Enhanced Weathering Policy Primer

Assessing the Opportunity

Introduction

There is clear scientific consensus that, in addition to rapid and deep reduction of global greenhouse gas emissions, carbon dioxide removal (CDR) will be required at an immense, multi-gigatonne (Gt) annual scale by mid-century to meet the goals of the Paris Agreement and limit warming to 1.5 or even 2°C.[1] CDR encompasses a range of approaches, and to meet the massive challenge to achieve gigatonne scale will require a portfolio of solutions.[2] Many of these pathways are new technologies that could potentially take years to develop, demonstrate, and deploy.

Methods of CDR that offer meaningful co-benefits, and that can be delivered at significant scale in the coming years, with the potential for low cost, are of particular interest.

Enhanced weathering (EW) is a promising CDR approach that builds on the longstanding agricultural practice of applying pulverized rock (such as limestone) to working lands to manage soil pH.[3] EW accelerates the natural carbonate-silicate cycle and durably removes carbon dioxide (CO_2) from the atmosphere via the spreading of certain types

1 IPCC AR6 Synthesis Report p 50, 2023.
2 Defining Carbon Dioxide Removal: Issue Brief, Carbon Business Council, May 2023.
3 Riedl et. al. "5 Things to Know about Carbon Mineralization as a Carbon Removal Strategy." World Resources Institute, June 2023.

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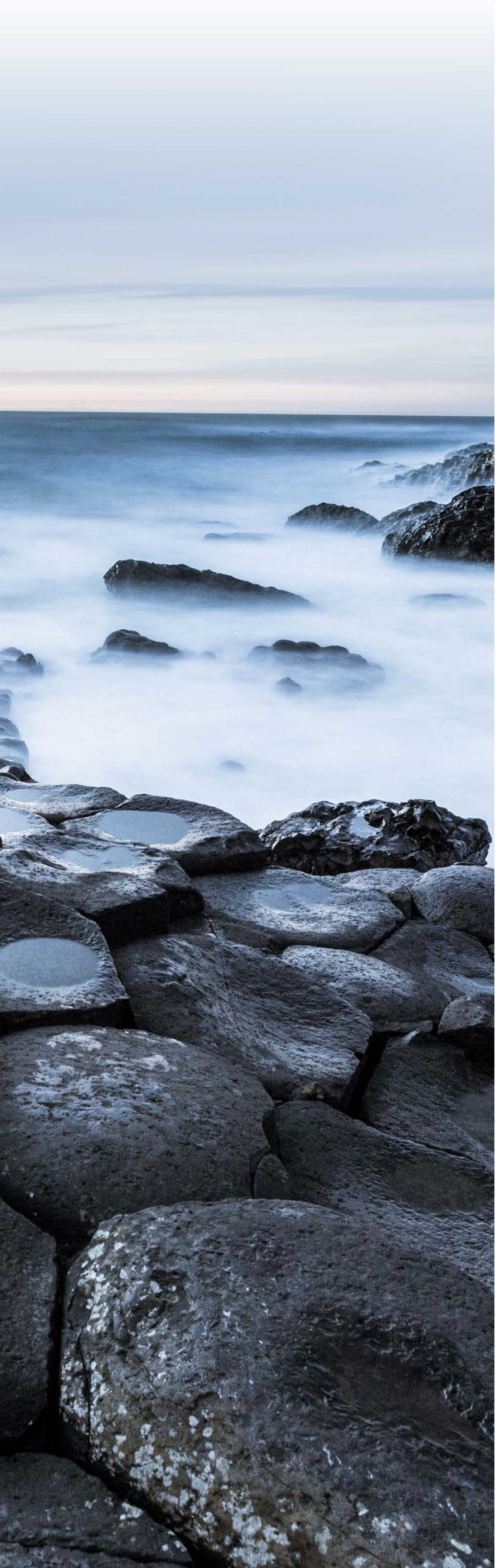
of ground alkaline material (for example, silicate rock such as basalt or olivine) over agricultural soil. In addition to raising soil pH (and reducing soil acidification), the increased surface area of this ground alkaline material reacts with CO_2 in the soil to form stable bicarbonate ions — accelerating the time scale of natural weathering from centuries and millennia to months and years. The bicarbonate travels through the soil and river networks to the ocean, where the carbon is stored for tens of thousands of years.

