - Global Carbon Budget 2015. [accessed 2024 Apr 14]. https://essd.copernicus.org/articles/7/349/2015/.

92. Lenton A, Matear RJ, Keller DP, Scott V, Vaughan NE. 2018. Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. Earth System Dynamics. 9(2):339–357. doi:10.5194/esd-9-339-2018.

93. Renforth P, Henderson G. 2017. Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics. 55(3):636–674. doi:10.1002/2016RG000533.

94. Raymond PA, Hamilton SK. 2018. Anthropogenic influences on riverine fluxes of dissolved inorganic carbon to the oceans. Limnology and Oceanography Letters. 3(3):143–155. doi:10.1002/lol2.10069.

95. River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering - Zhang - 2022 - Limnology and Oceanography - Wiley Online Library. [accessed 2024 Apr 14]. https://aslopubs.onlinelibrary.wiley.com/doi/full/10.1002/lno.12244.

materials will be closer to the threshold for precipitation beyond which they are more likely to abiotically generate solid carbonate minerals.[96]

Uncertainty in enhanced rock weathering carbon accounting

Some sources of carbon accounting uncertainty in ERW projects may be constrained through project-based sampling and aggregated data from ERW projects broadly. However, other sources of uncertainty are likely to remain poorly quantified even as additional data become available. **Table 4** describes the probable trajectory that four known sources of uncertainty will take as more data become available. In general, processes that take place in the soil column are easier to measure directly and constrain with targeted experiments, such as experiments using mesocosms. Broadly distributed processes such as biological and chemical interactions in rivers or the ocean are more challenging to constrain with direct measurements.

Durability

Durability is the capacity for stored carbon to withstand reversal, or re-emission, to the atmosphere. In ERW projects, the ultimate storage location for CDR is the ocean, where reversals cannot be monitored directly as they can in other project types. However, the durability of bicarbonate stored in the ocean is generally considered to be very high. When uncertainties in carbon transport and fate are appropriately accounted for, carbon stored in the ocean is generally expected to be stable for tens of thousands of years. This durability term is exceptionally high among nature-based projects.

Leakage

Leakage refers to an increase in emissions outside of a project's boundaries as a result of project activities. In the case of ERW, both economic and physical leakage are important considerations.

Economic leakage in ERW projects may occur through on-farm yield reductions, necessitating expanded land use beyond project boundaries for equivalent yield. Studies to date have largely shown yield increases rather than decreases following silicate mineral application, but yields should be monitored in ERW projects nonetheless. Alternatively, diversion of feedstocks used for metal extraction to ERW projects—such

96. Raymond PA. 2017. Temperature versus hydrologic controls of chemical weathering fluxes from United States forests. Chemical Geology. 458:1–13. doi:10.1016/j.chemgeo.2017.02.025.

Table 4. Sources of uncertainty in ERW carbon accounting and key research priorities

