This manuscript is a non-peer review preprint that has been submitted to the Philosophical Transactions of the Royal Society B on 16th October 2025. Subsequent versions of the manuscript might have different content.

Unlocking Gigatonne-scale Carbon Dioxide Removal with strategic tipping point frameworks

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Abstract

Achieving global climate mitigation requires a rapid acceleration of Carbon Dioxide Removal (CDR) to gigatonne (Gt) scales by 2040. Linear growth in climate solutions is insufficient to reach these targets, but system-change practices and leveraging interventions that trigger self-reinforcing feedbacks ("tipping points"), offer a solution. Enhanced Rock Weathering (ERW) in Brazil is uniquely positioned to utilize this approach. ERW accelerates natural rock weathering to remove atmospheric CO_2 by spreading rock powders in agricultural settings. Simultaneously, the rock powders have the potential to restore degraded soils, increase nutrient use efficiency and reduce the reliance on synthetic fertilizers. ERW can remove CO_2, reduce emissions and positively impact communities and ecosystems. In Brazil, these targets align, creating conditions for system change. This study explores the enabling conditions and interventions that place Brazil at the forefront of uniting the emerging ERW industry with sustainable agrogeological transformation. These conditions include pioneering research, an established community movement and representation body, and a ‘first-of-its-kind’ national legal framework for feedstock production. The paper highlights the importance of regional

development hubs and feedstock valorization to drive the diffusion of innovation, enabling multiple positive feedback mechanisms to accelerate the system toward a sustainable agronomic transition with Gt-scale CDR potential.

1 - Introduction

Alongside rapid decarbonisation, significant Carbon Dioxide Removal (CDR), in the multi-Gigatonne ($GtCO_2e$) range, is an essential component of global net-zero strategies[1–4] requiring immediate investment and urgent scaling[1–3]. The premise of CDR is to remove CO_2 from the atmosphere and store it in a durable reservoir. It offers a pathway to compensate for so-called 'residual' emissions and the only solution available to tackle historic emissions. No single CDR solution can provide the future capacity required, and we must consider a portfolio of both temporary (conventional) and permanent (novel) solutions[2]. The scale of ambition for CDR requirements is large, however, requiring the industry to become the fastest growing industry in human history, where its success requires coordinated efforts across a diverse range of actors.

Tipping point frameworks offer a strategic approach to accelerate climate action by leveraging the non-linear dynamics of socio-economic systems[5–7]. This shifts policy and investments beyond linear interventions (e.g. a single CDR purchase), focusing instead on identifying critical thresholds to trigger self-reinforcing feedbacks. The objective is to catalyze a rapid, systemic transition to a new, highly stable state. In doing so, climate mitigation is reframed as an exercise in systems change and allows for a more strategic use of interventions for transformative impact. Methods to operationalise tipping points frameworks have been presented[5–8], but, to date, the deliberate use of tipping points for positive transformations is hindered by the difficulty in identifying opportunities for intervention and the relative importance of system components[6,9,10].

Enhanced Rock Weathering (ERW) is a key CDR technology that offers a strong opportunity for leveraging tipping points. This process aims to accelerate the natural CO_2 regulating power of silicate weathering through the sourcing, grinding and spreading of cation-rich silicate rock powders on agricultural lands. The dissolution of the rock powder by acid in soil waters effectively removes CO_2, storing it as a stable bicarbonate phase in groundwaters, rivers and the oceans, or potentially soil inorganic carbonate in some settings[11,12]. CO_2 evasion, caused by strong acids, can also be reduced due to system wide acidity neutralisation[13,14]. ERW encapsulates multiple co-benefits in agriculture, including improving soil health, regulating soil pH, decreasing nutrient runoff, improving yields, pest management and plant nutrition[15–19], making the CDR technology fully embedded in socio-economic systems. Indeed, food production is a corner-stone of society, influenced heavily by policy, technological innovation and market dynamics at global and local levels.

Here, we explore the key components of a tipping framework for scaling ERW with reference to specific enabling conditions and through the lens of understanding the accessibility, affordability, and attractiveness of the technology. We focus on Brazil as a case-study due to the high potential for ERW CDR[11] owing to optimal weathering conditions in the tropics, a low CO_2 electricity mix, the availability of feedstock resources and agricultural land. Crucially, Brazil has a history of creating unique enabling conditions through political interventions, such as the 'first-of-its-kind' national legal framework for rock powders, that can both serve as a case-study and offer opportunity for further refinement. Parallels are drawn to the analogous successful uptake of bio-innoculants in Brazilian agriculture, indicating a likelihood that the agricultural practices can be tipped in favour of alternatives such as rock powders. We argue that Brazil is well positioned as a key area for accelerating global climate change mitigation through strategic interventions, ultimately unlocking Gt scale CO_2 removal potential.

2 Discussion

2.1 Context and technology background

2.1.1 The tipping framework

The goal of using tipping models is to promote behaviour change in order to enter a new, highly stable state of socio-ecological-technological activity (Fig. 1). Here we define the current business-as-usual (BAU) state as one where rock powders are used as a niche agronomic activity, and the desired state is one where rock powders are used for ERW operations at Gt CDR scale (Table 1). This transformation reflects aligning agronomic practices for sustainability, followed by further optimisation for CDR outcomes. The hypothetical transition involves scaling over 200x from a calculated ~0.0054 $GtCO_2e$/yr gross potential CDR capacity today, to a position of climate relevant impact with ~1.2 $GtCO_2e$/yr (Table 1; see *Methods*).

These two stable states are depicted as valleys in a stability landscape diagram (Fig. 1), separated by a rise which represents the social, technical or financial barriers, preventing a transition between states. These barriers are highly embedded and resilient against change[16,20–22] (*see 2.2.3*) leading to high stability for the BAU scenario (narrow valley, Fig. 1). The transition from the BAU state to one dominated by widespread rock powder use, but at low application rates, can be considered as a bifurcation tipping model. Here, once the majority of farmers are using silicate rock powders to some degree in agronomy, it is likely the system will be self perpetuating *(see 2.2.1.2)*. However, we consider the additional increase to higher application rates, that are critical for climate relevant impact, as the optimum system state for aligned agronomic and CDR benefit. This CDR optimised state is represented by a deeper valley in the stability landscape model that requires maintenance. This is because farmers have no incentive to increase application rates when the crop performance is unlikely to scale linearly, hence the system would likely revert to a state optimised for sustainability, but not CDR.

