Innovative Financing for Global South Inclusive Carbon Dioxide Removal:

Enhanced Rock Weathering on Agricultural Lands

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Executive Summary

Enhanced Rock Weathering (ERW) is an engineered carbon dioxide removal (CDR) solution that accelerates the natural weathering process of certain kinds of rocks to remove carbon dioxide from the atmosphere. ERW involves the application of finely ground rock amendments to soils, as finely grinding the rock creates greater surface area for the naturally occurring chemical reactions that capture atmospheric carbon and convert it into stable dissolved forms. These stable forms of carbon then flow out through groundwater into the oceans, where they are stored on the scale of thousands of years.

ERW has high potential to contribute to global carbon dioxide removal goals as well as to deliver considerable agricultural co-benefits for farmers. However, the current ERW industry is limited in size and scope with only around 250,000 tonnes of carbon dioxide removal sold across all types of enhanced weathering projects to date ("CDR.fyi.," n.d.). Most of these tonnes are from projects deploying in the Global North, despite Global South geographies providing more suitable conditions for CDR through ERW. For example, even disregarding the Global South's ideal temperatures, humidity, and soil types for ERW, a rough back-of-the-envelope analysis illustrates it can be about 3.6 times cheaper to operationalize ERW in the Global South than the Global North (Table 1). In addition, revenues from ERW could contribute significantly more to the national economies of Global South countries than Global North countries – for example, ERW could contribute about 2.2% of Kenya's current GDP compared with 0.1% of Germany's current GDP (Table 2).

However, one of the main challenges in catalyzing an ERW market that is inclusive of emerging economies is the way projects are currently financed. Investment in ERW is driven by the private sector through deals in voluntary carbon markets. Private sector firms, focused on recovering their investments and maintaining a competitive edge, are unlikely to invest sufficiently in the broader research and development necessary to implement ERW at scale in diverse geographies. There are, however, innovative finance alternatives to scale ERW in the ways required to meet its CDR potential. An evolution of the advanced market commitment (AMC), a type of pull financing which aims to stimulate investment in products that may otherwise be ignored by the private sector, can help address current market failures with respect to access, innovation, service delivery, and risk management. An AMC that blends resources from funders interested in achieving diverse goals, such as climate aims and poverty alleviation, can help incentivize distributionally equitable CDR investment. We present in this paper an example of how this diverse market commitment might work in practice, to accelerate the deployment of ERW as a public good for both carbon dioxide removal and sustainable development goals.

Section 1:

The Case for a Globally Inclusive ERW Industry

Enhanced rock weathering (ERW) is a form of permanent carbon dioxide removal (CDR) that leverages the weathering process of certain types of rocks, mainly silicate rocks rich in magnesium and calcium, to remove carbon dioxide from the atmosphere. It involves the application of finely ground rock amendments to soils, thereby accelerating the natural weathering process which captures atmospheric carbon and converts it into stable dissolved forms. Due to the nascent nature of the technology, estimates of ERW's CDR potential range widely – from 9 Gt of CO_2 or less (Kelland et al., 2020) to more than 25 Gt of CO_2 (Strefler et al., 2018). Even at the lower bounds, however, ERW has significant potential to contribute to global climate change mitigation goals. Scientists concur that CDR is necessary to reach net zero emissions (Babiker et al., 2022) and estimate that at least 1.5 Gt of CO_2 removals will be needed annually to address hard-to-avoid emissions (Bergman and Rinberg, 2021).

To date, however, ERW deployments have been limited in both scale and scope. Around 250,000 tonnes of carbon dioxide removal have been sold across all types of enhanced weathering projects ("CDR.fyi.", n.d.). Most of these tonnes originate from projects based in Global North countries, particularly the United States and the United Kingdom, which have emerged as key hubs for ERW research and commercial activity (Carbon Direct, 2024). Only three of the 19 existing ERW suppliers are located in the Global South (Carbon Direct, 2024).

There are two key considerations to maximize the contribution of ERW to reaching global climate change mitigation goals. ERW must scale rapidly and across geographies most favorable for CDR through ERW. It must also scale with careful consideration of key progressive principles, like environmental and social justice, in order to build a truly effective industry (Nawaz et al., 2024). Due to an important ERW co-benefit – the improvement of agricultural yields when ERW is deployed on agricultural land – there are promising ways to do so.

To enable the ERW industry to grow quickly and effectively, it is therefore important to develop ERW in a globally inclusive way, particularly with respect to the Global South. This is due to four key characteristics of Global South ERW deployments.

1. ERW'S CARBON DIOXIDE REMOVAL POTENTIAL IS HIGHEST IN THE TROPICAL LANDSCAPES OF THE GLOBAL SOUTH.

ERW accelerates natural rock weathering chemical reactions, which capture atmospheric carbon and convert it into stable forms, by finely grinding silicate rocks and applying them to soils. These chemical reactions work best in hot, humid climates and acidic soils, such as those common in the tropical landscapes of the Global South (Boudinot et al., 2023). For example, one study found rock dissolution rates were two magnitudes higher under 19˚C conditions than under 4˚C (Pogge von Strandmann et al., 2022).[1] In addition, ERW's potential to remove carbon dioxide at scale relies upon deployment where suitable land is abundant. Five of the seven countries with the highest

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[1] Rock dissolution rate is an important indicator of CDR rates, as the quicker minerals are released from ERW rock amendments, the quicker carbon sequestration reactions can occur.

CDR potential – China, India, Brazil, Indonesia, Mexico – are in the Global South (Beerling et al., 2020). Globally-inclusive industry development is thus necessary to fulfill ERW's potential as a CDR pathway.

2. ERW DEPLOYMENTS IN THE GLOBAL SOUTH CAN PROVIDE MEANINGFUL LIVELIHOOD CO-BENEFITS TO LOCAL COMMUNITIES.

ERW is typically deployed on agricultural land to take advantage of existing infrastructure for input distribution, the availability of land, and a key co-benefit of the technology – improved soil health. Improvements occur because minerals in ERW rock amendments act much like agricultural lime to address soil degradation, particularly in acidity and soil nutrient retention capability, thus improving yields (Swoboda et al., 2022). Soil degradation is a challenge to livelihoods in many Global South countries, particularly sub-Saharan Africa and South Asia, where a large proportion of the population relies on agriculture for employment (Losch, 2022). Sixty-five percent of productive land in Africa is considered degraded (United Nations, 2021), which contributes to the large yield gaps observed in the region (Mueller and Binder, 2015). Identifying and scaling technologies that support countries in combatting soil degradation can contribute to meeting global poverty reduction goals, as well as to food security.

3. IT IS MORE COST-EFFECTIVE TO DEPLOY ERW AS A CDR PATHWAY IN GLOBAL SOUTH COUNTRIES.

A back-of-the-envelope analysis by PxD finds that low- and middle-income countries in the Global South, for example Kenya (see Table 1), have a competitive advantage for ERW operationalization. Even if the carbon removed per hectare were not higher in the Global South due to its ideal environmental conditions, many deployment activities there cost substantially less to execute than in the Global North.