Source of uncertainty	Mineral weathering rates	Role of non-carbonic acids	Release of carbon en route to ocean	Release of carbon from the ocean
Location	Soil column	Soil column	River systems	Ocean
Description	Carbon drawdown rates are inferred in ERW from the rate of mineral weathering, which is driven by moisture, temperature, and other factors and may be measured in multiple ways.	Some proportion of the cations released during weathering are driven by acids other than carbonic acid. This proportion may be higher in systems that receive abundant nitrogen fertilizer, which then forms nitric acid, and/or systems in which rock amendments contain significant amounts of sulfur, which then forms sulfuric acid.	Dissolved bicarbonate may precipitate to form carbonate minerals. The process of precipitation releases some of the drawn down carbon. Bicarbonate in rivers may also be released as carbon dioxide if a river experiences a strong acidification event.	Once dissolved bicarbonate reaches the ocean, some carbon may precipitate out of solution as carbonate minerals. The process of carbonate precipitation releases some carbon back into carbonic acid form, which may then be released to the atmosphere as carbon dioxide.
Evidence available to constrain uncertainty	There are well-established rates of mineral weathering under ideal conditions based on controlled laboratory experiments and more limited evidence based on in situ experiments.	Acids can be measured in-project using pore water lysimeters, or can be inferred from acids in collected rainwater, mass of applied fertilizer, and mass of sulfur-bearing rock amendments.	River system models are constrained by widespread, fairly accurate measures of aqueous alkalinity.	Broad ocean models are based on principles of chemistry, biology, and physics and are constrained by measurements.
Recommended research to decrease uncertainty	Include intensive soil sampling on research farms to assess landscape heterogeneity impacts on uncertainty in accounting methods. Compare model estimates of mineral weathering rates and measured actual mineral weathering rates (and other measured soil variables) over time across multiple geographies and soil types. Detailed studies over significant land areas and time scales should aim for actual carbon mass balance to test and validate carbon accounting methods using more easily measured proxies.	Measure non-carbonic (i.e., nitric or sulfuric) acid concentrations from pore water lysimeters at multiple depths and time points throughout growing seasons, especially in fertilized systems, to assess relationships between strong acids in pore water and fertilizer application rates and timing.	Include modeling studies grounded in knowledge of biogeochemical processes and large-scale datasets. Research efforts should include whole-watershed studies that include time series with direct carbon concentration measurements to test assumptions about bicarbonate transportation rates and efficiency through drainage networks.	Include modeling studies grounded in knowledge of biogeochemical processes and large-scale datasets.

as feedstocks enriched in nickel—could lead to increased mining or sourcing outside of project boundaries to meet increased commodity demand. Mitigating these risks involves documentation of yield shifts and consideration of potential alternative uses for mineral feedstocks.

Physical leakage could occur if project activities result in increased emissions downstream from project land areas. For example, as previously described, the carbon drawn down in the soil column during mineral weathering could be re-released to the atmosphere if increases in alkalinity in downstream waterways and/or the ocean lead to increased carbonate mineral precipitation. Estimating the magnitude of this risk is difficult given how widely distributed drawn down carbon becomes after leaving the soil column and how many potentially complicating geochemical and biological processes can occur throughout a watershed or river network and in the ocean. In locations like the US that have well-established river monitoring networks and alkalinity datasets, it may be possible to anticipate locations and waterways where carbonate precipitation is likely to be an issue. Projects can address this risk somewhat through model estimates of potential leakage based on location-specific factors.

As discussed in detail in the “Measurement, monitoring, reporting, and verification” section, there is disagreement in scientific communities on the anticipated magnitude of leakage, or CO_2 losses back to the atmosphere, in river networks and/or the ocean. In assessing ERW projects, credit buyers should be aware of this disagreement and understand the potential risks associated with underestimated leakage.

Conclusion and summary recommendations

An exciting new CDR pathway, ERW has the potential to offer large volumes of highly durable, cost-effective removals with numerous co-benefits such as increased crop yields and a reduced need for agricultural amendments. However, important uncertainties and risks remain related to human and ecosystem health and safety and quantifying the climate impact of ERW projects with confidence. At this stage, buyer involvement may be most appropriately focused on driving the evolution of ERW as a CDR solution through investment and market scaling rather than on buying CDR credits from ERW projects to count toward climate mitigation goals. Some of the current risks can be constrained with appropriate safeguards and additional research. Strong buyer signals for increased quality and reduction of current uncertainties may help steer the CDR market toward an improved understanding of ERW as a solution and increase confidence in its climate impact. Opportunities and risks for buyers of credits from ERW projects are summarized below along with broad recommendations for future efforts to mitigate these risks.

Final takeaways

- ERW is a promising CDR pathway. Substantial risks remain.
- Buyers interested in ERW credits today should aim to scale ERW and advance ERW science through purchase, demonstration, and learning, but not aim to meet current climate commitments or annual targets through the use of ERW credits.
- Key risks center on carbon accounting and potential harms from mineral feedstock contaminants.
- Some risks are addressable through best practices and targeted research efforts, but some uncertainty may never be fully quantified.
- Buyers should make responsible and conservative choices based on awareness of risks, mitigation strategies, and tolerance for risks that cannot be reduced.

