Article:

Steeley, I.L. orcid.org/0009-0002-3544-5811, França, E.S. orcid.org/0009-0001-7277-3091, Epihov, D.Z. orcid.org/0000-0001-5711-5480 et al. (2 more authors) (2025) Agroforestry and enhanced rock weathering: a dual strategy for sustainable cacao. PLANTS, PEOPLE, PLANET. ISSN: 2572-2611

https://doi.org/10.1002/ppp3.70097

Received: 7 March 2025 | Revised: 13 July 2025 | Accepted: 20 July 2025
DOI: 10.1002/ppp3.70097

Plants People Planet PPP Open Access

REVIEW

Agroforestry and enhanced rock weathering: A dual strategy for sustainable cacao

Isabella L. Steeley[1] | Edson S. França[2] | Dimitar Z. Epihov[3] | Noah J. Planavsky[4] | David J. Beerling[1]

[1]Leverhulme Centre for Climate Change Mitigation, School of Biosciences, University of Sheffield, Sheffield, UK

[2]Cocoa Innovation Centre, Santa Cruz State University, UESC, Brazil

[3]Plants, Photosynthesis, and Soils cluster, School of Biosciences, University of Sheffield, Sheffield, UK

[4]Yale Center for Natural Carbon Capture, Yale University, New Haven, Connecticut, USA

Correspondence
Isabella L. Steeley, Leverhulme Centre for Climate Change Mitigation, School of Biosciences, University of Sheffield, Sheffield S10 2TN, U.K.
Email: i.steeley@sheffield.ac.uk

Funding information
Mondelez International, Grant/Award Number: X/177300-12-2; Biotechnology and Biological Sciences Research Council, Grant/Award Number: X/177300-11-2; Mondelēz International, Inc

Societal Impact Statement

Cacao production is both economically vital and environmentally intensive, presenting a major sustainability challenge as a crop largely cultivated by smallholder farmers in climate-vulnerable regions. This review synthesises evidence that integrating agroforestry with enhanced rock weathering (EW) may significantly reduce emissions from cacao production. Our projections indicate that applying EW to 10% of the cocoa harvest area gives a notably high mitigation potential. Although these findings suggest EW could substantially offset emissions, our review emphasises the urgent need for rigorous field trials to validate projections and explore possible synergies or unintended consequences. The integration of EW and agroforestry could offer a scalable solution to align cacao production with global climate and sustainability goals while supporting long-term agricultural resilience.

Summary

As one of the most emission-intensive foods, chocolate presents a significant challenge in meeting consumer demand and sustainability goals. Focusing on carbon sequestration and climate resilience, this review explores the potential of agroforestry and enhanced rock weathering (EW) as a dual strategy towards climate-positive cacao. Here, we describe how agroforestry systems, particularly multi-strata systems such as cabrucas, can enhance carbon sequestration, tolerance to global climate change and ecosystem services. We analyse the mechanisms by which EW can augment these benefits, focusing on its impact on offsetting carbon emissions during production, nutrient release and improved soil health. The combined efficacy of these strategies is assessed. Research gaps and areas of concern are identified, principally around monitoring carbon removal, biodiversity impacts and nutrient cycling. Our review highlights the importance of integrated approaches to address the complex challenges facing the cocoa sector. Further research is needed to quantify the economic and social benefits of agroforestry and EW, as well as to develop best management practices for different agro-ecological contexts.

KEYWORDS
Agroforestry, Cacao, Carbon Dioxide Removal, Climate-smart agriculture, Enhanced Rock Weathering, Tropical Agroecosystems

1 | INTRODUCTION: COCOA'S CARBON PROBLEM

Theobroma cacao L, "Food of the Gods" has held profound social and economic significance as a food, drink and medicine for 5,300 years (Zarrillo et al., 2018), and this continues to the present day. The global chocolate market was estimated at $119.39 billion in 2023 (Horizon, 2023), with a projected revenue forecast of $23.54 billion for cacao beans by 2030. Globally, the industry supports approximately five to six million farmers, with 40 to 50 million people depending on cacao for their income (Beg et al., 2017). With an 8.4% compound annual growth rate expected between 2024 and 2030 (Horizon, 2023), cacao remains among the most valuable cash crops and agro-economic commodities and production has been increasing to meet this demand. However, over the past 60 years, a direct correlation has been observed between increases in cacao bean production and the area of land harvested (Figure 1). In contrast to typical row crops (e.g., corn), increased production has not been invoked by increases in yield.

Cacao has a significant yield gap problem; in 2023, the global yield average was 480.5 kg/ha (Faostat, 2024) approximately 90% lower than the modelled water-limited yield potential of 5,000 kg/ha (Zuidema et al., 2005) and 84% lower than the experimentally derived yield potential of 3,000 kg/ha (Appiah et al., 2000). This has been attributed to low technological adoption (Aneani & Ofori-Frimpong, 2013), disease outbreaks (Agyeman-Boaten & Fumey, 2021) and climate events (Gateau-Rey et al., 2018), among other factors. Many cacao farmers (30–58%) earn a gross income below the World Bank extreme poverty line, and the majority (73–90%) do not earn a Living Income in the two highest cacao-producing countries (Van Vliet et al., 2021); yield gaps and low farm-gate prices perpetuate this cycle of poverty (Bensch et al., 2023; Tittonell & Giller, 2013). As identified by cacao farmers in Cameroon, barriers to intensifying existing cacao farms include a lack of technical support and knowledge, prohibitive land ownership rights, limited financial assistance and labour and high input costs (Alemagi et al., 2015; Kenfack Essougong et al., 2020).