Beyond its significant potential climate impact, EW holds the promise of offering substantial agronomic and economic co-benefits to farmers. When applied to acidic soils, EW increases the bioavailability of certain critical crop nutrients that improve soil health and enhance crop productivity, increasing yields and optimizing the use of costly and emissions-intensive chemical fertilizers. Many EW feedstocks additionally contain micronutrients that can further increase crop productivity. From an economic perspective, buyers and sellers of CDR credits from EW projects have the opportunity to price and structure purchases such that a share of the revenue from credit sales can become a meaningful and recurring source of incremental income for farmers.

In this policy primer, a working group of Carbon Business Council member companies, partners, and scientific experts highlight the EW opportunity, identify key challenges, and offer a set of focused recommendations for policymakers, the emerging EW commercial sector, and other CDR ecosystem actors to responsibly accelerate the advancement, deployment, and scaling of enhanced weathering.



The Enhanced Weathering Opportunity

- **Scalability and low cost.** EW offers high-quality long-duration CDR with multi-Gt annual global scale potential at a cost that could, over the coming decade, decline below $100 per tonne.[4,5] The pathway employs ground alkaline material, including Earth-abundant mineral feedstocks such as basalt and olivine, and leverages logistical capabilities, supply chains, and delivery channels from mining and agriculture — two of the largest global economic sectors — to durably remove CO_2 from the atmosphere. Energy requirements for EW (transport and, when necessary, extraction and processing of feedstock) are low relative to the pathway's CDR potential, and scaling initial deployments will not require significant new technology development, infrastructure, or capital expenditure.[6] EW is a relatively new field, but a few dozen companies have formed in recent years to address this promising commercial and climate opportunity across six continents.
- **Agronomic co-benefits.** In addition to the CDR benefit offered by EW, the application of crushed alkaline material to agricultural lands has the effect of raising soil pH, and therefore reducing soil acidification. EW deployment can thus serve as a replacement for the 30 megatonnes (Mt) of agricultural lime (crushed limestone, or "ag-lime") spread by U.S. farmers each year to manage soil pH.[7] (The application of ag-lime, or "liming," can be carbon negative or a source of CO_2 emissions depending on specific conditions of sourcing, transport, and application of the ag-lime feedstock.[8]) By raising the pH of acidic

4 Beerling et. al., Potential for Large-Scale CO_2 Removal via Enhanced Rock Weathering with Croplands. Nature, July 2020.

5 Fuhrman et. al. "Diverse Carbon Dioxide Removal Approaches Could Reduce Impacts on the Energy-Water-Land System." Nature Climate Change, March 2023.

6 Moosdorf et. al. "Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering." Environmental Science & Technology, March 2014.

7 West and McBride, "The Contributions of Agricultural Lime to Carbon Dioxide Emissions in the United States." Agriculture, Ecosystems, and the Environment, June 2005.

8 Kukla et. al. "Adding Nuance on Agricultural Lime in the CDR Verification Framework." Carbonplan, October 2023.

soils to more optimum levels, EW increases the bioavailability of important crop nutrients such as nitrogen, phosphorus, and potassium, which early studies have shown can deliver potentially significant agronomic co-benefit in the form of improvements to soil health, increased crop yield, and optimized use of chemical fertilizers. Many EW feedstocks can contain additional phosphorus and potassium, as well as key micronutrients such as iron, silicon, zinc, manganese, and molybdenum that can also increase crop productivity.[9] Beyond the CDR benefit and potential cost savings on offer, replacement of ag-lime and optimized use of chemical fertilizers can lower the emissions intensity of farming, both in terms of avoided CO_2 emissions from the production of fertilizer, as well as reduced N_2O release from agricultural lands.[10,11]

- **New income stream for farmers.** Farming is a cornerstone of the world economy, responsible for sustaining and nourishing a growing global population and foundational to every nation's society and culture. Globalization, climate change, and other external factors have made it increasingly challenging for individual farmers to make a profit. In addition to potential cost savings from replacement of ag-lime for pH management and optimized use of chemical fertilizers, sharing in the revenue from CDR credits generated by EW projects offers a potentially significant recurring incremental income stream for farmers. The promise of EW is particularly strong in warm and wet zones of the Global South, which can offer accelerated weathering rates and where smallholder farmers work lands that are often subject to soil acidification with limited access to chemical fertilizers.[12,13] These smallholder farmers represent a globally distributed frontline community that can potentially benefit greatly from the deployment of EW. (Significant potential additionally exists for deployment of EW on the massive tracts of Global South land area dedicated to large-scale commercial agriculture.) Deployment of EW in the Global South is a promising opportunity that merits increased scientific research and socio-political assessment.