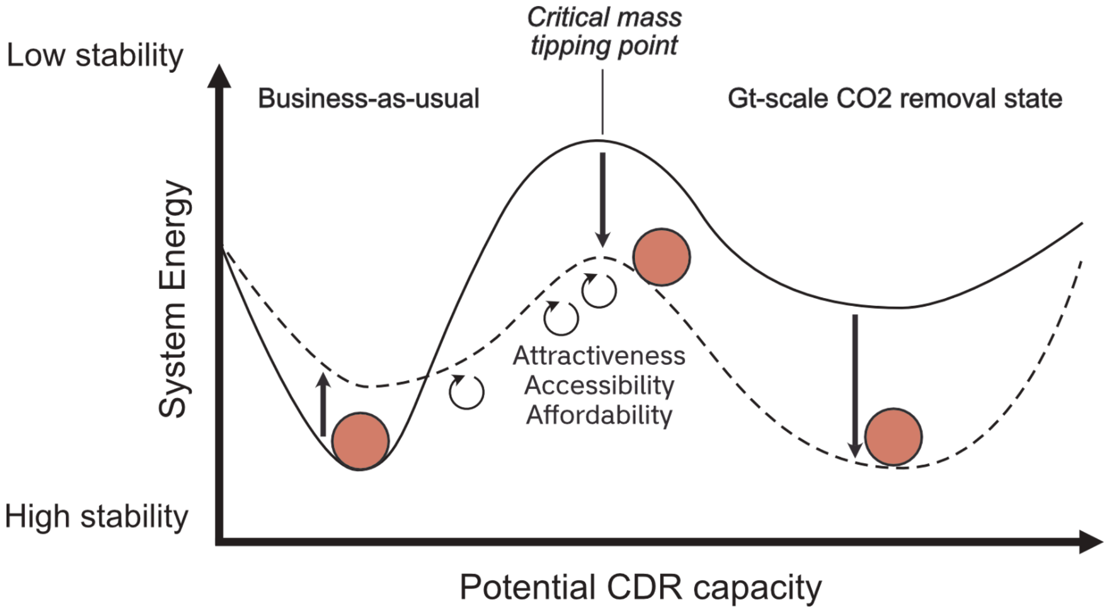

Figure 1: Abstract dynamic stability landscape to illustrate the system state transformation of aligning ERW with agronomic practices to maximise CDR capacity. The red ball represents the position of the current system and movement through to the new state. Lower points in the landscape represent more stable system states, while higher points represent unstable thresholds or energy barriers. The solid line indicates the BAU future, with high stability (steep valley) due to high social-economic barriers, requiring dedicated intervention to reach higher adoption levels and CDR capacity. The dashed line represents the system transformation required. The key attributes of accessibility, affordability and attractiveness drive positive feedbacks (arrows) that can be used to move between the states by decreasing the desirability of BAU, decreasing barriers, and increasing the stability of the Gt-scale-state (dashed line). Maintained carbon finance at Gt-scale prevents the system losing stability and returning to a lower CDR potential state.

Operationalising tipping models requires three key elements (Table 2): 1) enabling conditions, 2) positive feedback mechanisms, and 3) interventions[6]. In particular, positive feedback mechanisms (Table 3) can lead to significant, long-term change through non-linear responses, rapidly transforming behaviours. These aspects are discussed through the paper narrative, referencing Table 3 for definitions.

For ERW the transformation involves reaching a critical mass of farmers using rock powders in agriculture, typically 10–40% of the population[6] (Fig. 1). In contrast to some discussions on tipping frameworks for technologies, such as solar power and green ammonia[6,23], price parity with an incumbent technology is less important for ERW to reach a tipping point. This is due to the price of feedstocks being less than synthetic fertilizers and, as with other new technologies, price declines are expected with greater scale, helping to stabilise user uptake. However, the use case reality is that rock powders are introduced to optimise agronomic practices rather than completely replace the incumbent solution; for example, there is no source of Nitrogen (N) in silicate rocks, but they are a sustainable direct source of Phosphorus (P) and Potassium (K), and more holistically address soil health[15,24]. That said, economic considerations (affordability; Fig. 2) are essential to overcome barriers to technology uptake, reflecting the compounded cost of rock powders with existing practices; achievable through carbon finance (*see 2.2.3 and 2.3*). Importantly, the value received by practitioners (i.e. the price-performance ratio) heavily impacts the diffusion of innovation through positive feedback mechanisms (*see 2.2.3.3*). External interventions therefore need to primarily focus on improving the attractiveness and accessibility of rock powders (Fig. 2; Table 2) which can still involve capital investments.

Through interventions, the stability of the incumbent state is reduced, the magnitude of the barrier between states is decreased and the new hypothetical stabilized state becomes achievable (Dashed line; Fig. 1). The rate of change is controlled by the existence of positive feedback mechanisms, i.e. the connections that amplify the impact of an intervention (Fig. 2, Table 3), which are influenced by the sensitivity of the system and existence of multiple interacting elements.