Table 1: Comparing ERW Operational Costs in Example Global South and Global North Countries[2][3]

CATEGORIES	KENYA (GLOBAL SOUTH)		GERMANY (GLOBAL NORTH)	
	Monetary Cost (per tonne Rock)	**Emission** (tonne CO_2/ha/yr)	**Monetary Cost** (per tonne Rock)	**Emission** (tonne CO_2/ha/yr)
CDR Rate		(4.10)		(4.10)
Rock Mining	$1.52	1.23	$2.55	1.23
Rock Grinding	$4.10	0.09	$8.59	0.39
Transport	$7.58	0.55	$8.60	0.55
Mechanical Spreading Operations & Maintenance			$12.10	
Mechanical Spreading Fuel			$14.20	
Manual Spreading	$1.53			
Total	**$14.73**	**(2.23)**	**$46.04**	**(1.93)**
Cost per tonne CO_2 sequestered*		**$331.45**		**$1,205.68**

** table notes on following page*

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[2] For details of the assumptions used, please see Appendix 1.

[3] PxD would like to thank Kamran Khan Niazi for his contributions in developing this cost-benefit analysis of ERW in Global North vs Global South contexts.

** Assuming a rock application rate of 50 tonnes/ha (~20 tonnes/acre) à la (Strefler et al., 2018), which aligns with industry standards. This rate is corroborated by Lithos Carbon during AirMiner's webinar, as an upper limit commonly practiced in the field.*
**The carbon dioxide removal rate is estimated at 4.10 tonnes CO_2/ha, which represents the third quartile of aggregated carbon sequestration rates from published laboratory and field-trial results.*
**Monetary costs per tonne of rock for mining, grinding, transport, and spreading are derived from local production costs, energy prices, and labor rates. (1) Mining costs include inputs such as explosives and electricity, with prices based on regional market data. (2) Grinding electrical costs are estimated based on the kWh needed per tonne of rock, with prices and the electric grid emission factor adjusted for regional differences. (3) Transportation costs are based on distances between mines and fields, assumed at 100 km for both Kenya and Germany, and on freight rates from local transport associations. (4) Spreading costs are either manual or mechanical costs calculated from local wage rates and machinery operation costs, respectively.*
**Emissions from each category are estimated based on operational energy demands and transport logistics. (1) Mining and grinding emissions are based on energy consumption figures and operational data, tailored to the grain size of the processed rock, which is assumed to be 50 μm. (2) Transportation and spreading emissions account for diesel consumption in transport and machinery, applying emission rates of diesel trucks.*

The cost per tonne of CO_2 removed could be between three to four times cheaper in an illustrative Global South country, like Kenya, than in an illustrative Global North country, like Germany, given cheaper labor and input costs. PxD uses Kenya and Germany as examples of Global South and Global North countries for ERW deployment, as we are able to cross-check our model assumptions with on-the-ground information from existing pilot studies. We recognize this back-of-the-envelope analysis makes significant assumptions about ERW activities, which may or may not hold up in real-world scenarios, so this analysis should only be interpreted as indicative costing estimates.[4] We welcome any feedback on our models and are happy to share more details regarding our approach, assumptions, and sources. Please contact info@precisiondev.org if you have any comments or questions.

4. THE ERW INDUSTRY COULD PROVIDE IMPORTANT MACROECONOMIC BENEFITS TO GLOBAL SOUTH COUNTRIES.

Given this competitive advantage, ERW could also become a significant source of foreign currency earnings for low- and middle-income countries in the Global South, as CDR grows as an industry (The Economist, 2023). The opportunity is large; a recent analysis from the Boston Consulting Group and Environmental Defense Fund estimates CDR will grow into a ~$10 billion to ~ $40 billion market by 2030 (Ponce de León Baridó et al., 2023).

PxD's back-of-the-envelope analysis of ERW market size for illustrative Global South and Global North countries – Kenya and Germany – finds that revenues from ERW could contribute about 2.2% of Kenya's current GDP compared with only 0.1% of Germany's current GDP (see Table 2). The ERW industry could thus make more of an impact on Global South countries than on Global North countries.

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[4] To test different assumptions, Cascade Climate, a nonprofit organization working to advance carbon dioxide removal through natural systems like ERW, hosts an interactive ERW MRV Cost Estimator and Database which allows users to input different ERW assumptions and their effects on ERW costs.

Table 2: Comparing ERW Markets in Example Global South vs Global North Countries

Variables	Kenya (Global South)	Germany (Global North)	Source and Assumptions
Arable land area (ha)	5,800,000	11,658,000	(World Bank, 2021) Assuming deployment across all available arable land as a theoretical maximum.
GDP (Million USD)	107,440	4,360,000	(World Bank, 2023b)
Annual GHG Emissions in Carbon Dioxide Equivalent (tonne CO2e)	165,400	736,700	(World Bank, 2020)
Carbon price (USD/tonne CO_2)	100	100	Assuming ERW generated carbon price will decline to match the abatement cost, taking the lower bound of the prediction from Beerling et al. (2023)
Carbon Sequestration rate (tonne CO_2/ha/yr)	4.1	4.1	Assuming the CDR rate as the third quartile of compiled rates from field and laboratory studies by Kukla et al. (2024), for both Kenya and Germany
ERW Market Size (Million USD/yr)	2,378	4,779.78	
ERW CDR (tonne CO2/yr)	23,780,000	47,797,800	
Projected ERW Market Contribution (% of GDP)	2.22%	0.11%	

Realizing the benefits of ERW deployment in the Global South, however, requires investment to build the enabling environment needed to bring about credible, high-integrity CDR. This enabling environment includes advancing the scientific understanding of CDR through ERW, developing fit-for-context measurement, reporting, and verification (MRV) approaches, and developing capacity to build the ERW field in the Global South (see Box 1). ERW is currently financed by voluntary carbon credit markets where private entities voluntarily buy and sell carbon credits representing tonnes of carbon removed or reduced. Such investments are not adequately incentivized for low- and middle-income countries in the Global South, resulting in the limited scope of ERW deployments to date: Most resources are flowing to the Global North where companies deliver high-quality credits by leveraging existing support infrastructure (e.g., using state-of-the-art soil testing facilities to meet the evidentiary threshold required by today's voluntary carbon credit buyers). It is thus necessary to consider how different financing approaches can help catalyze an effective and responsible ERW market which removes carbon dioxide with the speed and scale required to meet global climate goals, as well as with consideration of environmental justice.

BOX 1: GAPS IN SUPPORTING INFRASTRUCTURE FOR ERW

High-integrity CDR through ERW requires a thorough, site-specific understanding of how the technology removes and stores carbon dioxide, as well as ways to accurately estimate the final amount of carbon dioxide removed and stored. Currently, the scientific literature to support such understanding is much more developed for Global North deployments than for the Global South.