- **Insetting.** The agricultural sector is expected to be a primary contributor to "residual emissions" — i.e. those emissions that cannot be abated to achieve a 2050 net-zero target.[14] Mining represents another difficult-to-decarbonize sector, responsible for an estimated 0.4Gt annual direct greenhouse gas (GHG) emissions emissions (scopes 1 and 2).[15] Insetting refers to a company's implementation of climate mitigation projects, including CDR, within its operations or supply chain in order to neutralize residual emissions as part of a net-zero or other climate commitment. EW represents a compelling means for large agricultural and mining companies to inset (i.e. compensate for) the hard-to-abate emissions from their operations and supply chains by financing EW projects themselves. Beyond the insetting opportunity, the EW business case for companies in mining, agriculture, and other relevant sectors is strong: CDR is expected to grow to become a $1 trillion commercial sector in the second half of the century.[16] By developing EW capability and operational scale via insetting to meet their net-zero targets, agricultural and mining companies can position themselves to be major players in a massive commercial sector in the second half of the century.

9 Beerling et. al. "Enhanced Weathering in the U.S. Corn Belt Delivers Carbon Removal with Agronomic Benefits." PNAS (in press), 2024.

10 E. Blanc-Betes et al. In Silico Assessment of the Potential of Basalt Amendments to Reduce N2O Emissions from Bioenergy Crops. Global Change Biology: Bioenergy, 2020.

11 M. Val Martin et al. Improving Nitrogen Cycling in a Land Surface Model (CLM5) to Quantify Soil N2O, NO and NH3 Emissions from EW with Croplands. Geoscientific Model Development Discuss 2023.

12 Boudinot et. al. Enhanced Rock Weathering in the Global South: Exploring Opportunities for Enhanced Agricultural Productivity and Carbon Dioxide Drawdown. Precision Development, January 2023.

13 Manning, et. al. Enabling Food Security Through Use of Local Rocks and Minerals. The Extractive Industries and Society, 2020.

14 H.J. Buck et. al. "Why Residual Emissions Matter Right Now," Nature Climate Change, March 2023.

15 Delevigne et. al. Climate Risk and Decarbonization: What Every Mining CEO Should Know. McKinsey Sustainability, January 2020.

16 Mannion et. al., Carbon Removals: How to Scale a New Gigaton Industry. McKinsey Sustainability, 2023.

- **Deployability.** EW is high-quality CDR that can feasibly be deployed at multi-megatonne (Mt) annual scale in the coming years, and scale up to potentially multiple gigatonnes globally by 2050. Because EW leverages existing infrastructure, supply chains, transport, and delivery channels from two massive global economic sectors in mining and agriculture, the pathway does not require significant new technology development, construction of new industrial facilities, or other major capital expenditure to begin scaling. Permitting, which can be a challenge for certain other CDR pathways, is generally not an obstacle for deployment of EW: spreading crushed rock on agricultural lands is already a common farming practice. Current operations of the mining sector already move enormous quantities of material, generating 72Gt of waste rock and 8.9Gt of tailings annually.[17,18] Not all mining residues represent appropriate feedstock for EW, and their use must be carefully assessed on a case-by-case basis. The National Academy of Sciences, Engineering, and Medicine estimates an up to 10Gt standing stock of alkaline mine waste potentially suitable for EW, so that new mining will not necessarily be required for initial scaling of EW.[19,20]