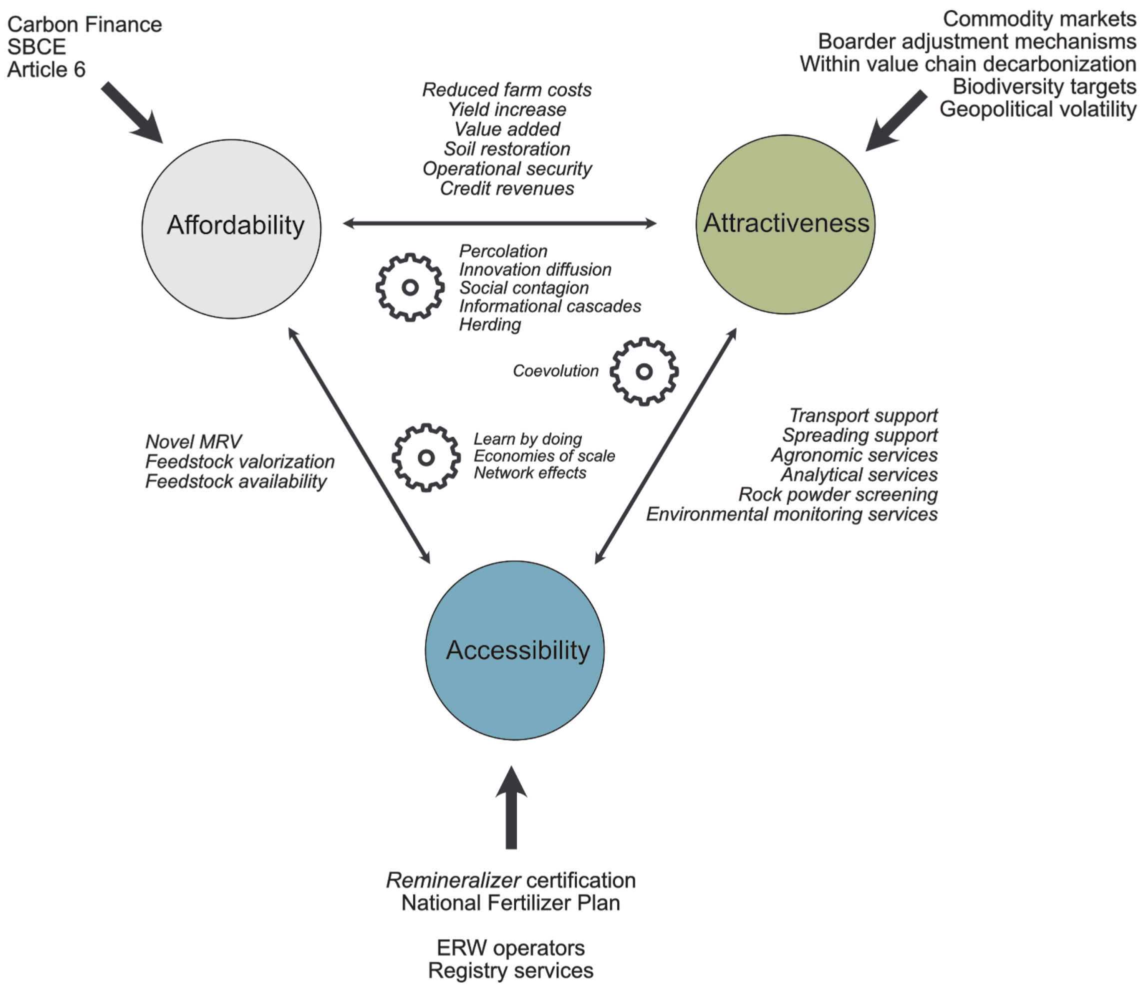

Figure 2. Schematic of tipping point model for scaling ERW focusing on the interacting nodes of Affordability, Attractiveness and Accessibility. Key external enablers are illustrated that impact the nodes. Primary connections are described, and primary positive feedback mechanisms illustrated internally. See Table 3 for descriptions of feedback mechanisms.

2.1.2 The state of ERW

Enhanced Rock Weathering is a novel CDR method with growing international interest. Over the last few years, academic research in the technology has grown significantly[25] and commercialization is accelerating. From a carbon management perspective, ERW is primarily considered a CDR method. However, it also offers potential for agricultural decarbonisation by reducing the need for synthetic fertilisers, especially as a source of P, K and micronutrients. ERW with silicate rocks also offers an alternative pH management approach to agricultural limestone (AgLime), helping optimise carbon intensive operations for feedstock proximity and transport distances. Silicate rock powders can further mitigate CO_2 degassing, that is applicable in some settings with AgLime[14,26] and can help manage anthropogenic Nitrous Oxide emissions in agriculture[27,28]. Moreover, total system acidity neutralization is a key benefit, which is not yet widely considered.

Early estimates of the scalability of ERW suggest the potential for Gt CDR if applied widely, contributing significantly to the Nationally Determined Contributions (NDCs) of some countries[11]. These attributes make ERW well placed for using tipping point frameworks due to its wide-reaching impact and cross-sector functionality. Moreover, whilst monitoring approaches are evolving[29,30], offering a significant potential to decrease unit economics for carbon credits, deployment is relatively simple, leveraging established infrastructure. Thus uptake does not rely on future, unproven innovation.

Commercial traction is being validated by substantial financial commitments from early adopters. For example, the advanced market commitment from *Frontier* includes $117M (322,947t CDR) for ERW, making up 22% of *Frontier's* technology portfolio and comparable to the $116.8M (180,963t CDR) committed to Direct Air Capture (DAC). Additionally, $55M was awarded to ERW operators through the X-prize Carbon Removal challenge in 2025. Brazil is a key early case study, with $64.8M in seed funding for two ERW startups between 2022 and 2024. In parallel there is public interest in large-scale ERW deployments from at least one major mining operator. The aforementioned investments are a key indicator of accelerating growth. Total capital and intellectual investments in ERW are, however, still lower than for other novel CDR technologies[2].

This nascent market is reaching critical milestones in the early roadmap toward climate targets. In 2024, the world's first third-party verified ERW credits were issued for a deployment in Brazil, through the *Isometric* registry, followed by credits issued by *Puro* for a USA deployment in 2025.. Nascent ancillary MRV services are also emerging through novel measurement technologies whilst multiple registries are actively developing and maintaining crediting protocols, and the EU is considering inclusion within the Carbon Removal and Carbon Farming framework. Early methodology support[30] and financial regranting was led by a philanthropically funded technology mobilizer, *Cascade Climate*, solidifying the industry's foundation for verification and credibility and enabling industry-aligned research and development**.** Despite these foundational developments and growing interest, ERW remains in an emerging, sub-critical state, underscoring the need for a strategic acceleration.

2.2 Enabling conditions, interventions and feedbacks

2.2.1 Brazil's historic interventions

2.2.1.1 To birth of Rochagem

Soil fertilization is the basis of global food security and has broader implications for the biodiversity of managed ecosystems. Tropical regions, particularly Brazil, hold an immense geodiversity and optimum vegetation growth conditions. However, extreme edaphoclimatic conditions result in highly leached soils, with low nutrient content, making it difficult to meet the demands of the agricultural sector focused on commodity production, which for over half a century has increasingly relied on soluble synthetic fertilizers. These fertilizers aggravate soil acidity. To counter this trend, the use of AgLime for pH management has grown. These practices entail high financial and environmental costs, leading to continuous soil degradation and creating a dependency on increasing amounts of soluble fertilizers[21]. This drives up production costs and contributes to the eutrophication of water resources and the emission of greenhouse gases (GHGs).

Globally, rock powders have been researched as a sustainable soil management strategy since the 18th century. In Brazil, the potential of rock powders was identified in the mid-20th century (Fig. 3), spurred by academic interest in their benefits, which gave rise to the Rochagem movement. Brazil pioneered academic research in the 1970-80s[31–33]. But it was only in the early 2000s that new studies elevated this technological pathway to a new status[16,34]. The University of Brasília and the Brazilian Agricultural Research Corporation (EMBRAPA) presented promising initial results from their research on rock powders, showing significant improvements in soil fertility profiles and plant performance[35]. These results, combined with interest from Brazilian public institutions, supported the establishment of a regulatory framework of soil remineralisers[36,37] (*see section 2.2.1.2*). Subsequently, in 2021, the Brazilian Government created the National Fertilizer Plan[38] (NFP; 2020–2050), which aims to strengthen policies for enhancing the competitiveness of production and distribution of sustainable fertilizer inputs and technologies in the country, including *remineralisers*, to reduce external dependence and increase the supply of local/regional fertilizers (*see section 2.2.1.2*).