ADDITIONAL SCIENTIFIC RESEARCH ON ERW MECHANISMS AND POTENTIAL IS NEEDED, PARTICULARLY FOR THE GLOBAL SOUTH

Theoretical estimates of CO_2 removal and storage from ERW, as an open-system CDR technology, are very uncertain (Beerling et al., 2018). Kukla et al. (2024) synthesized carbon dioxide removal estimates from the existing literature and found CDR rates spanning four orders of magnitude. This is because environmental characteristics (e.g., climate, soil type) are key determinants of ERW carbon dioxide removal outcomes. For example, lower soil pH levels, which indicate more acidic conditions, can accelerate the dissolution of silicate minerals, thus potentially increasing CDR potential (Renforth et al., 2015). Temperature and humidity are also critical elements. Studies have found that rock dissolution rates can be two orders of magnitude higher in elevated temperatures (Pogge von Strandmann et al., 2022).

Currently, there is not enough scientific evidence to systematically characterize how these variables affect ERW CDR rates, particularly for conditions prevalent in the Global South. For example, there are 23 experimental ERW studies in the existing ERW literature, of which only 10 were field trials. Of the field trials, only three were conducted in Global South geographies: Costa Rica (Ryan et al., 2024), Malaysia (Larkin et al., 2022), and China (Guo et al., 2023; Wang et al., 2024). No peer-reviewed published research has been undertaken in Africa. Field trials are critical to build the evidence base; while laboratory studies can control temperature and humidity, they often fail to capture the complexity of the natural environment. For example, natural drying and wetting cycles can significantly influence the saturation and dissolution rate of minerals (Pogge von Strandmann et al., 2022; Buckingham et al., 2022) and thereby the ultimate CDR rates.

MEASUREMENT, REPORTING, AND VERIFICATION AT THE FIELD LEVEL IS A KEY BARRIER TO IMPLEMENTING GEOGRAPHICALLY DIVERSE ERW PROJECTS

Most firms deploying ERW projects leverage direct, field-level measurement of carbon dioxide removal in order to measure, report, and verify carbon dioxide removal outcomes. Direct measurement approaches vary, but all try to measure some aspect of how carbon moves through various chemical and biological processes, from initial rock application all the way to ultimate ocean storage, in order to estimate carbon dioxide removal (Holzer et al., 2023). Instruments for such direct measurement approaches are costly and also require trained personnel to successfully operate and interpret the results. The scarcity of adequately resourced centers of specialization for CDR measurement in the Global South makes it a significant challenge for firms to operate in these contexts.

Establishing a fully equipped ERW laboratory entails substantial investment in a suite of specialized instruments (Table 3). More importantly, it requires specialized expertise to operate these instruments successfully, as well as the technical capacity to analyze results. For example, a key component of the MRV process is assessing the initial rock feedstock's suitability for carbon dioxide removal through ERW. This requires rock properties to be analyzed by X-Ray diffractometer (XRD) and X-Ray Fluorescence (XRF) instruments for mineral identification and chemical composition. These instruments can cost between USD $75,000 and $115,000 each, and trained technicians are required to operate them successfully.[5] Many of the ERW startups in the Global South that participated in stakeholder interviews currently send samples to laboratories in the United States or the United Kingdom for this analysis, due to the lack of specialized laboratories with this equipment and especially due to the lack of trained technicians to conduct the appropriate analyses. Many other types of specialized instruments are required to build a credible MRV system for current ERW market stipulations, and their costs can quickly accumulate, making their procurement a significant up-front capital expenditure for projects. For example Inductively Coupled Plasma Mass Spectrometry (ICP-MS) systems, necessary for trace element analysis, and one of the instruments critical to the leading field-level MRV approach, has a line price of around USD $100,000.[6]

Table 3: Laboratory Equipment for Monitoring ERW Processes (non-exhaustive)

Equipment	Measurement	MRV Analysis of
X-ray diffractometer (e.g., D8, Bruker; Empyrean, Malvern Panalytical)	Rock mineralogy and soil properties	Rock feedstock
X-ray fluorescence instrument	Mineral and chemical composition	Rock feedstock
Laser particle sizer (e.g., Mastersizer, Malvern Panalytical; Horiba)	Particle size distribution	Rock feedstock
Surface and pore size distribution analyzer (e.g., Nova, Anton Paar)	Surface-area of powdered rock	Rock feedstock
Benchtop pH/electrical conductivity meters (e.g., Hanna)	pH and electrical conductivity of pore water	Initial weathering rates and field processes
Simultaneous inductively coupled plasma atomic emission spectrometer (e.g., TST)	Cations and anions, trace metals	Initial weathering rates and field processes
Inductively coupled plasma mass spectrometer (e.g., Thermo Fisher iCAP ICP-MS)	Concentrations of trace elements, trace metals	Initial weathering rates and field processes
Ion chromatograph (e.g., Agilent)	Cations and anions in pore water	Initial weathering rates and field processes
Lysimeter, sensor, and data logger	Dissolved inorganic carbon, total alkalinity	Initial weathering rates and field processes
Dumas analyzer	Total carbon in weathering products	Initial weathering rates and field processes

Modeling carbon dioxide removal outcomes is a more cost-effective MRV approach than obtaining and analyzing field samples. Ideally, models take into account feedstock inputs, such as the amount, type and composition of the rock used, and environmental inputs, such as soil properties, temperature, moisture levels, and water flow, to estimate ultimate carbon dioxide removal and storage. However, there is currently not enough data on all these parameters and how they affect CDR rates across a range of geographies to build credible models for ERW. Further development and calibration to account for complex field, water-

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[5] Prices obtained from consultations, and quote requests from suppliers such as Thermo Fisher, KS Analytical Systems, and SpectraLab Scientific Incorporation. The quotes provided reflect a range of costs depending on the instrument's configuration, features, and capabilities.
[6] See footnote 5.

shed, and ocean processes – all of which impact how much carbon is ultimately removed – is needed.

DEVELOPING INDUSTRY STANDARDS FOR KEY OPERATIONAL DECISIONS IS REQUIRED FOR THE DEPLOYMENT OF HIGH-INTEGRITY PROJECTS

Operational decisions around feedstock type, grain size, and rock application rates also impact ultimate CDR rates as well as critical community considerations for ERW deployments.

For example, feedstock type affects not only CDR rates but also the risk of heavy metal contamination through rock amendments to soils. Heavy metals are well-known environmental pollutants and can have delterious effects on human health, through both food and other environmental channels. However, there is a lack of systematic data, and therefore guidance, across geographies and feedstock types on how heavy metals accumulate through ERW application. There is some evidence that soil retention of heavy metals such as nickel and cadmium can be proportionally higher at higher temperatures (Haque et al., 2020; Dietzen et al., 2018; Beerling et al., 2020).