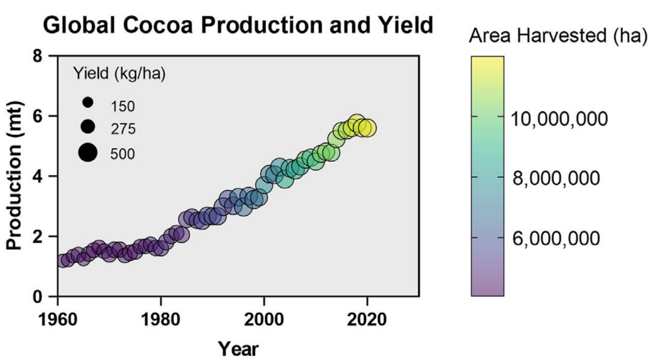

FIGURE 1 **Global Cocoa Production and Yield from 1961 to 2023.** Global cocoa production, yield and area harvested data extracted from Faostat, 2024.

Climate change is expected to exacerbate these issues given the vulnerability of cacao to extreme weather events (Gateau-Rey et al., 2018). Maximum dry season temperatures and water availability are projected to become limiting factors, and climate suitability for growing cacao is shifting (Igawa et al., 2022; Schroth, Läderach, et al., 2016). To close the yield gap and improve livelihoods, the cacao industry must adopt productivity adaptations that are accessible, affordable and practical for smallholder farmers. Research on the implementation of climate-smart agricultural practices has become pertinent, particularly with cacao production being a driver of greenhouse gas (GHG) emissions itself.

Chocolate is a GHG emissions-intensive food product, contributing to 2.4% of the food and drink sectors' GHG emissions within the UK and 4.7% of the primary energy consumption (Konstantas et al., 2018). The environmental impact of cacao production on GHG emissions has been studied extensively, as shown in Table 1. Chocolate, on average, is estimated to have a global warming potential (GWP) of 2.9–4.2 kg CO2 eq./kg (e.g., Konstantas et al., 2018) with land use change and fertiliser use contributing the most to GHG emissions (Ntiamoah & Afrane, 2008; Ortiz-R et al., 2014). Land-use change (LUC), particularly deforestation for cacao expansion, is estimated to increase cocoa's GWP by a factor of three to four (Konstantas et al., 2018). Locally, deforestation can contribute up to 98% of cocoa emissions (Wiltshire et al., 2008). These high emissions are propelled in part by the short-term economic benefits of establishing new plantations on recently deforested land, rather than replanting existing low-yielding areas (Benefoh et al., 2018). Productivity on cleared virgin forests is high due to a phenomenon known as the 'Forest Rent', where soil nutrients become exposed, reducing fertiliser requirements, until the soil becomes depleted after 20–30 years, inciting further deforestation (Amponsah-Doku et al., 2022). Furthermore, the ever-increasing demand for cacao, with trading prices in April 2024 spiking to a record high of $12,000 per tonne (cocoaprice, tradingeconomics.com), could further incentivise unsustainable cacao expansion. Cacao-driven deforestation incurs significant carbon losses, with estimates exceeding 185 Mg C/ha-1 (Leuschner et al., 2013) along with soil degradation and biodiversity loss in critical hotspots (Sassen et al., 2022). Recent studies highlight the severe environmental consequences of cacao cultivation, revealing it as the underlying cause of over 37% of forest loss in protected areas in Côte d'Ivoire and over 13% in Ghana between 2000 and 2020 (Kalischek et al., 2023). These findings reflect the urgent need for sustainable and responsible practices within the cocoa industry to mitigate its detrimental environmental impact.

TABLE 1 Life Cycle Analysis (LCA) values for Global Warming Potential for 1 kg of dried cacao beans across three cacao cultivation systems. N.A. indicates not applicable, as these values were not calculated in the cited research.

Country in which LCA was conducted	Conventional Monoculture (kg CO_2-eq/kg dried cacao beans)	Conventional Agroforestry (kg CO_2-eq/kg dried cacao beans)	Organic Agroforestry (kg CO_2-eq/kg dried cacao beans)	Reference
Ghana	0.050	0.060	N.A.	Parra-Paitan & Verburg, 2022
Ecuador	N.A.	0.300	0.034	Caicedo-Vargas et al., 2022
Bolivia	2.980	3.740	1.560	Armengot et al., 2021
Ecuador	1.900	1.090	0.841	Pérez-Neira, Copena, et al., 2020
Mean	1.643	1.298	0.812	
SD	1.482	1.687	0.763	

LCA studies were chosen for comparison based on their comprehensive impact assessment and unity in metrics –cradle to farm gate emissions.

FIGURE 2 Cacao Cultivation Systems. (Steeley, 2025).