Enabling Scale

- **Engagement and awareness.** Farmers have been applying crushed rock to fields for millennia, but the term "enhanced weathering" is effectively unknown outside the CDR sector and the academic field of geochemistry. Given low profit margins and the numerous risks and variables associated with annual crop production, farmers are understandably conservative when it comes to adopting new agricultural practices. Regulators and policymakers are largely unfamiliar with EW, and the general public even more so.[21] Some large commercial actors in the mining and agricultural sectors have begun to engage on EW, but many still have not. A concerted and coordinated public engagement and education campaign — tailored for key audiences starting with farmers, regulators, and policymakers, and extending to agricultural communities, corporate stakeholders, and the general public — to highlight EW's agronomic co-benefits, CDR potential, deployability, and scalability is greatly needed. With farmers in particular, two-way engagement and purposeful dialogue will be essential to understand current needs and priorities, and how EW can be most beneficial to them.

- **Effective project design.** While there is emergent scientific consensus as to the general potential efficacy of EW as high-quality, long-duration CDR, mineral weathering rates are subject to a range of factors, from feedstock characteristics (mineralogy and particle size) to soil type, pH, and water fluxes. Additionally, a project's carbon efficiency can be contingent on the extent of feedstock processing required, mode and distance of transport, and other techno-economic factors.[22] The heterogeneity of deployment contexts for EW is thus substantial, which makes scientifically informed site selection and project design critical to climate impact. As EW scales, it will be essential to maintain a clear focus on ensuring project efficacy and quality, and avoiding deployments with inappropriate feedstocks, and at sites that are geochemically unsuitable, techno-economically unfavorable, or socio-politically inappropriate. Continued scientific and social research, deployment-led learning, and transparent sharing of data relating to these questions and variables will be key to responsibly advancing EW.

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17 Global Tailings Review, August 2020.
18 Kahsar et. al. RMI Applied Innovation Roadmap for CDR. Slide 147. November 2023.
19 NASEM. Negative Emissions Technologies and Reliable and Sequestration: A Research Agenda. 2019
20 Renforth et. al. "The Negative Emission Potential of Alkaline Materials." Nature Communications, March 2019.
21 Spence et. al. Exploring Cross-National Public Support for the Use of EW as a Land-Based CDR Strategy. Climatic Change, 2021.
22 E. P. Kantzas et al. Substantial Carbon Drawdown Potential from EW in the United Kingdom. Nature Geoscience, 2022.

- **Monitoring, reporting, and verification.** High-quality monitoring, reporting, and verification (MRV) is essential to building the market trust necessary for CDR to achieve gigatonne scale in the coming decades. As outlined in the Carbon Business Council's 2023 Issue Brief on the topic, the core of MRV is quantification of a project's efficacy in terms of net removal of CO_2 from the atmosphere. This can be challenging for CDR approaches which leverage open-system geochemical processes that cannot always be clearly or easily measured, and may occur over varying time intervals.[23] These open-system approaches — which include EW — have great potential for scalability at low cost. MRV protocols for EW have begun to emerge, and will continue to develop over the coming years.[24] The EW community should share data on deployments where possible, and continue collaborating to develop workable operating protocols for MRV based on the best available science, which is expected to dynamically advance over time. High-quality MRV for EW projects will be expensive in the early years of the field, requiring extensive direct measurements of CDR rates, and likely decline in cost over time as science advances, stakeholders learn, and projects scale. Modeling will have an increasing role to play in EW MRV as scientific certainty grows, further contributing to future cost reductions and economies of scale.

- **Funding.** EW will require substantially increased funding support in the coming years to reach its potential. In the US, certain CDR pathways have begun to receive meaningful support at the federal level – via for example the 2021 Infrastructure Investment and Jobs Act and 2022 Inflation Reduction Act.[25] However, EW has been almost entirely neglected; the situation is similar in the European Union (EU) and other jurisdictions globally. Funding needs for EW range from continued fundamental scientific research on benefits and risks and MRV protocol development, to demonstration projects and on-farm technical assistance to scale early deployment. Due to the unique techno-economics of EW's deployment model, which consists primarily of operating expenses (with low capital expenditure) and credit revenue that will be earned over time, project developers additionally lack fit-for-purpose project finance mechanisms across the EW value chain — from feedstock sourcing, extraction, processing, and transport, to deployment on working lands. It will be important for the finance community to develop a clear understanding of an EW project's revenue profile so that funding mechanisms can address the time-lag between expenditures and generation of CDR credits. Structured commodity finance offers a potential tool to fund key components of the EW supply chain as the market scales, but fit-for-purpose funding instruments