With respect to grain size and rock application rates, emissions from grinding feedstocks into the appropriate size for ERW are a key driver of ERW GHG emissions, and must be considered in order to understand the technology's CDR efficiency. Grinding emissions, primarily determined by grain size, could reduce the net carbon drawdown from ERW by 10–30% (Beerling et al., 2024). However, existing scientific literature on ERW might have limited lessons on this issue for real-world, large-scale deployments, which have a narrower range of feasible grain sizes and application rates per hectare than researchers who choose specific parameters for research purposes. Most experimental studies utilize an application rate of 50 tonne/ha, which is assumed to correspond with ERW's theoretical maximum potential of carbon sequestration (Strefler et al., 2018). In reality, this rock application rate might be too high for feasability in large scale deployments on agricultural land, particularly in the Global South. For example, it is not clear how smallholder farmers will react to the application of multiple tonnes of rock on their field when typical application rates for a similar and commonly used input, agricultural lime, are at maximum at around 2 tonnes/ha (Hijbeek et al, 2021).

Lastly, the ERW industry must develop guidelines for farmer engagement in ERW projects – both with respect to co-benefits as well as revenue- and cost-sharing. The co-benefits, particularly yield improvements, that farmers can expect from ERW application can differ vastly across geographies and cropping systems (Boudinot et al., 2023). Given the emerging nature of yield evidence, the different models for farmer engagement that different ERW companies use (with some requiring farmers to pay for various aspects of the ERW process, such as spreading), and the different carbon credit revenue-sharing approaches, ERW impacts on farmers across projects can differ widely. It is thus important, as the industry matures, to develop just and transparent farmer engagement guidelines to ensure high-integrity projects. This is particularly relevant when operating in the Global South where farmers tend to be smallholders from traditionally marginalized communities.

Section 2:
ERW's Financing Gap

Financing for CDR through ERW primarily occurs within voluntary carbon markets. Voluntary carbon markets are a mechanism for the voluntary trade of carbon credits, with one credit representing one tonne of carbon dioxide removed or reduced. Buyers are typically private sector firms seeking to meet their voluntary environmental and/or net-zero targets. Suppliers span a range of entities from private sector project developers to non-profit organizations, but all generate credits by implementing activities that either remove or reduce carbon dioxide.

Voluntary carbon markets are decentralized, highly fragmented, and opaque, due to the lack of a unified marketplace. Trades are typically conducted over the counter (OTC) between specific buyers, suppliers, and brokers. These OTC deals can vary significantly in price and quality. On the supplier side there are many different types of removal and reduction projects, credit registries, and methodologies to certify outcomes, which all shape credit quality and price. On the buyer side there are differing approaches to using credits, including tonne-for-tonne offsetting of GHG emission, insetting, the Science Based Targets initiative's Beyond Value Chain Mitigation; these approaches determine how a buyer prioritizes different carbon credit characteristics.[7]

This private sector-led and largely OTC approach to carbon credit trading incentivizes suppliers to compete in providing the most compelling version of these credits to buyers. This results in a market which exhibits the following challenges:

1. **Slow field learning:** If firms are competing to get to market quickly to recover their investment, they will be less inclined to share their approaches and results as they go. In addition, the knowledge generated by this investment is necessarily proprietary (because firms must be able to monetize their intellectual property so that they can recover their investment) – this means that other firms will not be able to adopt these approaches freely and cheaply.
2. **Investment skewed towards high-income countries:** If firms are rewarded primarily for the speed of getting to market, this will generally mean focusing research and development (R&D) in, and on solutions for, high-income countries, because these are perceived to be a better environment than lower income countries for research, testing, measurement, and risk-taking.
3. **Investment limited by absence of common standards:** Simple, trusted, and agreed-upon standards underpin deep and liquid markets. It is a public good to have an agreed way of describing and measuring carbon dioxide removals, yet one of the key ways that firms compete is by differentiating their ERW measurement approach. It will be very hard to stimulate sufficient investment in the absence of agreed success metrics.
4. **Insufficient attention to broader public objectives:** Firms must respond to the market incentive of voluntary carbon markets, which means primarily removing tonnes of carbon and being able to attribute each tonne removed. Public priorities might, however, include other goals and trade-offs. For example, if the total amount of carbon removed is more important than precise attribution, then a portfolio approach might be more efficient. Public priorities include the impact on agricultural productivity and food security, and sustainable incomes for people in low-income countries. Carbon markets alone do not incentivize these broader objectives.

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[7] Recent efforts by industry watchdogs have tried to establish common principles for high-quality credit assessment that all stakeholders can agree on, such as the Core Carbon Principles (Integrity Council for the Voluntary Carbon Market, 2024). In general, however, the most important characteristic for buyers of credit is that there are real GHG impacts from the credited project (Ponce de León Baridó, 2023).

This kind of market will fail to build the key public goods necessary to develop the ERW mechanism and thus catalyze the market. Much of the investment to generate evidence for ERW CDR outcomes and develop MRV systems occurs within private firms building ERW carbon projects. Yet doing so has some positive externalities, including shifting from expensive, in-field direct measurement to cost-effective model-based MRV approaches, which most of the successful ERW firms now utilize.

Purely private-sector financing mechanisms are unlikely to invest enough in such evidence generation and R&D. Firms tend to focus on R&D that advances their own particular approach, as they cannot capture benefits from developing the field. If firms shared insights or invested more broadly in ERW R&D, their competitors could use these insights to create their own ERW projects at lower cost. Having a variety of firms across the globe working and competing on credible ERW deployments, however, is exactly the type of market catalyzation the CDR field should aim for.

Section 3:
Innovative Financing Principles to Catalyze the ERW Market

THE NEED FOR INNOVATIVE FINANCING MECHANISMS

It is widely recognized that mitigating climate change, including through carbon dioxide removals, is a global public good (World Resources Institute, 2024). It is therefore difficult for private investors and firms to charge the world's population for the benefits of CDR and recoup their costs of R&D and service delivery. Without some sort of additional incentive, the level of private investment in carbon dioxide removals will be far lower than is merited by the benefits to society of accelerating the discovery and implementation of solutions to mitigate climate change.

A traditional answer to the under-supply of public goods is public-sector provision. Governments could fund public R&D and public delivery of climate mitigation. However, there are good reasons to engage private and social enterprises in developing innovative solutions, as well as, or instead of, relying on public provision. Enterprises may be more entrepreneurial, and more willing and able to take risks, than public-sector R&D bodies. Enterprises may be able to employ expert staff, whereas public-sector salaries may be constrained. Enterprises may be more disciplined at identifying unpromising avenues of research, and more willing to exit them, than the public sector. Enterprises may have existing intellectual property that is not available to their competitors and the public sector.

Because mitigation of climate change is a global public good, there is a need for a mixture of regulation, subsidies, taxes, and public provision to address the market failure that would otherwise lead to underinvestment. In particular, to accelerate private investment in carbon dioxide removals, some sort of public or philanthropic incentives must be provided to enterprises. There are many possible designs of such mechanisms, but to be effective these incentive mechanisms should incorporate key characteristics that guide how market failures are addressed.