In the last 20 years, more than one hundred theses and dissertations have been produced in Brazil on Rochagem, exploring several rock types, agricultural crops and diverse agroecosystems. The results of these studies have been shared through five editions of the Brazilian Stonemeal Congress and the international Rocks for Crops conferences, as well as in national and international journals.
This body of work facilitated the establishment, in 2022, of the Brazilian Association of Soil remineraliser and Natural Fertilizer Producers (ABREFEN), which aims to promote and valorize

remineralisers as strategic and essential inputs for Brazilian agriculture. The number of registered remineralisers complying with legislative specifications continues to grow with 78 products registered with the Ministry of Agriculture, Livestock, and Supply (MAPA), and total production volumes of ~1.8 Mt in 2023[39].

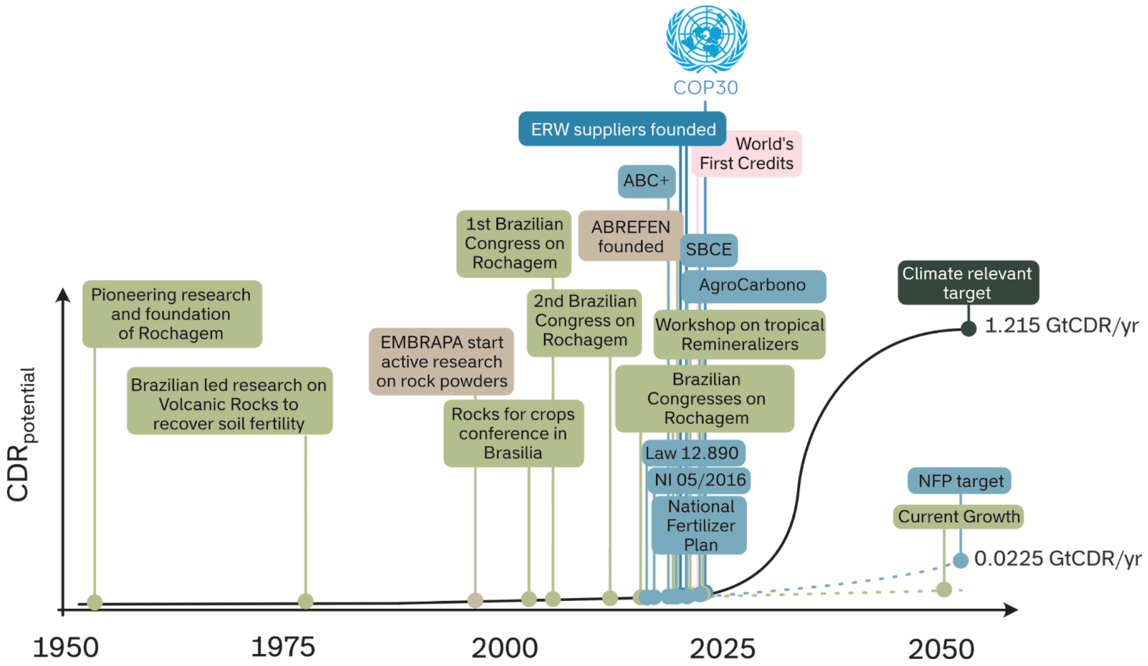

Fig 3. Key historic reference points of Brazil's influence for using rock powders in agriculture with schematic illustration of growing gross CDR potential. The Brazilian system is poised to accelerate toward a tipping point, driving exponential progress toward international CDR goals beyond anything that can be achieved with current growth rates and targets.

2.2.1.2 Legal enablers for feedstocks

As outlined (*see 2.2.1.1*), the rochagem community created the world's first legal framework for the exclusive certification of rock powders in agriculture ('*remineralisers*')[16,21,22,37,40] which consolidates and goes beyond the incorporation of rock powders into agricultural regulations seen elsewhere[41,42]. *Remineralisers* are regulated for the quality, sourcing, registration and labelling of rock powder products for agriculture. Regulation further includes the specific requirement for agronomic demonstration of feedstocks. *Remineralisers* are mostly produced as a minority byproduct of aggregate production[43], and certification excludes chemical material processing. Certification is a central pillar for ERW operations and a key determinant of accessibility and credibility, allowing for readily available feedstock material specific for use in agriculture.

Whilst fertilizer regulations may be sufficient to allow for ERW feedstock to be used in agriculture, they do not optimise or reward for CDR, highlighting potential for future consideration. The *remineraliser* regulation is also only partly aligned to attractive ERW feedstock attributes as it specifies a minimum sum of base oxides (CaO, MgO, K_2O; 9%) and upper grain size limit (2mm). However, there is a broad inclusion of rock types[24], of which only a selection may be suitable for CDR when considering appropriate mineralogy and reactivity (Fig. 4; Table S2).

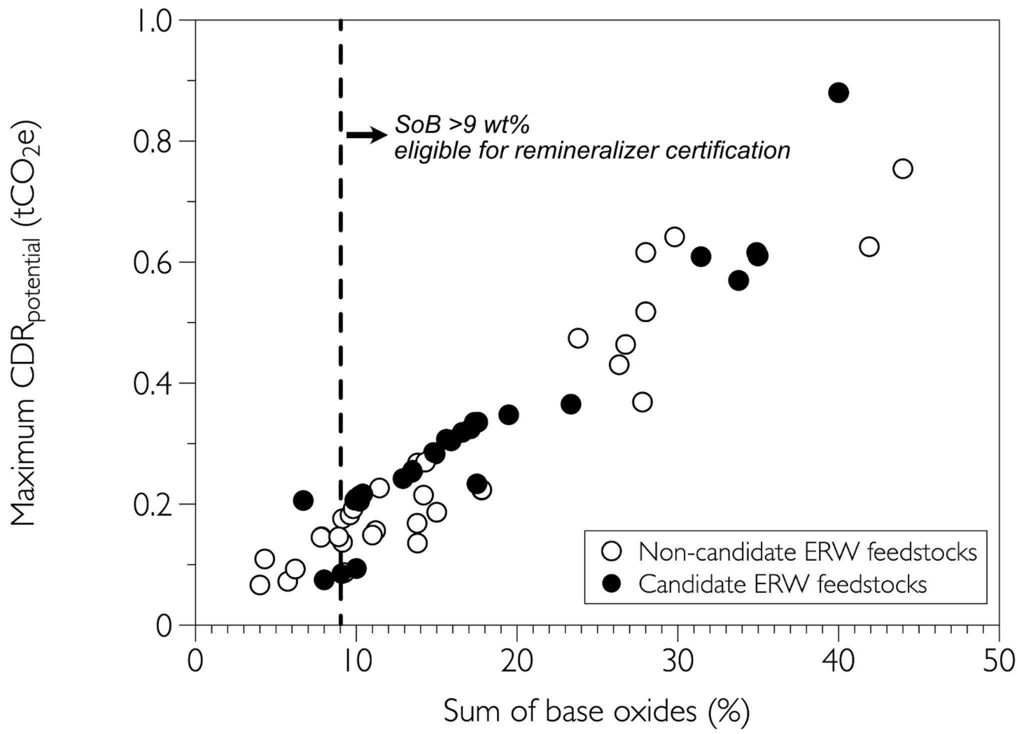

Figure 4. Calculated maximum CDR potential for a selection of Brazilian silicate rock powder products researched for agronomic benefits[24] *as a function of the sum of base oxides. Maximum CDR potential following the Steinour/Renforth formulation assuming 100% storage efficiency. According to MAPA requirements, certified remineralisers must have a sum of base oxides >9wt%.Potential candidate ERW feedstocks include; basalt, phonolite, dunite, basaltic andesite, kamafugite, olivine melilitite and glauconitic siltstone. Non-candidate feedstocks include; granite, schists, biotite syenite, gneiss, sandstones, generic siltstones and shales*