23 Ellis and Sanchez, "Quantification Uncertainty and Discounting," The Great Unwind, March 2023.
24 M. O. Clarkson et. al. A Review of Measurement for Quantification of Carbon Dioxide Removal by Enhanced Weathering in Soil. In review, 2023.
25 Carbon Removal in the Bipartisan Infrastructure Law and Inflation Reduction Act. World Resources Institute, December 2022.

will take time to develop and evolve. Just as the US Department of Energy (DOE) Loan Programs Office has helped to fill the project finance gap for early projects in other fields of climate-tech, the public sector can play a meaningful role in helping to catalyze initial scale deployment of EW in the coming years.

- **Worker, community, and ecosystem safety.** While EW offers a range of co-benefits in addition to CDR, there are several potential risks that can stem from improper project design and deployment. EW researchers and project developers are conscious of these risks, and the field as a whole is committed to safe and responsible deployments that take steps to mitigate any potential negative externalities to workers, communities, and ecosystems. It is critical that workers involved in the application of EW feedstocks to agricultural fields wear masks or other personal protective equipment to prevent the inhalation of fine-grained particulate matter, which can be hazardous to health. Certain EW feedstocks can contain trace metals that at high sustained application rates can be potentially dangerous to food systems and ecosystems — a concern that can be mitigated and managed by choice of feedstock and application rates, and monitored over time. Similarly, high sustained application rates of EW at significant localized scale can potentially affect the alkaline chemistry of hydrological and river systems. Again this can be managed via application rates, and any eventual large-scale EW deployments should include water chemistry monitoring of nearby groundwater and rivers. As EW scales globally, it will be important for stakeholders across the field to continue to research, monitor, and assess these potential risks in all deployment geographies, to ensure that they are mitigated via safe, effective, and scientifically sound project design and planning.

Recommendations

- **Focus on farmers.** As the EW field advances, it is essential that policy advocates, commercial actors, and other ecosystem stakeholders maintain a clear focus on delivering value and benefits to farmers. In the US, the Farm Bill represents an important opportunity to prioritize funding to research and conservation programs that build awareness and offer regional on-farm demonstrations of the EW opportunity (for example "sentinel sites'').[26] In addition, ratifying the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) interim Conservation Practice Standard (CPS) 805, which addresses management of soil pH, would unlock the ability to incentivize producers to adopt EW through the Environmental Quality Incentives Program (EQIP). Key channels in the US for increasing education around new conservation activities and best practices in addition to USDA NRCS programs (which are commonly oversubscribed[27]) include state-level agricultural departments and extension programs at land-grant universities. Globally, the opportunity exists to include and prioritize EW in Mission Innovation's CDR track, with a particular eye towards scaling demonstrations and deployment in the Global South. From a commercial perspective, buyers of high-quality CDR should support EW project developers' efforts to deliver economic benefit to farmers (in addition to the agronomic benefits detailed above) with a willingness to pay prices that are sufficiently high to accommodate a meaningful revenue share to farmers. Buyers can also take steps to encourage an equitable global distribution of EW projects, again with a particular focus on supporting deployment in the Global South.

- **Implement method-neutral policy.** Governments worldwide should seek to implement method-neutral, criteria-based policies and funding support for high-quality CDR.[28] There have been some hopeful initial signs of such a policy approach. In October 2023, the US DOE initiated a $35M CDR Purchase Pilot Prize, followed in February 2024 by a $100M Carbon Negative Shot Pilot Funding Opportunity Announcement, both of which include EW as an area of interest. Proposed legislation in the US such as the federal Carbon Dioxide Removal Leadership Act (CDRLA), CREST Act, and the Massachusetts CDRLA — which would each enact method-neutral, criteria-based public procurement programs for high-quality CDR — offer similar promise. In the EU, critical deliberations are ongoing regarding the Carbon Removal Certification Framework (CRCF) — which among other important implications may lay the groundwork for eventual inclusion of CDR in the $800 billion EU Emissions Trading System (or a parallel negative emissions compliance market).[29, 30, 31] However, more is needed. Achieving gigatonne-scale CDR will require a portfolio approach; policy should be reflective of this reality and scaled accordingly. An important next step for the US Congress, for example, would be the creation of a method-neutral tax credit for long-duration CDR, either by expanding 45Q or implementing a new structure. Third Way's October 2023 report "Scaling to the Skies" offers suggestions as to policy design options. Internationally, along with a method-neutral EU CRCF, a method-neutral Article 6.4 framework for international carbon markets is critical, as well as clear inclusion of EW in national CDR inventories.[32]