DESIRABLE CHARACTERISTICS OF AN INCENTIVE MECHANISM

The characteristics of a mechanism to finance the acceleration of carbon dioxide removals, in ways that address market failures systematically and coherently, include the speed with which the solutions are developed, their cost, their scalability, and their impact on countries and people with low incomes. Incentive mechanisms should incorporate such characteristics as follows:

1. **Speed –** An inexpensive mechanism for carbon dioxide removal is developed quickly.
2. **Cost-effectiveness of carbon dioxide removals –** The mechanism is cost-effective to deliver at scale.
3. **Scalable –** Carbon dioxide removals should be implemented wherever the social benefit of carbon dioxide removals exceeds the social cost of those removals. Restrictions on the use of knowledge, such as licensing fees or intellectual property rights, which increase the private cost of carbon dioxide removals above the true social cost, or prevent deployment of the technology, may limit opportunities for scale. This suggests that once this technology is invented, it should be freely available so that carbon can be removed quickly and cheaply.
4. **Cost-effectiveness of R&D –** Investment in innovation should be sufficient to accelerate the development of rapid and cost-effective mechanisms, but should not invest in R&D that is unlikely to yield material improvements.
5. **Contestable –** Any enterprise or government that can deliver carbon dioxide removals cost-effectively should be able to provide that service and benefit from the market willingness to pay for the service.
6. **Inclusive –** Incomes generated by payments for carbon dioxide removals should, where it is cost effective, be generated in the countries where the carbon is removed and, where possible, the benefit of producer surplus should go to people with low incomes who are contributing labor and land.
7. **Certain –** The mechanisms should deliver carbon dioxide removals with sufficient certainty and permanence – at least in aggregate – to have the necessary impact on climate change.

INCENTIVE DESIGN TRADE-OFFS

There are obvious trade-offs between these desirable characteristics. For example, there may be a trade-off between the speed of developing a solution, and the broad access to that solution in the long run. Rapid innovation may be incentivised by a period of temporary exclusivity, enabling the firm to charge a higher price during a period when they are protected from competition. This increases the cost of, and reduces access to, the innovation; without this, the firm may not have an incentive to invest in innovation.

Similarly, there may be a trade-off between speed and inclusivity. It may be that innovation can be achieved faster in countries with large, well-resourced research sectors, but that these innovations are slanted towards opportunities in those Global North countries.

Different decision-makers may attach different weights to these characteristics, and may attach no weight at all to some of them. A focus on a subset of these objectives is especially likely where a fund or a budget has a mandate to pursue a particular goal and seeks to maximize its cost-effectiveness measured against that stated objective. For example, a fund whose goal is the rapid and cost-effective development of carbon dioxide removal processes may focus on the speed and cost-effectiveness of R&D, but might pay little or no attention to the future scalability, contestability, or inclusiveness of the innovations that they support.

These trade-offs are a permanent feature of the innovation landscape. They are a consequence of the economics of knowledge. When we choose mechanisms to reward innovation – such as public funding for research, and patent protection – we are making choices about these trade-offs. They are not peculiar to innovations for global public goods. And they do not automatically vanish when we reward innovation for climate change mitigation. The way we support innovation involves making implicit choices about these issues. The devil, as always, is in the detail of the mechanism we choose. We take a look at three key trade-off areas below: access and innovation, service delivery, and risk management.

ACCESS AND INNOVATION

Effective incentive mechanisms would:

1. decouple the price for access from the price paid to innovators;
2. set the access price to the social marginal cost (often zero);
3. set the innovation price to a level that reflects the value of the innovation (this is likely to be very high in the case of innovations to accelerate carbon dioxide removal), the expected impact of the innovation on higher rewards, and affordability.

There is a familiar trade-off between access and innovation. If we reward innovators by paying them for the use of their knowledge, then the price they charge serves two divergent purposes:

1. The price determines the amount that the innovator is paid. The prospect of a higher price encourages more investment in R&D, and so faster and better innovation.
2. The price determines who can afford to use the innovation. If the price is far above the social marginal cost of the innovation, then the innovation will be under-used, and there will be significant losses to human well-being.

A commonly-cited example of this trade-off is medicines, which are expensive to design and test, but are often cheap to produce. Once designed, medicines should ideally be made widely available at low prices to anyone who needs them, but at low prices there are insufficient rewards for the R&D that was needed to develop them.

When one price serves two different purposes, as in this case, there is bound to be a trade-off. A higher price generates more investment in innovation, but a high price also reduces access and scale. In this kind of arrangement, with one price serving two different purposes, the price reflects where society wishes to position itself on the scale between mainly incentivising innovation (high price), or mainly ensuring access (low price).

The only way to avoid this tension is to decouple the prices, so that the price being paid to the innovator is separate from (and higher than) the price that must be paid to use the innovation. Some sort of separate payment – perhaps from a public authority or a grantmaker – pays the difference. In this case, the question is what the two prices should be, and how much subsidy can be afforded.

The allocatively-efficient price for using the innovation is the social marginal cost, which could be zero. For example, if a firm invests in research to establish the amount of carbon that is sequestrated through enhanced rock weathering in particular circumstances, the social marginal cost of that knowledge being used by another firm is zero. If other firms are forbidden to use that knowledge, or forced to repeat the research, then that cost is a net cost to society.

Conversely the efficient price paid to the innovator depends on the extent to which higher payments are likely to lead to faster or more effective innovation. If higher rewards lead to more investment and faster innovation, this can have huge social and economic benefits. While theory tells us the allocatively-efficient price (namely, the social marginal cost of using the innovation), it does not tell us the most efficient price to pay to the innovator. In general, though, for important innovations, higher prices paid to innovators will produce high long-run returns.

The choice of prices (for access and for innovations) is constrained in another way: affordability. The gap between these two prices must be met by some sort of public or philanthropic subsidy. These resources are finite, and there are opportunity costs to using resources in this way.

SERVICE DELIVERY

Effective incentive mechanisms would:

1. **pay when the service has been delivered;**
2. **encourage competition among suppliers;**
3. **require buyers to commit to a minimum price in advance.**

A second set of considerations in mechanism design is the incentives for delivery.

In a world of perfect information, the person paying for a service can monitor accurately whether the supplier is delivering the service to a high quality, and as quickly and efficiently as possible. But in the real world, without perfect information, this performance cannot be monitored. (This is sometimes known as the ‘principal-agent’ problem.) In these circumstances, the payer may seek to create incentives for the service to be delivered quickly and well. Often this incentive will take the form of competition and choice: If the supplier knows that several alternative suppliers are also chasing market share, then they have the incentive to do the work well and quickly, so that they can attract customers.

In many economic transactions, payment is for delivery. This creates the incentive for the service supplier to provide a good quality, timely service, because that is how they get paid. If the payment is in advance, irrespective of what is delivered, there may be less incentive for the supplier to move quickly, invest under uncertainty, or work hard to meet goals for quality and quantity.