2 | CURRENT STRATEGIES TOWARDS SUSTAINABLE CHOCOLATE

Although cacao production is often associated with deforestation and environmental degradation, there is the potential for cultivation in multi-strata systems that may mitigate these concerns. As an understory tree, cacao can thrive in shaded, forest-like environments such as the Cabruca system practiced in Bahia, Brazil or the Chakra system in Ecuador (Luna & Barcellos-Paula, 2024; Neves Cavalcante et al., 2023). Within these systems, cacao trees are cultivated in association with native trees in a discontinuous and random manner, providing essential environmental services such as soil protection, shade and pest and disease resistance (Andres et al., 2018; Neves Cavalcante et al., 2023), refer to Figure 2. Climate resilience presents an additional incentive for shaded cacao farms as shade trees can provide a favourable microenvironment that buffers extreme climate events by reducing the mean annual temperature amplitude by 1.1°C compared to monoculture systems and increasing humidity by 2.7% (Niether et al., 2018).

While cacao agroforests do not match primary forests regarding species richness, they can support tropical biodiversity and key ecosystem functioning species (Cassano et al., 2009; Ferreira et al., 2023; Maney et al., 2022; Tadu & Djiéto-Lordon, 2014). In Cameroon, where agroforestry is the predominant system, threatened trees represent approximately 25% of total woody individuals associated with cacao, demonstrating the conservation abilities of cacao farms for vulnerable tree species (Saj et al., 2017). Additionally, multi-strata agroforests can act as habitat and wildlife corridors for endemic and threatened fauna, including primate species such as the Golden-Headed Lion Tamarin in Brazil and the Rowloway Monkey and White-Naped Mangabey in Ghana (Asare et al., 2014; Oliveira et al., 2010; Yao et al., 2015). While studies report increased species biodiversity in cacao agroforests compared to other agricultural land uses, these systems continue to be drivers of species complexity, functional diversity and specialist loss (Jarrett et al., 2021; Maney et al., 2022; Reitsma et al., 2001).

Adoption of multi-strata cacao systems remains low in most cacao-producing countries, largely due to the reduction in yield associated with high levels of shading (Ruf, 2011). However, management of shade trees can mitigate these yield penalties, with research showing that the overall shade tree cover, rather than the complexity of the shade structure, triggers yield reductions. In a study by Clough et al. (2011) increasing shade quantity, measured by overall shade tree cover, was correlated with a reduction in cacao yield, whereas qualitative aspects of shade, such as the number of tall trees and the number of forest tree species, were revealed to maintain species richness without having a significant correlation with yield (Clough et al., 2011). Shade trees can also provide pollinator habitat, which could increase yields, as low pollination is a known limiter of cacao production (Forbes & Northfield, 2017; Lander et al., 2025). Consequently, targeted shade management that maintains moderate shade levels and a complex habitat structure can support high yields without compromising biodiversity in cacao farms, along with supporting broader environmental goals, including re-agro-forestation and increased carbon sequestration.

Cacao agroforests planted on formerly cleared land could be a type of "re-agro-forestation" which is the reinstatement of forest cover that enhances biodiversity while simultaneously maintaining agricultural productivity. This land-sharing approach has gained interest in Brazil with the Forest Act of 2012, which puts pressure on landowners to convert illegally deforested land, often cleared to make way for cattle, back under forest cover (Nepstad et al., 2014; Schroth, Garcia, et al., 2016). Cacao is considered a native tree, which this law acknowledges as permitted reforestation if planted with other native trees. If cacao demand and price continue, re-agro-forestation could become economically favourable to reforest cleared land, and similar legislation could be implemented in other countries.

Establishment of new farms with re-agro-forestation in Brazil has been estimated to reduce emissions by 135 Mg C ha^{-1} in comparison to planting cacao after forest clearing (Schroth, Garcia, et al., 2016). Cacao agroforestry can store considerable amounts of soil carbon, recorded to be around 302 Mg ha^{-1} to 1 m depth, in some cases equivalent to natural forest (Gama-Rodrigues et al., 2011). Low-shade cacao agroforests (<30%) can store 210% more above-ground carbon than monocultures, and within multi-strata systems, a 660% increase was documented (Blaser et al., 2018). Building on the potential of agroforestry systems to promote biodiversity and enhance carbon sequestration, it is equally important to consider the role of farm management practices in reducing environmental impacts.

GHG emissions from conventional cacao production are high, mainly due to chemical fertiliser use, in one study accounting for 96.7% of the carbon footprint (Miharza et al., 2023). Recent studies have demonstrated that cacao farms managed organically can substantially lower GHG emissions compared to both conventional agroforestry (6.3% - 10.7%) and monoculture systems (22.7% - 34.2%) as they are 4–5 times more energy efficient than monocultures and require fewer chemical inputs (Pérez-Neira, Copena, et al., 2020; Pérez-Neira, Schneider, & Armengot, 2020). Although there are discrepancies among LCA studies, resulting from variations in input parameters and system boundaries, refer to Table 1 and Figure 3. Systems that include conventional Good Agricultural Practices (GAP) are associated with higher emissions (2.29 kg CO_2e per kg of cacao), despite assumptions of zero deforestation (Vervuurt et al., 2022). The emissions associated with inputs and residue management aimed at pest and disease control outweighed the increase in cacao yield. The trade-off between high cacao yields and GHG emissions highlights the need for a revision of GAP recommendations to better align with climate mitigation objectives. This stresses the fact that merely boosting yields in the hope of minimising land use is not sufficient to mitigate carbon emissions. It necessitates the implementation of CO_2 removal (CDR) to reduce the industry's ecological footprint.