Further potential for a future improvement of accessibility to ERW suitable feedstocks can be seen in the NFP[38] (*see 2.2.1.1*). The NFP does not outline any legal requirements for *remineraliser* use, but focuses on improving infrastructure, research and bureaucratic systems for domestic fertiliser production as a whole industry. In contrast to the comparable EU initiatives, such as the EU Integrated Nutrient Management Action Plan, the NFP contains a specific target to reach 75 Mt/yr of *remineraliser* production requiring an ~42 times increase in total production and 4 times increase in growth rate[20]. If met, this target could provide ~0.0225 $GtCO_2e$ of CDR potential (Table 1, Fig. 3).

We consider the NFP targets as an interim position in the stability landscape (Fig. 1), which itself could potentially represent the critical mass of *remineraliser* users needed to transform to a stable, self perpetuating state (*see 2.1.1*). If the 75 Mt production target were met, and applied at an average application rate of 1.5t/ha, this would cover ~50 Mha; i.e. 18% of total agronomic land in Brazil or 83% of planted crops (*Table 1*). This is within or beyond the adoption rates needed for critical mass[6,9]. Whilst marking a sustainability milestone, these targets are both too late and too low for a CDR optimised state; ~50 times lower CDR capacity than the Gt-scale envisaged here. That said, if a high proportion of users have some existing experience with remineralisers, they are more likely to be receptive to an increase in application rate to ERW relevant amounts (10–20t/ha), if additional incentivization is presented through carbon finance. In this case, adoption would fall to only ~1–3% of available land where critical mass transformation is not plausible. Aligning ERW with sustainability practices therefore offers an approach to accelerate and magnify the impact of this flagship policy.

2.2.1.3 Carbon policy

Brazil has established historical experience with the voluntary carbon market and has made recent advancement in carbon management laws. Brazil's national cap-and-trade system (Law No. 15,042/2024) creates a strategic policy environment that provides regulatory clarity for carbon removal. The law introduces the Brazilian Greenhouse Gas Emissions Trading System (SBCE) and a new class of tradable assets called Certificates of Verified Emissions Reduction or Removal (CRVEs). The SBCE combines a cap and trade system with voluntary carbon markets and cooperative approaches under Article 6.2 and 6.4 of the Paris Agreement. In a world first, the SBCE integrates agreements for the future transfer of Internationally Traded Mitigation Outcomes (ITMOs), conditional on NDC achievement and obtaining the surplus to sell in order to generate liquidity. Article 6 trading is technology agnostic so long as it meets the standards set forth in Article 6.2 or 6.4 respectively, and could thus include ERW.

Although agriculture is currently excluded from the SBCE, CRVEs can be generated through agricultural practice changes, thereby incentivising revenue generation in a similar manner to the established decarbonisation schemes such as RenovaBio. This framework therefore paves the way for ERW to be eligible to generate CRVEs once approved methodologies are in place. CRVE generation could begin rapidly, building upon current methodologies in the VCM.

Further, there are established inclusion opportunities for CDR initiatives in agriculture and conservation including the Low Carbon Agriculture Plan (ABC/ABC+ Plan) for sustainable agriculture and the Agrocarbon Chamber (Câmara Temática do Agrocarbono Sustentável) which aims to discuss public policies that promote sustainable production linked to environmental conservation. The Brazilian government has also explicitly promoted the value of carbon removal recently through The Petroleum Act (Law No. 9,487/1997), which redirects 1% of gross fossil fuel revenue toward energy sector R&D, with specific prioritization for Carbon Capture and Storage (CCS) under CNPE Resolution No. 07/2025. Expanding this prioritisation to other CDR technologies, or creating an equivalent funding mechanism for other industries, would be beneficial for the sector, but this action demonstrates the relevance of CDR for large industries in Brazil.

2.2.2 Feedbacks from regional development

Regionality, and focusing efforts in smaller populations, is an effective method for reaching critical mass rapidly[6], and especially relevant in Brazil. This effect is due to strong social based positive feedback mechanisms, such as informational cascades, percolation, herding, and social contagion[6,7] (Table 3). For agriculture, these feedbacks have significant potential because farmers place a high trust in peer learnings[44]. Local agronomy figureheads also play an important role, potentially associated with a lower threshold for adoption due to higher trust.

Remineraliser certification has enabled a de-centralized network of 58 registered mines, with potential for over 500 rock powder producers across Brazil based only on current mining rights[20,39]. As multiple regions develop as '*remineraliser hubs*', networking effects become important, whereby a robust ecosystem of ERW-specific service providers emerges: specialized consultants, analytical services, equipment manufacturers, verification bodies, and financing mechanisms. This is partly established in Brazil through the decentralized agronomic analytical network (e.g. 150 EMBRAPA registered laboratories[45]) and consultant services. We argue that the existence of this comprehensive, interconnected network makes it easier and more valuable for any new participant to adopt ERW, as they can leverage shared resources and expertise.

Regional development is moreover aligned with the need to minimise transport related CO_2 emissions, the largest emission source for Brazilian ERW where there is a favourable energy mix for feedstock comunition[43]. With time, transport sharing, widespread rail or shipping networks, or road transport electrification, can open up larger regions around feedstock producers, making the technology more accessible and affordable, and CDR efficient. However, private and government infrastructural investment will only occur once market demonstration occurs, in effect delaying coordination and coevolution feedback mechanisms (Table 3). Hence, streamlined regulations that benefit regional development early is a key enabler for ERW.

2.2.3 Fertilization and incumbent technologies

2.2.3.1 Price volatility and attractiveness

The incumbent technology-regime of synthetic fertilisers for soil management is firmly ‘locked in’ (c.f.[9]), representing a resilient barrier to *remineraliser* uptake. As discussed (*see 2.12*), practitioners use rock powders in addition to other land management strategies (non-organic or organic) whilst optimising practices to maximise returns. None-the-less, because synthetic fertilizers are widely available through established expertise and agronomic consultancy, their use is promoted as a social norm. The formulaic and prescriptive nature of the technology makes it highly accessible, actively reducing the attractiveness of *remineralisers*. By contrast, there are no standard guidelines for *remineraliser* type and application rates.