Paying the supplier after the service has been delivered is a good way to create incentives for delivery. But it can have the opposite consequence if the supplier is not sure that they will ever get paid, even if they deliver the service well. In this case, the supplier may be cautious about investing in delivery.

This can be a particular problem where there is a single buyer. If I invest in delivering the service, but there is only one buyer, I am at a commercial disadvantage when it comes time to pay. The buyer could refuse to pay, or demand a discount, and I would have no way to recover my costs. If I know that this may happen, I may decide not to produce the service in the first place, or to cut my investment so that less money is at risk. This is known as the ‘hold-up’ or ‘time-inconsistency’ problem.

One way to avoid this problem is to enter into contracts in advance, so that the buyer cannot try to renegotiate the price after the service has been delivered.

RISK MANAGEMENT

Effective incentive mechanisms would:

1. **reward project developers on success, allowing them (and their investors) to decide whether to continue or exit;**
2. **provide precommitment of funding so that funders, not developers, bear the risk of changes in future priorities.**

Innovation is risky. Time and money are spent pursuing ideas, not all of which will be successful. In the case of ERW, it may turn out that less carbon is sequestered than is currently expected, or that there are unintended consequences that have not yet been identified. It might be that ERW is successful, but is made obsolete by some other, cheaper alternative, making it difficult for an investor in ERW to recover their investment. These uncertainties create risks for firms and investors (who may invest money in an idea which never succeeds) and for funders (who may make grants for services that do not succeed, or enter into contracts for services that no longer represent value for money).

Managing these risks well, using available information, is key to successful innovation. In particular, for many organizations that invest in R&D, a key organizational ability is to decide which avenues to pursue, and which to exit.

A mechanism designed to finance innovation should accommodate the need to manage risk well. A project developer has more information than a funder about whether their approach remains promising. If they are paid whether or not they succeed, it is rational for them to continue to pursue the idea, given that there is a small chance they might succeed and they have nothing to lose. But if they are paid only on success, they may be more likely to cut their losses as soon as it is clear that success is unlikely. For society as a whole, it is better if this decision is taken by the organization that has the most insight into the probability of success.

Conversely, the funder has a clearer idea of whether their preferences may change. Perhaps in years to come they may have other priorities for funding. Funders, not project developers, can assess this risk. So funders should take responsibility for deciding in advance whether to commit to funding, and how much funding to commit to.

SUMMARY OF EFFECTIVE MECHANISM DESIGN

Taking these together, we have eight characteristics of an effective mechanism to incentivize the development of an ERW mechanism. An effective mechanism would:

1. **decouple the price for access from the price paid to innovators;**
2. **set the access price to the social marginal cost (often zero);**
3. **set the innovation price to a level that both reflects the value of the innovation (in the case of innovations to accelerate carbon dioxide removal, this is likely to be very high), the expected impact on innovation of higher rewards, and affordability;**
4. **pay when the service has been delivered;**
5. **encourage competition among suppliers;**

6. **require buyers to commit to a minimum price in advance;**
7. **reward project developers on success, allowing them (and their investors) to decide whether to continue or exit;**
8. **provide precommitment of funding so that funders, not developers, bear the risk of changes in future priorities.**

We now address how this might work in practice.

Section 4:
A Diverse Market Commitment for ERW

One type of innovative financing mechanism with demonstrable success in catalyzing markets for public goods is the advanced market commitment (AMC). Its premise is that donors make a legally binding commitment to fully or partially finance a good, at a pre-specified price and up to a fixed target volume for buyers. Buyers would then be able to pay a lower price for the good and determine the exact volume of the good they ultimately want to purchase. AMCs are thus especially appropriate for goods where markets fail to create enough incentive for supply creation and R&D.

AMCs were first pioneered in the public health setting. The first AMC was developed for a vaccine targeting pneumococcus strains (AMC Secretariat of Gavi, the Vaccine Alliance, 2021) prevalent in the Global South, which at the time – circa 2007 – killed more than 700,000 children under five in developing countries annually (Kremer et al., 2020).

In the case of CDR, an evolution of the AMC can help incentivize the production of the public goods necessary for long-term success of the ERW industry. Traditionally, AMCs target a single outcome and are funded by funders of similar outcomes, who are interested in the same outcome. In the case of ERW, where we value both the livelihood benefits of ERW activity in the Global South and its CDR potential, incentivizing both livelihood and CDR outcomes by blending different types of outcomes-funders together could grow the market more equitably.

At a very high level, such a diverse market commitment could blend poverty-alleviation funders and climate funders to offer an AMC that provides a premium for carbon dioxide removal through ERW deployed in Global South geographies. The need for this premium would eventually disappear as the R&D investment decreases due to technological improvements. Decreasing costs would help to attract other types of buyers, particularly governments, which are cost-sensitive but could procure at the scale needed to reach global net-zero goals. Firms would be required to publicly share data that was critical for generating evidence across the field, and a platform or structure to manage this data-sharing would be necessary.[8] There are many remaining questions in actioning such an AMC (see Box 2), but we highlight below broad contours of how such a fund may work.

FUND STRUCTURE

AMCs have traditionally been funded by similar groups of outcome funders who are interested in pursuing the same outcome. For example, corporates interested in stimulating the market for CDR have banded together to form AMCs focused on specific CDR pathways. Frontier is a collection of corporations, such as Shopify and Stripe, which has been in operation since 2022 and aims to make

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[8] Cascade Climate hosts an ERW Data Quarry, which aggregates commercial data from ERW companies who have agreed to share their data publicly.

$1 billion-worth of durable CDR purchases by 2030. Another group is the recently-launched Symbiosis Coalition, which includes buyers like Google and Microsoft. It aims to purchase 20 million tonnes of CDR by 2030, with a focus on nature-based solutions.

In a diverse market commitment, funders of different types of outcomes band together to fund activities that provide outcomes of interest to all funders involved. In the case of ERW, climate funders could work together with development funders to support ERW deployments. By working with climate funders, development funders would explore a new technology for livelihood improvement, that is, ERW technology used for increased agricultural productivity, which they otherwise might not have the capacity to engage with. By working with development funders, climate funders would learn from development sector experience in scaling innovations throughout the Global South – and in doing so could enable ERW to meet its CDR potential.

Another evolution of the diverse market commitment is that, in this fund structure, rather than directly purchasing carbon dioxide removal, funders' commitments are used to pay a previously-agreed-upon and publicly-shared premium per tonne of carbon removed. This premium applies only if the removal meets certain quality criteria. Funders in the diverse market commitment therefore neither pay the marginal cost of removing a tonne of carbon nor determine the contracted volume of carbon dioxide removal. Rather, the volume of carbon removed is determined by other entities that are interested in CDR purchases but may not be able to pay at current prices. These entities, for example industrial corporations unwilling to pay for frontier CDR technologies, determine how much carbon dioxide removal they want to buy from a specific supplier at marginal cost. The diverse market commitment then pays a premium per tonne to the supplier, should the removals meet specific criteria. By funneling market commitments to a premium rather than to direct purchases, the diverse market commitment can fund more CDR than its own commitment amount can purchase, while pushing suppliers to create a competitive product.