3 | THE POTENTIAL OF ENHANCED ROCK WEATHERING

Enhanced rock weathering (EW) may be a promising solution to achieve net-zero carbon targets in the cocoa industry. EW involves accelerating the natural process of rock weathering to sequester carbon dioxide (CO_2) (Hartmann et al., 2013). This is accomplished by crushing silicate rocks rich in Ca^{2+} and Mg^{2+}, to increase the reactive surface area (Moosdorf et al., 2014). This rock dust can then be spread across a range of grasslands, forests or agricultural land and incorporated into the soil, where rocks can dissolve faster under the elevated CO_2 released from roots and decomposers (Beerling et al., 2018; Schuiling & Krijgsman, 2006). Increases in alkalinity export are driven by increases in pH caused by the sequestration of protons by the silicate matrix and the formation of monosilicic acid. The increase in pH allows for increases in the concentration of aqueous bicarbonate ions (HCO_3^-) with $CO_{2\,(aq)}$ acting as a buffer. These are summarised by the weathering equation for diopside below:

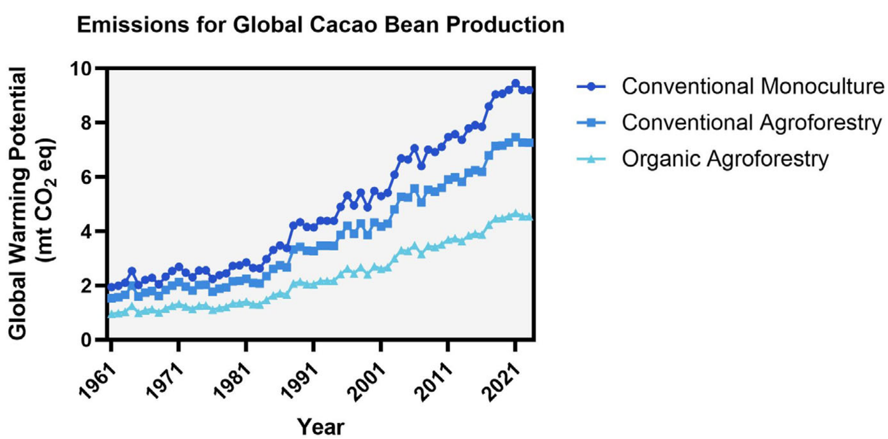

FIGURE 3 **Estimated Emissions for Global Cacao Bean Production from 1961 to 2023.** Average global warming potential (GWP) values for 1 kg of dried cacao beans at farm-level production are sourced from Table 1. These values were multiplied by the average global production value for each year (Faostat, 2024) to calculate total GWP for three cultivation systems: conventional monoculture, conventional agroforestry and organic agroforestry. Under each scenario, it is assumed all cacao is grown using the respective cultivation system, which is an oversimplification of the methods used to produce cacao. See Dataset S1 for further information.

$$CaMgSi_2O_{6(s)} + 4CO_{2(aq)} + 6H_2O_{(l)} \rightarrow Ca^{2+}{}_{(aq)} + Mg^{2+}{}_{(aq)} + 4HCO_3{}^{-}{}_{(aq)} + 2H_4SiO_{4(aq)} \quad (1)$$

Silicate weathering reaction allows for a carbon sequestration ratio of 2 mol CO_2/mol divalent cations.

Subsequently, bicarbonate together with its counterbalancing cations is transported through groundwater and runoff; in many cases, ultimately makes its way to the oceans (Equation 1) (Green et al., 2024). This leads to CO_2 storage as dissolved inorganic carbon or more enduringly as carbonate compounds (Equation 2) (Knapp & Tipper, 2022; Pokrovsky et al., 2009). This is illustrated by the formation of calcite below:

$$Ca^{2+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)} \rightarrow CaCO_{3(s)} + CO_{2(g)} + H_2O_{(l)} \quad (2)$$

Silicate weathering with carbonate precipitation is unlikely to occur in acidic tropical soils but instead occurs over a 10,000-year timescale, leading to a carbon sequestration ratio of 1 mol CO_2/mol divalent cations and the transfer of carbon from the atmosphere to the geologic record (Renforth, 2019).

The large-scale CDR potential of EW remains a subject of debate. The Intergovernmental Panel on Climate Change (IPCC) estimates that EW could sequester between 2 and 4 Gt CO_2 yr^{-1} globally (IPCC, 2022) and one modelling study projected the cumulative carbon sequestration potential of EW to be 215 Gt CO_2 with a fixed application rate of 10 t ha^{-1} of basalt dust across 2006–2080 (Baek et al., 2023). The warm and humid climates in which cacao is cultivated may enhance chemical weathering rates, as increased precipitation and temperature facilitate mineral dissolution by lowering activation energy (E_a) barriers (Haque et al., 2023; Kump et al., 2000; Ryan et al., 2024). However, while dissolution kinetics are more optimal in these regions, the anions charge-balancing cations released during weathering may originate from non-carbonic sources in low-pH soils (Li & Ji, 2016; Taylor et al., 2021). In a tropical EW field trial in Northeastern Australia, soil acidity was shown to preclude CDR, as acids stronger than carbonic acid, mainly surface-bound protons, were the primary weathering agents (Holden et al., 2024). Similarly, strong acid weathering caused by nitrogenous fertilisation was shown to perturb CDR in a field trial with crushed returned concrete in Ireland (McDermott et al., 2024). The mechanism for this is nitrification, where ammonium ($NH_4{}^{+}$)-based fertilisers in the presence of O_2 are converted into nitrate ($NO_3{}^{-}$) by nitrifying soil bacteria, releasing protons into the soil (Goulding, 2016; Nishio & Fujimoto, 1990). Alternatively, $NO_3{}^{-}$-based fertilisers (e.g., $CaNO_3$) could be utilised as a measure to prevent nitrification-driven acidification and strong acid weathering (Weng et al., 2022). In the process of uptake, plants acquiring nitrate also export bicarbonate, thus driving the alkalinisation of the surrounding soil (Haynes, 1983; Pierre & Banwart, 1973). However, nitrogenous fertilisation in excess will cause $NO_3{}^{-}$ to leach through the soil (Quan et al., 2016); caution must be exercised in supplying reasonable rates of $CaNO_3$ fertilisation.