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26 Farm Bill & Carbon Removal: Policy Brief. Carbon Business Council, 2023.
27 N. Tham. USDA Conservation Programs: Nationally Valued and Oversubscribed. Bipartisan Policy Center, 2023.
28 Defining Carbon Dioxide Removal: Issue Brief. Carbon Business Council, 2023.
29 EU Carbon Removal Certification Framework. Carbon Gap Policy Tracker.
30 EU Emissions Trading System. Carbon Gap Policy Tracker.
31 Verma and Chesney. "Global Carbon Markets Value Hit Record $909B Last Year." Reuters Sustainable Business, February 2023.
32 Meeting the Goals of the Paris Agreement: An Open Letter from 100+ Carbon Removal Experts. Carbon Business Council, May 2023.

- **Support robust MRV.** Development, implementation, and iterative use of scientifically robust, but operationally tractable MRV protocols will be essential to the responsible deployment of EW. While it is imperative that project developers demonstrate that EW projects are safe and effective, early approaches to MRV for EW should tolerate reasonable levels of uncertainty, with a goal of ongoing refinement. Data transparency and sharing, deployment-led learning, and line-of-sight toward tightening standards as scientific capacity increases over time will be key to enabling this evolution. Carbonplan's CDR Verification Framework offers a promising prototype for how this might be implemented in practice, and members of the CDR community are in strong agreement as to the importance of high-quality MRV.[33] Public-sector support for this effort will be crucial, both in terms of funding support as well as diverse engagement with national labs, land-grant universities, and other research institutions. Philanthropic capital can similarly contribute to efforts to address this gap in the field.[34] Commercially, the field crossed an important inflection point with Frontier's December 2023 first major offtake purchase of EW.[35] In conjunction with this purchase, Frontier posted a library of resources for EW buyers, including a set of principles signed by major corporate CDR buyers and ecosystem partners that enshrine the importance of sustaining robust investment and support for high-quality MRV as the EW field scales.[36]

- **Invest in scaling alkalinity.** Alkaline minerals serve as feedstock for a number of promising CDR approaches, including EW. While there is significant standing stock, and existing annual by-production of this material from the incumbent mining industry to begin scaling these geochemical CDR approaches this decade, multi-gigatonne annual scale for a portfolio of high-quality CDR by mid-century will require a substantially increased, and smartly distributed supply of clean, low-carbon, and sustainably sourced alkalinity. (RMI's November 2023 Applied Innovation Roadmap for CDR provides a helpful analysis of this scaling challenge.[37]) This will be a large undertaking, requiring new and additional enabling infrastructure, which will take time to develop. World governments must begin this decade to plan for this, and to create policy incentives to unlock and scale new sources of alkaline feedstock. New mining and transport infrastructure must be strategically sited relative to favorable deployment zones for EW (to minimize transport cost and emissions), and safely, responsibly, and sustainably deployed and operated. While not an obstacle this decade, feedstock availability is the primary barrier to the long-term scalability of EW — and one that can be overcome with strategic and scientifically informed early planning and investment.

- **Maintain focus on responsible deployment.** Stakeholders across the sector strongly agree on the need to maintain a keen focus on the responsible development and deployment of EW. In addition to the EW buyer resources published by Frontier, in September 2023 a group of leading CDR companies and partner organizations published the Reykjavik Protocol, a set of principles that seek to guide the equitable, responsible, and safe go-to-market and environmental credit generation for open-system climate interventions, including EW. In October 2023, the Carbon Business Council launched its CDR Responsible Deployment Training as a free community resource to support XPRIZE Carbon Removal competitors and other CDR project developers with the responsible deployment of their solutions. And in 2024 the US DOE will be