The recent excitement surrounding ERW is well-founded. This approach may be a rare win-win-win offering potentially large volumes of durable, cost-effective CDR with possibly significant co-benefits to livelihoods and ecosystems in agricultural systems. However, scaling ERW responsibly requires an understanding of key risks and unknowns, especially related to heavy metals in mineral feedstocks and uncertain carbon accounting. Many of these risks can be mitigated with targeted research, monitoring, and implementation of best practices. However, questions remain regarding how much net CDR takes place for a given amount of rock amendment, whether this CDR can be reliably quantified, and over what time frame. The answers to these questions will impact the price of CDR credits from ERW projects. If such uncertainties can be satisfactorily reduced, the efficiency and cost of ERW projects can be better understood. If efficiency is shown to be high and costs are correspondingly low, this will increase confidence that CDR credits from ERW project represent actual removals from the atmosphere that are durably stored at a reasonable cost.

Some risks associated with ERW cropland projects can be mitigated more easily than others. Risks related to potential harms from heavy metals or other contaminants in mineral feedstocks should not be dismissed, but there appears to be a path forward to monitor for and mitigate these risks. Buyers should evaluate the risk mitigation measures in use by projects and push for more stringent controls on mineral feedstock quality, feedstock handling, and environmental monitoring for impacts.

On the other hand, there is still considerable disagreement within the scientific community about ERW carbon accounting and the magnitude of risks and uncertainties involved. The carbon that is removed from the atmosphere by ERW follows a long, winding path before reaching the stage of durable ocean storage. Along the way, in dissolved or mineralized forms, that carbon interacts with many different ecosystems and environmental chemistries. Biotic and abiotic reactions can introduce many unknowns, making it difficult to track the fate of removed carbon. Scientific consensus suggests that bicarbonate is very stable once it reaches the deep ocean. However, the transport of carbon to the ocean and equilibration of carbon in solution with ocean water introduces complex unknowns. Carbon accounting for ERW projects is a uniquely interdisciplinary problem, and resolving uncertainties will require contributions and research across many different fields.

Efforts are underway to understand and limit uncertainties in ERW carbon accounting, but there is still much debate about how serious these uncertainties may be. Published estimates suggest inefficiencies of 9–30% in the transport of ERW carbon to durable ocean storage,[97] and some experts suggest that the actual levels of uncertainty could be

97. Kanzaki Y, Planavsky NJ, Reinhard CT. 2023. New estimates of the storage permanence and ocean co-benefits of enhanced rock weathering. PNAS Nexus. 2(4):pgad059. doi:10.1093/pnasnexus/pgad059.

50% or higher.[98, 99] Many of the scientists involved in ERW research are advisors for one or more ERW project developers, which may create the potential for misaligned incentives in accurately estimating ERW accounting uncertainties. There is a strong need for research and discussion from a broader collection of independent scientists to improve confidence that early uncertainty estimates are not overly optimistic.

Buyers interested in ERW credits today should understand the risks and purchase ERW credits with the intention of scaling ERW and improving MRV methodologies, rather than using ERW credits to meet climate commitments that require a high degree of confidence in carbon accounting. There are numerous open questions in ERW, many of which can be solved with investment in research and by carrying over best practices from other industries. Early partners can help to move ERW science forward by contributing toward specific research objectives, including:

- Constraining uncertainty due to landscape heterogeneity through high-density soil sampling on mineral-amended fields,
- Constraining impacts of non-carbonic (i.e., nitric or sulfuric) acids using pore water lysimeter samples at multiple depths and time points throughout the growing season, especially in fertilized systems and systems in which rock amendments contain significant amounts of sulfur,
- Constraining uncertainty in weathering rates through comparison of model estimates and actual, measured mineral weathering rates,
- Constraining uncertainty in downstream processes through development and evaluation of biogeochemical process models of river networks and the ocean against large-scale datasets of measured variables, and
- Testing assumptions about drainage networks and bicarbonate transport efficiency by monitoring throughout watersheds containing mineral-amended fields.

These research initiatives will help further the science and increase clarity about whether ERW can provide credits with a high-enough level of confidence to be used for climate commitments at a reasonable cost. Given that ERW is an open-system CDR pathway, carbon accounting for ERW will likely always rely on proxy measurements and models that will carry some degree of uncertainty.