Carbonic acid is a weak acid with a pK_a of ~6.4 (Loerting & Bernard, 2010); therefore, CDR in highly acidic soils (<pH 5.2) will be low until proton neutralisation through continued silicate application and weathering is sufficient for carbonic acid dissociation (Dietzen & Rosing, 2023; Holden et al., 2024; Oh & Raymond, 2006). A correction factor for non-carbonic weathering in soils below pH 6.3 has been proposed (Dietzen & Rosing, 2023), but the effect of strong acids on CDR potential has not reached a consensus.

In addition to these purely abiotic controls, rock weathering is significantly influenced by the rhizosphere environment. A rhizosphere, the soil region influenced by plant roots, exhibits variations in pH and nutrient levels compared to bulk soil, with differences of up to two units (Youssef & Chino, 1989). Plant roots, micro-organisms and decomposing plant materials can also produce additional acidity by releasing protons and organic acids into the soil (de Almeida Leite et al., 2024; Fujii, 2014; Hinsinger et al., 2003; Perez-Fodich & Derry, 2019). Organic acids can complex with metal ions, weakening mineral surface bonds and facilitating silicate dissolution, even at near-neutral pH levels where proton-promoted dissolution is typically constrained (Sun et al., 2023; Welch & Ullman, 1993). While this may increase weathering rates, organic acids and protons could compete with carbonic acid, impeding inorganic carbon formation (Lei et al., 2025; Taylor et al., 2021). This may be compensated by the increase in pCO_2 from root and microbe respiration, which increases bicarbonate concentrations in soil above what is expected from carbonate solubility, promoting CDR (Bloom & Inskeep, 1986; Poschenrieder et al., 2018).

Agroforests have additional advantages for weathering, including deep tree roots, which regulate water fluxes and create macropores, facilitating weathering and exportation of reaction products (Billings et al., 2018; Wen et al., 2020). Tropical forested systems could exert greater biological weathering rates than temperate systems. Owing to their higher net primary productivity and faster microbial decomposition, tropical agroforestry soils have increased CO_2 production and concentrations available to react with rocks (Hashimoto et al., 2007). This could trigger carbon capture at greater rates in tropical systems' soils than temperate systems, particularly in the top 0–10 cm, where rock amendment would be spread. The interplay between strong acids, pCO_2 and CDR rates requires further investigation.

Modelling studies assessing the CDR potential of EW in tropical Brazilian croplands have estimated that deployment on over 25% and 75% of cropland could remove 0.1 and 0.2 Gt CO_2 yr^{-1}, respectively (Beerling et al., 2020). Similar estimates have been reported elsewhere (Jerden et al., 2024); however, field verification is lacking, as no trials have yet spanned a decade. Long-term experimental data on CDR potential in tropical systems, where weathering rates are expected to be high, remain scarce. Reported CDR rates vary considerably, with a field experiment in Malaysia estimating ~1 t CO_2 ha^{-1} sequestration after three years of basalt application (Larkin et al., 2022), and a laboratory study in Costa Rica projecting 3.2 t CO_2 ha^{-1} yr^{-1} following a 50 t ha^{-1} basalt application (Ryan et al., 2024). Currently, there is a high level of uncertainty associated with these CDR rates given the lag time of weathering products in the soil (te Pas et al., 2025), the potential re-release of CO_2 downstream (Zhang et al., 2022) and the emissions associated with the mining, crushing and transportation of rock dust (Moosdorf et al., 2014).

To assess the potential for EW to offset emissions from cacao production, CDR rates from these studies were applied to 10% of the available cocoa harvest area (Figure 4). This 10% scenario was selected as it represents a pragmatic, conservative estimate of partial adoption, allowing for a proof-of-concept scale while accommodating limitations in implementation capacity, financial resources and policy support. The results suggest that EW could substantially mitigate emissions from cacao cultivation through CDR. EW could lower GHG emissions through reduced chemical fertiliser requirements and suppressing N_2O release, but this is not considered here due to the lack of life cycle assessments of EW with cacao production. Field trials are essential to validate these projections and to account for strong acid weathering in tropical soils, potential synergies with other sustainable practices, or unintended consequences not captured in modelling studies.