Whilst accessible, the widespread reliance on synthetic fertiliser imports exposes farmers to geopolitical and economic risks[46], intimately tied to global events due to the need for fossil fuel resources to manufacture fertilisers[21,47]. This situation has been repeatedly made clear in the last decade, with the 2008 Financial Crisis[21], the COVID pandemic[47] and the 2021 Russian invasion of Ukraine, which resulted in up to a three-fold increase in fertiliser prices to Brazil’s current total of $22.5Bn/yr[46]. With the world’s highest dependency on imported fertilizers[48], price volatility has directly increased the attractiveness of domestic solutions like *remineralisers* in recent years, although use decreased again when international fertilizer capacity was re-established in 2023[20,39].

2.2.3.2 Value added and accelerating critical mass

Not only do silicate rock powders provide a suite of slow release macro nutrients (Ca, Mg, K, P), but they are a source of a wide suite of micro nutrients that are often not considered in traditional fertilization regimes[24]. An example of this is providing bioavailable Si through the dissolution of reactive silicate minerals. Silica has a complex role in nutrient cycling and plant growth, but can be important in some crop types, such as sugarcane[49]. There is also evidence that rock powders can help manage water availability[50] and improve stress resistance of plants, including against pests[15], illustrating the additional service value of the practice that can be leveraged to increase the attractiveness of the solution.

Through expansion, optimisation and demonstration of these benefits (i.e. the diffusion of innovation[9]), the attractiveness of *remineralisers* can be amplified by offering unique attributes that are otherwise not provisioned for under traditional fertilization approaches. The larger quality difference of the new technology compared to existing practices effectively decreases the critical mass required for driving system transformation[9], and the more these attributes are researched and communicated, the greater the potential for increasing practice uptake.

Valorization is important for enabling a number of positive feedback mechanisms. Rock powders are typically produced as a by-product of primary aggregate industries, creating a surplus that is often stockpiled. This is because production lines co-produce coarser products for aggregate demand in the construction industry, the primary economic interest of the production cycle. However, *remineraliser* certification adds value, allowing revenue diversification. Valorization therefore incentivises research and knowledge sharing in order to demonstrate the feedstock attributes. With an increasing number of suppliers and greater local product uptake, mines will be under pressure to compete against each other and against incumbent fertilizer products through price-performance optimisation and advertising their product benefits. Moreover, creating a distinct *remineraliser* market drives greater investment in support services for the feedstock supply chain and novel services (e.g. geological analysis), thereby establishing networking effects. These are key components of tipping models (Fig. 2)

With valorization for CDR, *remineralisers* may one day compete with the demand for coarser rock products. The Brazilian mining industry produced ~0.27Gt of aggregate material in 2023, with production exceeding commercialization by ~0.01Gt[51]. Stockpiling is thus used to buffer annual demand changes. As such today's *remineraliser* production of 0.0018 Gt does not displace aggregate demand. However, Gt-scale CDR goals will require *remineraliser* production twenty times higher than current total aggregate production, implying a modification of production lines or dedicated remineraliser facilities to meet demand. At first, *remineraliser* supply could be the limiting factor for operations, which could potentially lead to a short term operational price increase. However, as supply begins to meet demand for a secure market, prices would fall again, especially once suppliers modify production lines for higher capacity.

An important potential area for future policy alignment would be promoting CDR aligned geological resource management to ensure aggregate demand is met by less expensive, non-CDR rocktypes and recycled material[52]. This would mitigate socio-economic leakage, making ERW more efficient. Such industrial reform is only plausible through valorization of the resource.

2.2.3.3 Global sustainability demand and herding

Linking to global systems, food nutritional value can be improved using silicate rock powders[15,21], helping alleviate the global epidemic of declining food quality and helping address consumer needs[53,54]. Moreover, low CO_2 operations and sustainability are a growing component of consumer decision making and a key factor of the Science Based Target Initiative (SBTI) commitments. Here ERW could play a two-fold role decarbonising supply chains and helping to address residual emissions. This may be further strengthened when CDR is fully incorporated in border adjustment mechanisms, valorising low carbon production. CDR integration into Emission Trade Schemes and Article 6 also promises another future route[55]. In this respect, one particularly relevant land-use class is degraded pasture, where land can be restored to increase land use efficiency (i.e. animals/ha), and decrease drivers of deforestation, thereby potentially promoting sustainable sourcing initiatives, comparable to the Amazon Soy Moratorium (ASM)[56]. Pasture alone makes up ~60% of available agronomic land in Brazil (Table S1), contributing significantly to the Gt-scale CDR target area. Such market demand not only potentially increases product value (and attractiveness; Fig. 2), but, crucially, unlocks herding behaviour for farmers to be able to access markets (Table 3). By analogy, this was a key market driver of the ASM that helped create a hybrid governance structure[56]. Herding decreases the need for demonstration and education, hence lowering the barriers for technology uptake.

2.2.3.4 Analogous technologies in Brazil

The previous success of analogous technologies serves as a useful indicator for predicting the efficacy of tipping frameworks[10]. For instance, the widespread adoption of bio-inoculants in Brazil, now largely embedded in agriculture, offers a pertinent comparison. This emergent technology's success was facilitated by an advanced and specific regulatory framework[36], which brings credibility to the market in the same manner as for *remineralisers*. Moreover, application has demonstrated yield gains that decrease the requirement for synthetic N fertilization, reportedly worth an additional $22bn for soy bean production alone[57]. Research, development and adoption was largely driven by fertilizer cost volatility and market demand for sustainable farming[57] where farmers are increasingly receptive to uptake as higher quality solutions become more accessible and market demands require sustainable innovation, an example of herding behaviour. The inherent environmental stressors of low nutrient soils in tropical environments is further driving learning-by-doing (such as selecting for specific microbe properties, dose optimisation and re-inoculation strategies) and economies-of-scale, accelerating the attractiveness and affordability of the technology[57]. This success can be seen as a potential foreshadowing of trends for *remineralisers* and suggests that tipping models can be applied.

2.3 The role of carbon finance

2.3.1 Carbon credits to overcome established barriers

Finance is a clear barrier for initial *remineraliser* uptake, due to the cost of rock powders, transport and spreading (i.e. affordability and accessibility). This cost is compounded onto normal operational outgoings for a farmer, representing additional investments for a yet-to-be-proven gain. Moreover, given no existing guidance on application rates and fertiliser substitution, farmers are not equipped to commit to a practice change. Ultimately, there is a perceived risk around adopting a new technology, one that farmers are unwilling to bear without expert guidance and financial incentive. Operational adaptation is also required to overcome logistical barriers, where farmer practices are currently optimised for spreading smaller volumes of amendments, <5t/ha. Thus, an ERW application of *remineralisers* (10–20t/ha) requires multiple passes with the same spreading equipment or major investment into higher volume machinery. In addition to the logistical burdens (staff time, fuel, machinery cost and maintenance) this has the potential of negative impacts on soil, especially regarding compaction.