98. Unpublished communication with a panel of experts.

99. Enhanced Weathering in Agriculture v1.0 — Isometric. [accessed 2024 Apr 14]. https://registry.isometric.com/protocol/enhanced-weathering-agriculture.

Buyers need to know how to incorporate this uncertainty into their purchases and develop an understanding of acceptable risks using scientific quality assessment. In the coming years, scientific understanding of ERW is likely to advance rapidly, leading to rich and evolving conversations between scientists, project developers, buyers, and others across a wide range of relevant disciplines.

Preparing cropland for planting. (Source: Adobe Stock).

Appendices

Appendix A: Glossary of acronyms

Acronym	Definition
CDR	Carbon dioxide removal
DAC	Direct air capture
EBC	European Biochar Certificate
EPA	Environmental Protection Agency (United States)
ERW	Enhanced rock weathering
LCA	Life cycle assessment
MRV	Monitoring, reporting, and verification
NbS	Nature-based solutions
QA/QC	Quality assurance and quality control
SWOT	Strengths, weaknesses, opportunities, and threats

Appendix B: Landscape of players

Table 5. Landscape of players in the enhanced rock weathering project space

Company/academic institution	Organization type	Location	2030 offtake goals
Lithos Carbon	Private supplier	USA	1 billion tonnes
Eion	Private supplier	USA	500,000 tonnes
UNDO	Private supplier	UK	100,000 tonnes
V6 Agronomy	Private supplier	Canada	n/a
Inplanet	Private supplier	Brazil	10,000 tonnes
Fieldcode	Private supplier	Greece	n/a
University of Illinois, Urbana-Champaign	University Research	USA	Research
UNDO & University of Newcastle	University Research	UK	Research
Silicate	Private supplier	Ireland	1 billion tonnes
University of Sheffield	University Research	UK	Research
Carbonaught	Private supplier	Australia	1 billion tonnes
Climitigation/Vesta	Private supplier	USA	100 million tonnes
UC Davis Working Lands Innovation Center	University Research	USA	Research
The Future Forest Company	Private supplier	UK	1 million tonnes
Mati Carbon	Private supplier	India	1 million tonnes
Green Sequest	Private supplier	Poland	n/a
Vaulterra	Private supplier	USA	n/a
Zumwalt Acres	University Research	USA	n/a
ClimeRock	Private supplier	France	10 millions tonnes

Note: Table cells filled with "n/a" indicate that information is not available.

Appendix C: Cost estimates from literature

Table 6. Enhanced rock weathering cost estimates from literature

Title	Author	Year	Region	US$/t$CO_2$ lower bound	US$/t$CO_2$ upper bound
Techno-Economic and Life Cycle Assessment of Enhanced Rock Weathering: A Case Study from the Midwestern United States	Zhang, et al.[100]	2023	Midwestern US	45	472
Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom	Kantzas, et al.[101]	2022	UK	102*	318*
Potential and costs of carbon dioxide removal by enhanced weathering of rocks	Strefler, et al.[102]	2018	Global	60	200
Potential for large-scale CO_2 removal via enhanced rock weathering with croplands	Beerling, et al.[103]	2020	Global Review	54	220
Transforming US agriculture with crushed rock for CO_2 Sequestration and Increased Production	Beerling, et al.[104]	2023	US	100	150

Note: Costs were originally reported in pounds sterling and converted to US$ based on the exchange rate on June 18, 2024.

100. Zhang B, Kroeger J, Planavsky N, Yao Y. 2023. Techno-Economic and Life Cycle Assessment of Enhanced Rock Weathering: A Case Study from the Midwestern United States. Environ Sci Technol. 57(37):13828–13837. doi:10.1021/acs.est.3c01658.

101. Kantzas EP, Val Martin M, Lomas MR, Eufrasio RM, Renforth P, Lewis AL, Taylor LL, Mecure J-F, Pollitt H, Vercoulen PV, et al. 2022. Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. Nat Geosci. 15(5):382–389. doi:10.1038/s41561-022-00925-2.