4 | ENHANCED WEATHERING FOR CACAO CULTIVATION: SOIL HEALTH, NUTRIENT CYCLING AND SUSTAINABILITY

A relatively limited set of soil characteristics is required for productive cacao agroecosystems, including a pH range between5.7 and 6.22, organic carbon content close to 3%, available phosphorus and potassium levels greater than 16 and 90 ppm, respectively, and a cation exchange capacity between 9 and 15 *cmol c/dm*^{3}, among other parameters (Souza et al., 2018). Beyond its role in carbon sequestration, EW holds the potential to improve soil conditions necessary for cacao farming, foremost providing a means to increase and buffer soil pH. In tropical regions, where soil acidity frequently arises from high rainfall and leaching (Ng et al., 2022), the application of EW feedstocks could serve as an alternative to conventional agricultural lime ($CaCO_3$) (Edwards et al., 2017). Silicate rocks, which are rich in bases, could neutralise excess hydrogen ions (H^+) in the soil solution, thereby raising soil pH and improving conditions for nutrient uptake (Guo et al., 2023). Further, the solubility and consequently, the mobility of heavy metals such as nickel (Ni), lead (Pb), cadmium (Cd) and mercury (Hg), are strongly influenced by pH, reducing their solubility as the pH rises (Omokaro et al., 2025; Villalaz-Pérez et al., 2024). Corroborating this, numerous studies have highlighted the importance of maintaining soil pH to reduce the mobility of potentially toxic trace elements in cacao plantations (Araujo et al., 2018; Doe et al., 2022). Soil aluminium (Al) levels, which can be a problem in highly acidic soils, pose a significant concern for cacao cultivation. Elevated Al concentrations can adversely affect shoot and root biomass, stem height, root length, relative growth rate and net assimilation rate (Baligar & Fageria, 2005). Increasing soil Al saturation further inhibits the uptake of essential nutrients, including potassium, calcium and magnesium (Bossolani et al., 2020). The application of dolomite lime to acidic soils reduced exchangeable Al levels from 26 to 0.2 cmol kg^{-1} and increased root and shoot biomass in cacao by 1.31 and 0.39 g plant^{-1}, respectively (Baligar & Fageria, 2005). These findings have prompted further research into soil amendments aimed at preventing trace metal toxicity through pH regulation (Ramtahal et al., 2019). A study by Shamshuddin et al. (2011) demonstrated that the application of ground basalt, a key rock type for EW, at a rate of 20 t ha^{-1} increased pH, reduced exchangeable Al in infertile Oxisols, and simultaneously promoted cacao dry matter weight from 709 to 873 g pot^{-1}. These findings have been supported by additional studies (Shamshuddin et al., 2015).

Depending on the mineralogical composition of the applied rock, EW may also elevate nickel and chromium concentrations in soils

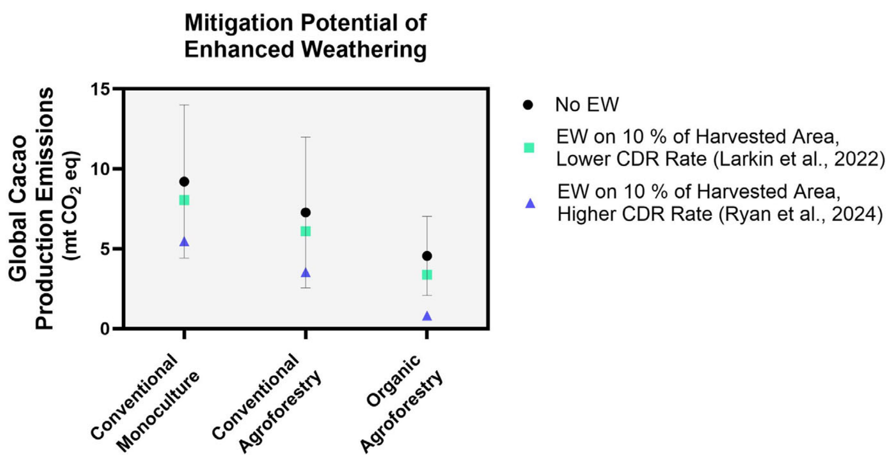

FIGURE 4 **Predicted Global CO_2 Emissions for 2023 Dried Cacao Bean Production with Enhanced Weathering.** Average production emissions were calculated using the same method as above. Error bars represent the Standard Error Mean. The potential of Enhanced Rock Weathering (EW) to mitigate carbon dioxide emissions was calculated using two carbon removal (CDR) rates (Larkin et al., 2022; Ryan et al., 2024), representing a high and low scenario. The CDR rates were multiplied by 10% of the global harvested area for cacao cultivation (Faostat, 2024) to generate a mitigation value, which was subtracted from the original average production emissions for each system. See Dataset S1 for further information.

(Vienne et al., 2022). To address these concerns, Brazil, recognised as a global leader in the application of natural rock powders for soil remineralisation, has implemented regulatory measures to manage the chemical risks associated with rock dust applications in agriculture (Presidncia da Repblica, 2013). Careful selection of rock sources, combined with rigorous and transparent monitoring of trace element concentrations, is crucial for balancing the climate mitigation potential of EW with its social acceptance and environmental safety considerations (Levy et al., 2024).