PRODUCT

To qualify for the premium, firms must prove that carbon has been removed at a set evidentiary standard and that the carbon dioxide removal occurred in a predetermined set of Global South countries. This premium compensates firms for implementing and verifying ERW in the Global South, which is likely to be resource-intensive in the short to medium term, given the lack of existing institutional support systems. Firms must also agree to share publicly a predetermined subset of data, which will contribute to global ERW scientific learning and advancement. This data may include data on operational decisions like grain size, agroecological characteristics of deployment land, as well as ultimate CDR rates.

PROJECT FINANCE

This diverse market commitment is an outcomes-funded instrument, which means funds are disbursed once carbon has been removed. To finance projects, firms still need to secure working capital from traditional investors. The existence of the diverse market commitment, however, should help firms make their investment case, as it showcases proven demand for a firm's product. This proven source of demand for Global South deployments de-risks investment in Global South-focused ERW firms, as investors see that deployment in such regions is a key characteristic of the demand for the product.

This type of diverse market commitment helps facilitate several important aspects of ERW market catalyzation:

1. Access – Uncoupling the cost of CDR from R&D costs, with buyers paying only the marginal cost and the diverse market commitment fronting the premium for ERW implementation in places that require additional R&D, facilitates broader access to the technology. Suppliers in the Global South can demonstrate to potential investors they will be able to make a return based on the set premium. Meanwhile, it makes ERW much more affordable to the average corporation as they only need to pay the marginal cost. This creates a much bigger demand pool for the same amount of donor commitment.

2. Service Delivery – In this diverse market commitment, private market actors rather than governments are still delivering CDR. Due to their political obligations, governments cannot easily fund specific technological approaches. Leaving R&D to the private sector, which has the capacity to quickly exit from strategies that are not working, is most effective for innovation acceleration. Speed is of the essence in the climate crisis, and due to the finite nature of a market commitment, firms are incentivised to act as quickly as possible to capture the premium.

3. Risk — By allowing third-party buyers to determine the ultimate volume of removals, suppliers are still incentivized to provide a competitive product to capture as much of the market as they can. Beyond meeting the evidentiary standard for carbon dioxide removal and Global South deployment, they must create a product that caters to buyers' preferences. However, suppliers are guaranteed that there is a large and existing demand for their product, should they be successful.

BOX 2: **REMAINING QUESTIONS**

In actioning this diverse market commitment, climate and development funders who contribute to the commitment must address several key questions.

Evidentiary standard – There must be an agreed-upon evidentiary standard for carbon dioxide removal. There are several groups that have put forward standards for ERW, including Isometric, puro.earth, and Cascade Climate.These standards aim for a high level of certainty in the amount of carbon removed, due to the current focus of the voluntary carbon market on tonne-for-tonne offsetting. Another entity which is working to develop standards for the industry is the Carbon Removal Standards Initiative, a non-profit organization focused on developing regulatory standards. Funders for the diverse market commitment are not making any compensation claims and the third-party buyers are only buying at marginal cost, so this introduces a potentially different evidentiary standard. Depending on how third-party buyers decide to use the carbon dioxide removals they purchase, whether for tonne-for-tonne offsetting or a more contributions-based approach, there could be less focus on direct, field-level carbon accounting, which is costly and hard to scale. The diverse market commitment contract could potentially pay against verification of deployment if the deployment meets certain quality guidelines.

The debate about how to use carbon credits is ongoing within the industry. For example, the release of the Beyond Value Chain Mitigation guidelines from the Science Based Targets initiative, an influential trade group which advises corporations on pathways to net zero, calls for a contributions-based, rather than offsetting, approach to CDR.

Premium size – Funders must also determine the premium size paid per tonne of carbon removed. One potential metric for a premium is the social cost of carbon. The United States Environmental Protection Agency (2023) updated its estimate of this number to $190/tonne in 2020. Using the social cost of carbon as a price metric uses a public-goods benefits framework, which may be better suited to a market commitment use case.

Role of governments – Many stakeholders within the CDR field view governments as the ultimate scale-enabler for the industry. As buyers, governments are uniquely placed to procure CDR at the scale necessary to contribute to global climate goals. As regulators, governments can enact subsidies or tax provisions, such as 45Q in the United States (Trendafilova, 2023) to support the development of nascent CDR industries. In this diverse market commitment, governments could operate as the third-party buyer entity which decides ultimate volumes. Acting in this role, governments would pay a low price for CDR, that is the marginal cost, and only pay if the results were delivered.

ERW presents a significant global opportunity for scalable, permanent CDR, thus positioning itself as a promising way to achieve the international climate objectives. However, realizing this potential requires careful market design to address key market inefficiencies and financing gaps, particularly for a globally inclusive ERW industry. The Global South is particularly suited to ERW, due to its favorable environmental conditions and cost-effectiveness. As scientific certainty grows and MRV approaches mature, ERW can drive progress in both carbon dioxide removal and socioeconomic development, in low- and middle-income countries. It is therefore essential to innovate effective market design and act decisively, to unlock the full potential of ERW CDR as a global public good.

Appendix 1: **Cost-Benefit Analysis Assumptions**

MONETARY COSTS

Four cost categories associated with implementation are listed below. Calculation methods, assumptions and source information are provided.

Implementation Cost Category	Calculation Methods	Assumptions/Source Information
Mining	$\text{USD/tonne}_{\text{rock}} = \sum [\text{Unit}]/\text{tonne} * \text{USD}/[\text{Unit}]$	• A summation of material unit costs to mine one tonne of basalt, based on the price and amount needed for explosives, electricity, diesel, lubricating oil, water, and handling.[9]
Grinding	$\text{USD/tonne}_{\text{rock}} = \text{kWh/tonne}_{\text{rock}} * \text{USD/kWh}$	• USD/kWh – Electricity cost by country (Neufeld, 2022). • $\text{kWh/tonne}_{\text{rock}}$ – The energy demand is based on grind size, applying a power function pulled from Strefler et al. (2018).
Transportation	$\text{USD/tonne}_{\text{rock}} = \text{USD/tonne}_{\text{rock}}\text{/km} * \text{km}$	• $\text{USD/tonne}_{\text{rock}}\text{/km}$ – Pulled from Della (2024) and Kenya Transporters Association (2022). Assuming the standard truck load for road transfer is 28 tonnes. • km – Distance from mine to fields. Assuming 100 km for both Kenya and Germany. • The transportation cost is assumed to be a linear function of distance, with a constant freight rate per tonne per kilometer. The analysis assumes homogeneous freight conditions for Kenya and Germany.
Spreading	$\text{USD/tonne}_{\text{rock}}$	• $\textit{USD/tonne}_{\textit{rock}}$ – Mechanical spreading operations and maintenance and fuel costs pulled from Strefler et al. (2018). Assumes diesel usage with cost figures adapted from Thrikawala et al. (1999), which included spreader costs and rate controllers in a study originally on fertilizer application, now adapted by Strefler (2018) for ERW. • $\textit{USD/tonne}_{\textit{rock}}$ – Manual Spreading cost pulled from wage rates in agriculture in Kenya (Kenya National Bureau of Statistics, 2022) and Europe (European Commision, 2021). Manual spreading includes labor costs only, calculated for different regions based on local labor rates, assuming it takes eight hours of labor to spread one tonne of rock per worker.