102. Strefler J, Amann T, Bauer N, Kriegler E, Hartmann J. 2018. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environ Res Lett. 13(3):034010. doi:10.1088/1748-9326/aaa9c4.

103. Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, et al. 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature. 583(7815):242–248. doi:10.1038/s41586-020-2448-9.

104. Beerling DJ, Kantzas EP, Martin MV, Lomas MR, Taylor LL, Zhang S, Kanzaki Y, Reinhard CT, Planavsky NJ, Eufrasio RM, et al. 2023. Transforming U.S. agriculture with crushed rock for CO_2 sequestration and increased production. doi:10.48550/arXiv.2308.04302. [accessed 2024 Jun 3]. http://arxiv.org/abs/2308.04302.

Table 7. Direct air capture cost estimates from literature

Title	Author	Year	Details	US$/t$CO_2$ lower bound	US$/t$CO_2$ upper bound
Considering technology characteristics to project future costs of direct air capture	Sievert, et al.[105]	2024	Capture and storage systems (solvent, sorbent, and mineral looping)	226	835
Roads to Removal, Chapter 7	Pett-Ridge, et al.[106]	2023	Capture and storage systems (solvent, sorbent, mineral looping, electro-swing, pH-swing)	160	570
Direct Air Capture: A key technology for net zero	IEA[107]	2022	Solid- or liquid-based technologies; transport and storage costs not included	125	335
Climate Change 2022—Mitigation of Climate Change	IPCC[108]	2022	Capture and storage	100	300
Ambient weathering of magnesium oxide for CO_2 removal from air	McQueen, et al.[109]	2020	Mineral looping using grid and solar electricity	46	159
A process for capturing CO_2 from the atmosphere	Keith, et al.[110]	2018	Solvent based DAC design for ~1MtCO_2/yr with natural gas	94	232
Negative Emissions Technologies and Reliable Sequestration, Chapter 5	NASEM[111]	2019	Solvent and sorbent based techniques	89	877

105. Sievert K, Schmidt TS, Steffen B. 2024. Considering technology characteristics to project future costs of direct air capture. Joule. 0(0). doi:10.1016/j.joule.2024.02.005. [accessed 2024 Apr 14]. https://www.cell.com/joule/abstract/S2542-4351(24)00060-6.

106. Roads to Removal – Options for carbon dioxide removal in the US. [accessed 2024 Jun 3]. https://roads2removal.org/.

107. Executive summary – Direct Air Capture 2022 – Analysis - IEA. [accessed 2024 Apr 14]. https://www.iea.org/reports/direct-air-capture-2022/executive-summary.

108. Intergovernmental Panel on Climate Change. 2023. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [accessed 2024 Apr 14]. https://www.cambridge.org/core/books/climate-change-2022-mitigation-of-climate-change/2929481A59B59C57C743A79420A2F9FF.

109. McQueen N, Kelemen P, Dipple G, Renforth P, Wilcox J. 2020. Ambient weathering of magnesium oxide for CO2 removal from air. Nat Commun. 11(1):3299. doi:10.1038/s41467-020-16510-3.

110. Keith DW, Holmes G, Angelo DS, Heidel K. 2018. A Process for Capturing CO_2 from the Atmosphere. Joule. 2(8):1573–1594. doi:10.1016/j.joule.2018.05.006.

111. National Academies of Sciences, Engineering, and Medicine. 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

Appendix D: Carbon dioxide removal credit sales 2021–2023

Table 8. Enhanced rock weathering carbon dioxide removal sales 2021–2023

Purchase date	Seller	CDR type	Buyer	Tonnes sold	Price per tonne
Fall 2022	Inplanet	ERW	Frontier	1,041	$480.00
Spring 2022	Lithos	ERW	Frontier	640	$500.00
Spring 2021	Future Forest Co.	ERW	Stripe	1,500	$200.00
n/a	Greensand	ERW	n/a	n/a	$119.41
August 2023	UNDO	ERW	Klimate	250	n/a
August 2023	UNDO	ERW	Klimate	250	n/a
June 2023	UNDO	ERW	Klimate	250	n/a
March 2023	UNDO	ERW	Klimate	100	n/a
April 2023	Greensand	ERW	Klimate	100	n/a
April 2023	UNDO	ERW	Microsoft	5,000	$185.00
December 2021	Eion	ERW	Stripe	500	$500.00
n/a	Eion	ERW	Patch	n/a	$500.00
Fall 2023	Mati	ERW	Frontier	1,513	$300.00

Note: Table cells filled with "n/a" indicate that information is not available.