The slow release of nutrients from EW necessitates the presence of healthy soil organic matter (SOM) to support sustained plant growth and heterotrophic soil respiration, which in turn elevates CO_2 levels in the soil air, increasing EW efficiency for soil carbon sequestration (Bertagni et al., 2025). Evidence suggests that finely ground silicate rock residues can increase mineral-associated SOM by 22%, as a result of the release of Al and Fe forming poorly crystalline minerals (e.g., imogolite, allophane, ferrihydrite) which interact with SOM to form complexes protected from microbial decomposition (Buss et al., 2024; Xu et al., 2024). Similarly, a study reported a positive correlation between weathering rates and soil organic carbon storage in regions characterised by high humidity and mineral abundance at temperate locations (Slessarev et al., 2022). However, redox fluctuations characteristic of tropical systems with alternating dry and wet seasons put into question the stability of the newly formed complexes, necessitating further research into rock weathering-SOM interactions at tropical EW trials (Chen et al., 2020).

An incubation experiment reported a substantial increase in soil CO_2 efflux following the application of wollastonite, a widely used mineral in EW, suggesting faster SOM decomposition (Yan et al., 2023). These findings suggest that EW may accelerate SOM mineralisation, especially in acidic soils, and potentially induce a "priming effect," whereby microbial activity stimulates the decomposition of existing SOM (Fang et al., 2023). A two-year trial conducted in the United States observed a decline in mineral-associated organic matter following silicate rock application; however, this was not accompanied by a corresponding reduction in soil organic carbon (Sokol et al., 2024). This could be understood by the increase in soil pH, influencing the decomposition of organic matter and microbial activity, responsible for the degradation and mineralisation of carbon. Conversely, there is evidence to suggest that in agroforestry systems, an increase in pH is associated with greater organic carbon retention, increased biomass and microbial activity, favouring the stabilisation of organic carbon (Soilueang et al., 2025).

Application of crushed silicate rock has the potential to enhance soil fertility and cation exchange capacity (CEC) in highly weathered tropical Oxisols (Gillman, 1980). Soil CEC is a measure of the negative charge of the solid phase of soil balanced by exchangeable cations (mEq/100 g) and describes the number of cations in the soil solution that are exchangeable, and therefore available for uptake by plant roots (Reganold & Harsh, 1985; Wang et al., 2023). Understanding soil nutrient dynamics is essential for optimising agricultural practices and meeting the increasing global demand for cacao. Although studies are limited, under field conditions, basalt application can significantly increase cocoa growth, as evidenced by increasing stem height and diameter over 24 months (Anda et al., 2013). Building on these findings that basalt amendments enhance overall soil nutrient status and promote cacao growth, it is crucial to examine the role of individual macronutrients in sustaining and further improving cacao production.

Potassium (K) is a key macronutrient for cacao production, promoting root development (Nguyen et al., 2002) and enhancing water stress tolerance, which improves the plant's resilience to environmental conditions (Boyer, 1973). Potassium is also essential for pod and bean development, with cacao pods containing 4.2–5.5% K in dry matter and beans containing 2.2–2.4% K (Mengel, 1980). Given that cacao cultivation depletes K from trees, it has long been established that K replacement requirements are directly linked to yield (Mengel, 1980). Field trials have demonstrated that K supplementation enhances cacao growth (Kaba et al., 2022). Basalt application as an EW amendment has been proposed as a source of K for cacao cultivation. Studies indicate that plants in tropical soils can access K from silicate rock amendments (Manning et al., 2017). A four-year field trial in the U.S. Corn Belt found that annual applications of crushed basalt (50 t ha^{-1}) released at least 23 kg K ha^{-1} y^{-1} (Beerling et al., 2024), in addition to potential increases in available K due to changes in soil pH. While this amount may be sufficient for average-yielding cacao trees, it is unlikely to meet the K demands of high-yielding trees or those in K-deficient soils (Mengel, 1980; Snoeck et al., 2016). However, there is an obvious need to generate K release rates during EW with a range of feedstocks in cacao agroecosystems.

The effectiveness of basalt as an alternative to chemical K fertilisers may depend on the specific agricultural system. Bahia et al. (2021) found that in shaded systems, there was a lower need for N, P and S and a greater need for K by cocoa trees compared to cacao grown in full-sun systems. Consequently, shade levels must be considered when assessing the fertilisation potential of EW, as responses may vary across different management systems (Ahenkorah et al., 1987). Given these factors, basalt application may be most effective as a supplement to conventional fertilisers, potentially reducing environmental impacts and costs associated with chemical fertilisation.

Phosphorus (P) is also a critical, commonly limiting nutrient in cacao cultivation, contributing to flowering, dry matter production and canopy development, which enhances light capture and photosynthetic efficiency (Asomaning et al., 1971). However, P availability in tropical soils is often limited due to fixation in unavailable forms, particularly in highly weathered, acidic conditions (Chacón et al., 2008). Soil pH plays a key role in regulating phosphate availability, as it influences the adsorption of phosphate anions onto soil colloids (Devau et al., 2009). Higher pH levels increase the solubility of iron and aluminium phosphates, reducing phosphate fixation and improving P availability (Sandim et al., 2014). Given these constraints, P deficiencies can limit cacao productivity, necessitating effective fertilisation strategies that align with the agricultural practices and tree health. Older, unshaded cacao plantations require higher P inputs than younger trees grown under shade (Ahenkorah et al., 1974; Ahenkorah et al., 1987). Additional studies have shown that P supplementation can enhance productivity and improve the effects of N, particularly in low-yielding trees (Isaac et al., 2011; Snoeck et al., 2010; Wessel, 1971).