The significance of these barriers is illustrated by the fact that, despite being a potentially cheaper fertilization approach and decades of development, *remineralisers* remain a niche land management activity. As a result, even in the cases where *remineralisers* are adopted (1.8 Mha; Table 1), average application rates remain low (<5t/ha[20]), up to ten times lower than needed for climate relevant impact and non-viable for CDR monitoring and crediting based on current MRV approaches[29].

Carbon finance overcomes barriers directly and indirectly. By paying for a share of the operational costs, affordability is clearly increased, and with it accessibility. This model transfers the costs and risks to companies that are better able to finance novel expenditure than individual farmers. ERW operators can also play a role in handling logistics of sourcing and transport, and educating or advising farmers in agronomic transition based on learnings from past operations. Operators are a critical part of formal knowledge dissemination, which can be amplified through informational cascades, word-of-mouth, percolation and social contagion. These system wide ancillary activities contribute to additionality arguments, even when less directly considered by metrics such as project scale financial additionality.

The demand signal created by carbon finance is also key to increasing feedstock production volumes and reaching Gt-scale. Without the demand drive for large production volumes, rock powder products will remain a minority income for mines.

Once initial barriers are navigated, and as profitability of operations increases, credit revenue sharing can become a major incentive for farmer uptake of the practice. As monitoring, reporting and verification of ERW becomes more streamlined, the profitability increases and revenue sharing increases. This is an example of the learning-by-doing feedback, but rather than accelerating toward cost-parity with incumbent technologies, the learnings primarily translate into greater attractiveness for practice uptake. The same is applicable to general agronomic optimisation. In Brazil, the success of revenue incentivisation is demonstrated through existing crediting schemes for decarbonisation, namely the RenovaBio CBio scheme[58] and Payments for Environmental Services[59]. Revenue sharing is likely especially important for making high application rate spreading cost effective for farmers.

2.3.2 Additionality at scale

Upon reaching a climate-relevant, Gt-scale CDR state for ERW, carbon finance transitions from an initial catalyst to a fundamental, ongoing economic driver that maintains the system's stability (deepening the 'valley' of the stability landscape; Fig. 1). This is important to ensure climate relevant application rates are maintained, resisting the inherent incentive to minimise agronomic operational costs by reducing application rates (a backward tipping point for CDR).

This transition will likely be enabled by the uptake of compliance markets that help close the funding gap for novel CDR[60,61]. For ERW, this transition is accompanied by a decrease in operational expenditure, partly enabled by ongoing learnings of today's measurement intensive quantification required for the current VCM. With a decrease in scientific uncertainties, novel, regional scale monitoring systems can evolve that are less measurement intensive, paving the way for lower cost operations that are more suitable for governmental and international trading programs.

Carbon finance—especially through compliance carbon markets—establishes a direct payment for the environmental service of CO_2 removal, be it as a credit or allowance based system. This is unlike traditional agronomy subsidies predominantly funded by general tax revenues, creating a continuous revenue stream that is crucial for covering the inherent operational costs of large-scale ERW (e.g., rock processing, transport, spreading) and ensuring it remains economically viable and attractive even at higher levels of efficiency and uptake. Without this consistent valuation of removed CO_2, the robust positive feedback loops that define the stable, desired state would weaken, and the system could gradually lose its energetic favorability, causing its long-term viability to diminish.

The design of compliance carbon markets, such as the SMBC, can strategically underpin this sustained stability. In models where emission allowances are auctioned, the revenue generated flows to the government. These revenue streams allow governments to recycle funds directly into payments for environmental services, programs that support ERW. Crucially, this mechanism does not inherently compromise additionality. Instead, the government, acting as a strategic investor, can direct these funds towards activities that are clearly beyond BAU, such as large-scale infrastructure development for feedstock production and transport, R&D, or direct payments for Gt-scale removal that would not occur without the explicit value signal from the compliance carbon market. At a project scale, this could be as simple as paying for higher application rates. This ensures that the financial input translates into genuine, additional climate benefits, making the high-CDR EWR state not just achievable, but perpetually maintained through a market-driven value for atmospheric CO_2 removal.

3 Conclusion

Scaling CDR technologies rapidly requires a novel coordination of interventions in order to maximise the impact of industry efforts by disparate stakeholders. This can drive powerful positive feedback mechanisms that enable exponential scaling to meet globally agreed climate targets. Emerging economies are particularly well placed to leverage such a framework, with Brazil demonstrating high potential.

Although aligned with ERW, the CDR potential of *remineralisers* was, historically, not the primary consideration for policymakers, researchers, or farmers. On the other hand, the *rochagem* movement means that Brazilian mining and agriculture now represents a socio-ecological-technological system that is uniquely positioned to be 'tipped' into a CDR optimised state, and realise the Gt CDR potential of ERW. This potential draws upon the regional feedstock production model with a credible legal certification framework, that lends itself well to streamlined production, product valorization, the rapid diffusion of innovation and critical mass tipping. This is amplified by the importance of peer-to-peer learning for farmers, creating strong percolation and social contagion feedbacks. The attractiveness of rock powders is demonstrably enhanced by exposure to cost volatility in current fertilizer solutions[39]. Consequently, policies that decrease the attractiveness and affordability of existing solutions would likely be effective in promoting greater *remineraliser* adoption.

Regional development models, facilitated through streamlined feedstock certification, product valorization and geological resource management are especially attractive for unlocking social feedback mechanisms. Currently, the complexity of regulation elsewhere inhibits such a model but can still be leveraged to valorize feedstocks (e.g. through Product Function Categories in the EU), giving credibility to rock powders as a fertilizer and CDR feedstock. There will, however, be additional challenges where resources are not co-located with deployments which require more remote technology promotion[62].

Success in socio-ecological-technological transformation necessitates a concerted effort from a diverse range of stakeholders, including policymakers, lawmakers, scientists, financiers, commodity purchasers, and communities. Crucially, both policy and market strategies must prioritize driving collective action towards sustainability and low-carbon objectives in order to establish herding behaviour. This enables networking effects, which can extend to other carbon removal technologies with important co-benefits, such as biochar or soil organic carbon management, further amplifying the climate impact of aligned interventions. This could potentially evolve into a hybrid regulatory framework, blending government policies with market-driven mechanisms. More generally, interventions need to focus on reaching critical mass and enabling feedback mechanisms. We therefore encourage decision-makers to examine the non-linear impacts of their choices, aiming to combine global climate mitigation with food and nutritional security, as well as with structural economic transformation, something that ERW offers[21].

Methods

We explore the applicability of tipping point frameworks for ERW in Brazil following a narrative approach, based on identifying key system components, connections and feedbacks that are outlined in the literature[6,10].