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[9] Please contact info@precisiondev.org for detailed information.

LIFE CYCLE ANALYSIS

Four emission categories associated with implementation and the CDR rate are listed below. Emission calculations are based on application rate and emission factors. CDR rate is given.

Implementation Emission Category	Calculation Methods	Assumptions/Source Information
Mining	tonne$_{CO2}$/ha/yr = tonne$_{rock}$/ha/yr × kg$_{CO2}$/tonne$_{rock}$ /10^{3}	• kg$_{CO2}$/tonne$_{rock}$ – Mining emission rate taken from Atima and Suthirat (2016). • The annual CO$_2$ emissions from mining are indicative of the total emissions resulting from the provision of the required mineral quantity for each hectare.
Grinding	tonne$_{CO2}$/ha/yr = kWh/tonne$_{rock}$× tonne$_{rock}$/ha/yr × g$_{CO2}$/kWh /10^{6}	• t$_{CO2}$/kWh – Pulled from Our World in Data (Ritchie et al., 2023) • kWh/tonne$_{rock}$ – This variable represents the kWh required to grind one tonne of rock to a specific particle size (particle size fixed to 50 μm). Formula pulled from Strefler et al. (2018). • Emissions from the grinding process are assumed to be directly proportional to the energy consumed, influenced by the grind size, and dependent on specific electricity grid emission factors.
Transportation	tonne$_{CO2}$/ha/yr = g$_{CO2}$/tonne$_{rock}$/km × km × tonne$_{rock}$ /ha/yr /10^{6}	• g$_{CO2}$/tonne$_{rock}$/km – Pulled from Environmental Defense Fund (2024), emission rate of diesel truck (page 12) • km – Distance from mine to fields. Assuming 100 km for both Kenya and Germany. • The CO$_2$ emission estimation assumes use of truck transport, correlating emissions with the traveled distance and using truck-specific emission rates from different regions.
Spreading	tonne$_{CO2}$/ha/yr = tonne$_{CO2}$/tonne$_{roc}$/km × tonne$_{rock}$/ha/yr × 1 km	• g$_{CO2}$/tonne$_{rock}$/km – Pulled form Environmental Defense Fund (2024), emission rate of US diesel truck as a proxy for both Kenya and Germany (page 12) • km – Assuming a spreading machine travels 1 km to cover a hectare of land
Carbon Dioxide Removal Rate	tonne$_{CO2}$/ha/yr	• Assuming the third quartile CDR rate from all compiled rates from field and laboratory studies, which is 4.1 tonne$_{CO2}$/ha/yr, for both Kenya and Germany.

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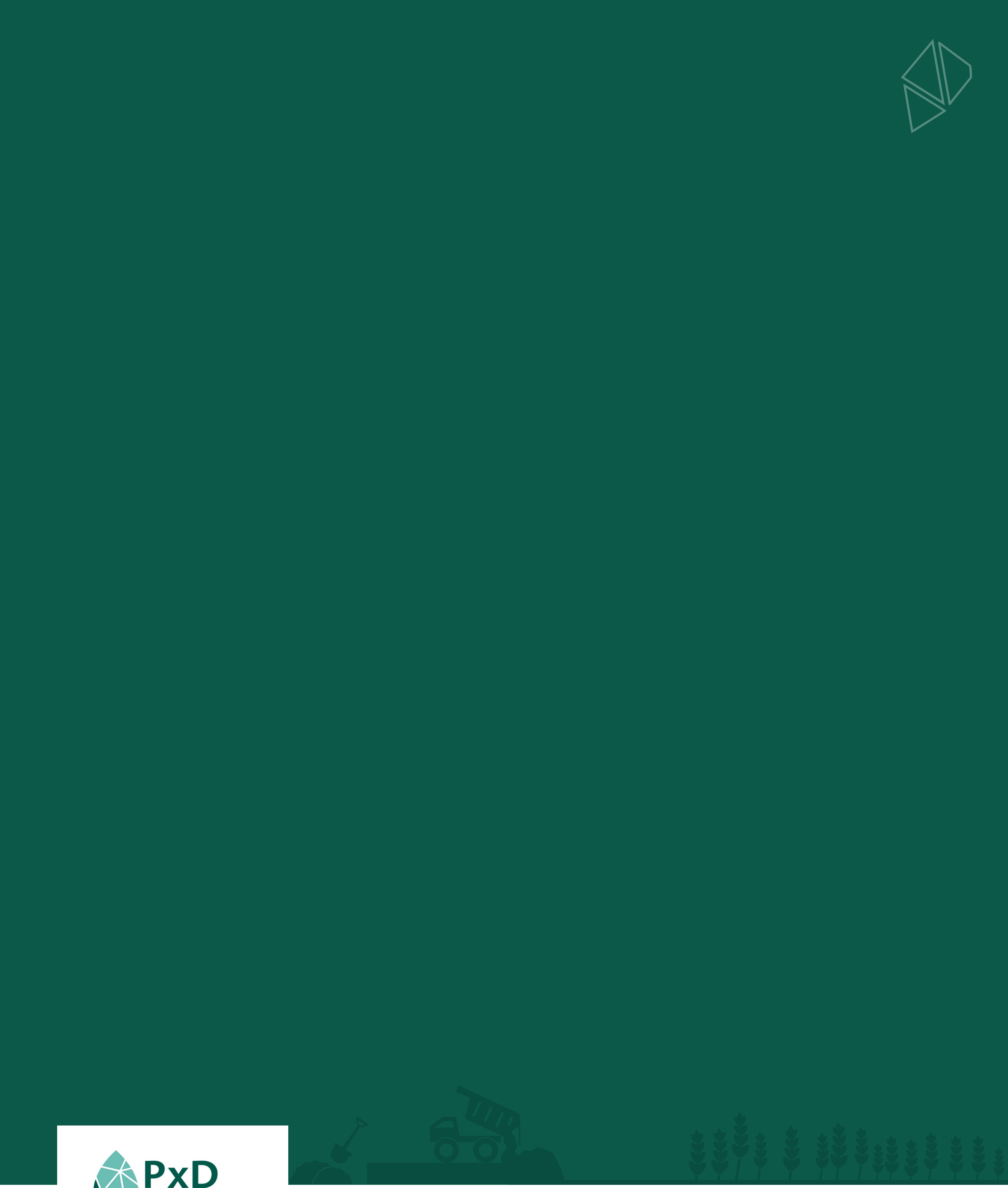

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