Table 9. Engineered carbon dioxide removal sales 2021–2023

Purchase Date	Seller	CDR type	Buyer	Tonnes sold	Price per tonne
Fall 2022	Arca	Mineralization	Frontier	380	$1,315.79
Fall 2022	Carbon To Stone	DAC	Frontier	846	$394.01
Fall 2022	CREW Carbon	Mineralization	Frontier	410	$813.01
Spring 2022	Travertine	Mineralization	Frontier	365	$1,369.86
Spring 2022	RepAir DAC Ltd	DAC	Frontier	199	$1,600.00
January 2021	Climeworks	DAC	Microsoft	1400	n/a
January 2022	Neustark	Mineralization	Microsoft	100	n/a
September 2023	Heirloom	DAC	Microsoft	315,500	$633.91
Summer 2023	Airhive	DAC	Frontier	943	$530.00
Summer 2023	Carbon Atlantis	DAC	Frontier	275	$1,816.00
Summer 2023	Holocene	DAC	Frontier	332	$1,506.00
Summer 2023	Spiritus	DAC	Frontier	713	$700.00
November 2023	Carbon Capture Inc.	DAC	Frontier	45,500	$439.56

Note: Table cells filled with "n/a" indicate that information is not available.

Appendix E: Impacts on human health and ecosystems

The pathways for impacts from ERW on human or ecosystem health can be grouped into two broad categories: (1) mobilization, transport, and availability of contaminants derived from minerals used for ERW; and (2) downstream effects or changes to system properties induced by ERW (e.g., changes to soil and water chemical properties) that result in unfavorable changes to existing or naturally occurring contaminants.

The toxicity thresholds for harm are independent of ERW feedstock source(s) and mobilization pathways. However, regulatory frameworks for ERW are not clearly defined, and public opinion may not follow nuanced scientific processes. Addition of crushed or pulverized rock to soil can lead to humans being exposed to trace elements through direct pathways (e.g., soil consumption, mobilized dust inhalation) or indirect pathways (e.g., uptake into food crops, leaching to groundwater. Assessing the overall impacts to an ecosystem requires an understanding of the current and predicted future states of the ecosystem under baseline and scenario conditions.

Direct exposure: Exposure through direct soil consumption is not considered although, for some elements, it is the basis for deriving soil concentration thresholds. Dust inhalation is a concern—with the possibility of direct inhalation during crushing and following dust mobilization or field application. One concern is that serpentine and amphibole minerals may be deposited or associated with naturally occurring asbestos deposits. Although not all forms of asbestos cause asbestos diseases such as mesothelioma, crushing and applying rocks containing, or even associated with, asbestos minerals may lead to enhanced scrutiny due to the potential occupational exposure and mobilization of dust particles.

Indirect exposure: Trace elements contained in ERW materials such as basalts undergo chemical changes and may be mobilized during the weathering process. Once released from the host rock, trace elements can accumulate in soil, be taken up by plants, or leach into groundwater. Mitigation options should first focus on selecting combinations of feedstock and soil that limit trace element mobilization and bioavailability. An example might be screening soil for manganese oxide content and limiting application of feedstocks containing elevated chromium concentrations because manganese oxides can oxidize trivalent chromium into the more toxic and mobile hexavalent chromium compound.[112] In cases where the only feasible combinations of feedstock and soil could pose a risk of contaminant mobilization, co-deployment of additional soil amendments could mitigate contaminant release from specific soils.

112. US Environmental Protection Agency (EPA). 2000. Chromium compounds. [accessed 2024 April 14]. https://www.epa.gov/sites/default/files/2016-09/documents/chromium-compounds.pdf.

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Cover image: Application of minerals to cropland (Source: Adobe Stock)