To define the current and hypothetical systems states we calculate the maximum CDR potential based on literature data for current usage and available agronomic areas[63]. The current CDR potential and areal estimates in Brazil are calculated using the average total rock powder production of 1.8Mt/yr (2019 to 2023) and an assumed average application rate of 1.5t/ha[39]. We assume a gross CDR potential of 0.3 tCO_2e/t_{rock}, reflecting a hypothetical basalt feedstock (equivalent to the maximum CDR potential that could be achieved through the total dissolution of rock powder and complete storage efficiency, calculated as a function of the sun of base oxides[64]). To convert gross CDR potential to net CDR we assume 40% efficiency to account for all upstream and downstream system losses. For the future scenario we assume an agronomic application of 20t/ha/yr across 75% of Brazil's agricultural land, where Brazil has a total available agronomic area of ~277Mha, including agro forestry, pasture, sugarcane, oil palm, soy, rice, coffee, citrus, perennial crops and cotton[63] (Table S1).

Acknowledgements

MC, MC, MD, VF, JK, EP, IN, MR, PS, JV and CL work for InPlanet GmbH, a for-profit ERW operator in Brazil. DACM and SHT acknowledge support from the Grantham Foundation for Environmental Protection and SHT gained support from the National Council for Scientific and

Technological Development (CNPq). We thank Maria Freitas for support. Artificial Intelligence (AI) was used to improve readability and language of the work.

Table 1

remineraliser production and CDR capacity under different stability states

		2050	
	2019-2023	NFP	Gt-scale CDR
Annual *remineraliser* production volume (Gt/yr)	0.0018	0.075	4.05
Area of application (Mha)	1.2	50	203
Percentage of total agronomic area (%)*	0.5	18	75
Percentage of planted crop area (%)	2	83	75
Average application rate (t/ha/yr)	1.5	1.5	20
Gross CDR potential ($GtCO_2e/yr$)	0.0054	0.0225	1.215
Net CDR potential ($GtCO_2e/yr$)†	0.0022	0.009	0.486

*includes all planted crop types, planted forest and pasture (Table S1)

†assuming a 40% CDR efficiency to account for losses due to operational emissions, infield inefficiencies and downstream losses.

Table 2

Key components of the tipping point framework

	Description	Examples	Brazilian context
Enabling conditions	Often related to price and performance (Affordability), beneficial attributes (Attractiveness) and supportive infrastructure (Accessibility)	Quality increase, price decline, improved reliability, decreased upstream or downstream environmental or economic costs	Rock powder as a byproduct of aggregate industries, localised feedstock supply networks, expensive synthetic fertilizers, quality gain as a fertilizer
Positive feedback mechanisms	Exist within and interact between different parts of a system to promote benefit	Diffusion of innovation, learning by doing, networking effects, percolation, social contagion, self-reinforcing expectations.	Farmer cooperatives, ABREFEN, EMBRAPA, Agronomists, ERW operators
Interventions	Intentional inputs to promote system change	Policy, financial commitments, public education, technological or social innovation	Remineraliser classification for rock powders, National Fertilizer Plan, CDR offtake agreements

Table 3

The Diffusion of Innovation model can be broken down into two primary domains (Social and Technological) and involve a range of micro-mechanisms that act as positive feedback mechanisms

Domain	Micro-mechanism (positive feedbacks)	Description	ERW examples	Key actors responsible
Social	Percolation	The spread of a phenomenon through a network or system via local, contiguous interactions	Initial adoption around regional feedstock suppliers leading to broader state level connection	ERW operators, farming consortiums, feedstock suppliers, EMBRAPA, ABREFEN
	Informational cascades	A situation where individuals make decisions sequentially, observing the actions of others and inferring information from those actions, even if it contradicts their private information or initial beliefs.	Endorsement by agronomic experts, large Agribusiness or researchers. Farmers adopt practice without their own research	ERW operators, farming consortiums, media, agronomists, research figureheads, agribusiness, EMBRAPA, ABREFEN
	Herding	Practice uptake driven more by social pressure, conformity, or a desire to avoid being left out	Practice is seen as key to accessing premium export markets or specific sustainability certifications	Farmers, commodity traders, international markets, consumers
	Social contagion	The rapid, often non-linear, spread of behaviors, ideas, or attitudes through a population, via direct or indirect social contact, similar to the spread of an infectious disease	Positive experiences with ERW regarding crop performance are shared organically and enthusiastically among farmer WhatsApp groups, local community meetings, and informal social gatherings across Brazil.	ERW operators, farming consortiums, farmers
Technological	Learning by doing	The process by which the efficiency and effectiveness of a process, technology, or skill improve over time as more experience is gained in its implementation	Teams gain cumulative experience in optimizing operations (production and application) MRV maturation allowing the CDR credit price to decrease	ERW operators, analytical service providers, feedstock suppliers, transport industry. EMBRAPA, ABREFEN
	Economies of Scale	The cost advantages that enterprises obtain due to their scale of operation, where the cost per unit of output generally	As the overall demand for ERW in Brazil grows, basalt quarries can invest in larger, more efficient crushing	ERW operators, analytical service providers, feedstock

	decreases as the volume of production or service delivery increases	machines, and transport companies can dedicate specialized fleets or fleet sharing schemes, leading to lower per-tonne costs for raw materials, processing, and delivery.	suppliers, transport industry
Network effects	A phenomenon whereby the value of a product or service increases for both new and existing users as more people use it, often by expanding a shared infrastructure or knowledge base	As more ERW projects are deployed in Brazil, a robust ecosystem of ERW-specific service providers emerges: specialized consultants, equipment manufacturers, verification bodies, and financing mechanisms.	ERW operators, analytical service providers, feedstock suppliers, transport industry
Co-evolution	A process where two or more interacting components or systems evolve together, each influencing the evolutionary trajectory of the other(s). In socio-technical systems, this involves the simultaneous development of technology, user practices, institutional frameworks, markets, and policy.	As ERW technology develops, it simultaneously influences and is influenced by the evolution of Brazilian agricultural practices and relevant policy	ERW operators, analytical service providers, feedstock suppliers, transport industry, policy makers, large agribusiness, commodity traders

Table S1

Agronomic areas in Brazil by land use category

Land use	Mha	%
Forest Plantation	8.94	3.23
Pasture	164.57	59.48
Sugar Cane	9.32	3.37
Mosaic of Agriculture and Pasture	42.16	15.24
Oil Palm	0.19	0.07
Soy Beans	39.87	14.41
Rice	1.02	0.37
Mosaic of Crops	8.24	2.98
Coffee	1.26	0.45
Citrus	0.23	0.08
Other Perennial Crops	0.59	0.21
Cotton	0.26	0.10
Total	276.67	100

Data sourced from MapBiomas[63]

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