33 Hausfather et. al. "Industry Call for CDR Standards Initiative." February 2023.
34 Wang and Mills. "Launching the Community Enhanced Rock Weathering Quantification Standard." Cascade Climate Blog, November 2023.
35 "Frontier Buyers Sign World's First EW Offtake Agreement," Frontier Blog, December 2023.
36 "Buyer Principles for the Responsible Procurement of Carbon Removal from EW in Working Lands," Frontier, December 2023.
37 Kahsar et. al. RMI Applied Innovation Roadmap for CDR. Slide 147. November 2023.

inaugurating the Responsible Carbon Management Initiative to encourage and guide project developers "to pursue the highest levels of safety, environmental stewardship, accountability, community engagement, and societal benefits in carbon management projects." These resources contribute to a growing toolkit for EW project developers as they seek to scale and advance the field. Given the massive opportunity to deploy EW worldwide, it is critical that ecosystem stakeholders take concrete steps to extend these resources globally, particularly to the Global South, to ensure high-quality projects as well as the equitable distribution of benefits to farmers.

Credits

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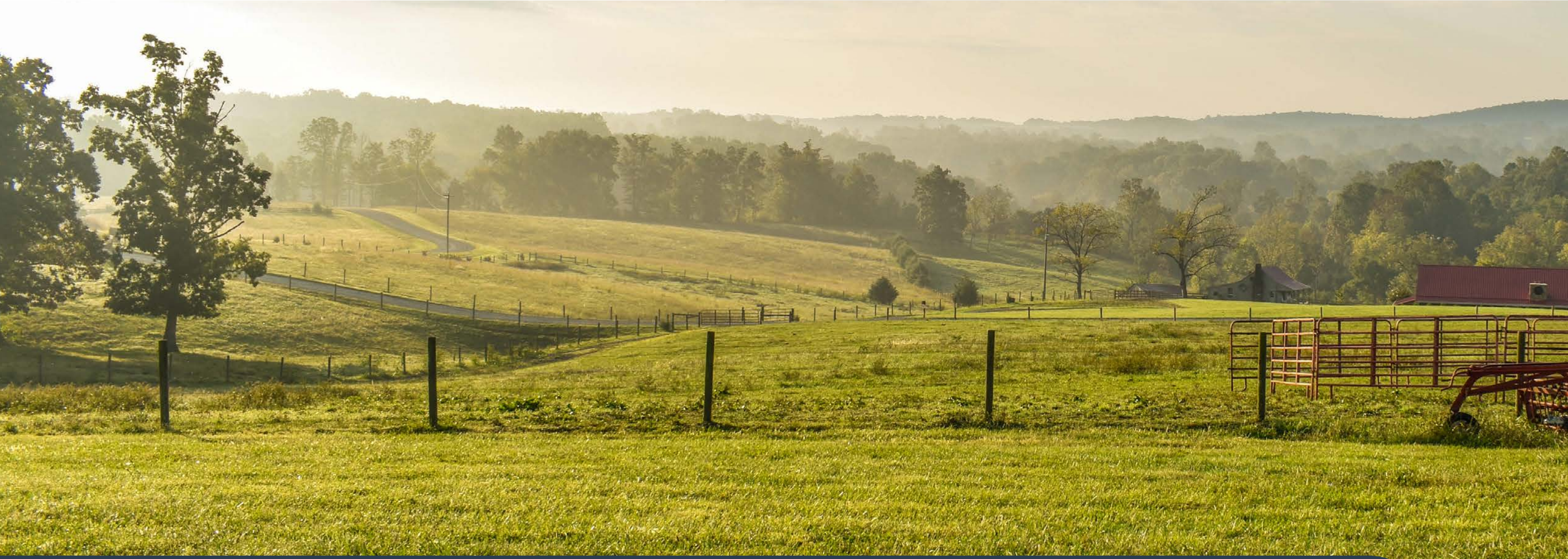

About the **Carbon Business Council**

The Carbon Business Council (CO2BC), a member-driven and tech-neutral trade association of companies unified to restore the climate, is the preeminent industry voice for carbon management innovators. Together, the nonprofit coalition represents more than 100 companies across six continents with more than $16.5 billion dollars in combined assets.

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