Given the challenges of P fixation in tropical soils, EW may improve P availability over time. Silicon-rich rock amendments have been shown to increase soil P availability by promoting competition between silicate and phosphate anions for adsorption sites (Sandim et al., 2014). In a tropical rubber plantation, EW using wollastonite increased total soil P levels and P availability through enhanced microbial P cycling and the release of root exudates in a two-year field experiment (Bi et al., 2024). Basalt, which shares similar mineral properties with wollastonite, may also serve as a slow-release source of P. A four-year field trial in the U.S. Corn Belt found that annual applications of crushed basalt (50 t ha^{-1}) released at least 7 kg P ha^{-1} y^{-1} (Beerling et al., 2024), but as with K, release rates are needed for cacao sites.

Nitrogen (N) fertilisation stimulates leaf flushing, canopy formation and vegetative growth, influencing cacao yield, especially in younger trees (Cañarte et al., 2023). While basalt application will not directly increase levels of N through its mineralogy, it has been shown to significantly reduce N leaching from the soil. The average decrease in N leaching has been estimated to be as high as 45% upon basalt amendment (Vienne et al., 2022), possibly due to Mo released during weathering, which is a central co-factor in the nitrogenase enzymes of bacteria involved in N_2-fixation to ammonia (Seefeldt et al., 2009; Epihov et al., 2017). Additionally, basalt application can enhance N assimilation and nitrogen use efficiency (Beerling et al., 2024). This may be through increased availability of soil Mo for plant uptake, which is often limited in acidic tropical soils (Barron et al., 2009). At a long-term trial in the US corn belt, Mo was shown to mechanistically increase nitrogen use efficiency through upregulated expression of a Mo co-factor, important for N cycle enzymes, within plants in response to basalt treatment (Beerling et al., 2024). Increases in available Mo may therefore enhance asymbiotic N_2-fixation by free-living soil bacteria (Epihov et al., 2021) and further contribute to the N nutrition of cacao, particularly in unfertilised or organic settings.

A further co-benefit of N retention could be a reduction in N_2O emissions, a potent GHG with a GWP of up to 298 times that of CO_2 (Mosca et al., 2014). One modelling study using field observations in the US predicted N_2O emissions could decrease by 16% in maize and 9% in miscanthus (Blanc-Betes et al., 2020). This result is supported by a maize mesocosm in the US in which cumulative N_2O emissions were reduced by 29–32% upon a basalt application of 5 t acre, likely caused by increased soil alkalinity and changes in soil structure (Chiaravalloti et al., 2023). Extrapolating to five regions that have high CDR potential (North America, Brazil, Europe, India and China), EW was shown in one model to reduce emissions from N_2O and NO by 18% but increase NH_3 by 2% (Val Martin et al., 2023). Despite limited corroboration from field trials, the curtailment of non-CO_2 emissions offers an additional mechanism to reduce the GHG footprint of cacao production.

Calcium (Ca) and magnesium (Mg) are necessary for healthy cacao seedlings and plant vigour (Carmona Rojas et al., 2022). Calcium, among a wide range of critical functions in cacao (see Lubis et al., 2022), contributes to cell wall integrity (Van Stkveninck, 1965) and disease resistance (Butler & Engelhard, 1990). For instance, higher Ca levels can reduce susceptibility to pathogens such as *Phytophthora* spp. (Campanella et al., 2002). Meanwhile, Mg is essential for chlorophyll synthesis and enzyme activation, facilitating photosynthetic activity and metabolic processes within the plant (Ishfaq et al., 2022). Basalt applications have been demonstrated to elevate levels of both Ca and Mg in the soil solution through multiple trials (Conceição et al., 2022; Plata et al., 2021). In fertiliser trials, specific nutrient ratios of Ca/Mg have exhibited positive correlations with cacao yield (Marrocos et al., 2020), and rock dissolution could impact these crucial ratios.

The essential micronutrients (B, Cl, Cu, Fe, Mn, Mo, Ni and Zn) and the elements not yet widely recognised as essential but which can contribute to the development of crops (Co, Se, Na and Si), are of vital importance for cultivated plants (Chepote et al., 2013; Epstein & Bloom, 2004; Souza et al., 2018; Taiz et al., 2014). Of these, zinc (Zn) is the micronutrient with the highest frequency of deficiency in soils cultivated with cocoa trees; essential for auxin prevention, enzyme activation, carbohydrate formation and indoleacetic acid (IAA); its deficiency results in shortening of the internodes and cell reduction (Chepote et al., 2013; Souza et al., 2018). The use of silicate rocks on soils with low starting TE contents may induce a 'micronutrient fertilisation effect' and alleviate issues associated with zinc deficiency (Dupla et al., 2023).

Except for Fe, Cl, Mo and Ni, whose demand for cacao is often met due to low requirements or indirect supply, other micronutrients require regular supplementation. In this context, the application of silicate rocks, containing traces of micronutrients in their composition, represents a viable alternative to complement the supply of these elements. Sodium (Na), classified as a beneficial element, may perform functions similar to those of potassium (K) (Epstein & Bloom, 2004). Gattward et al. (2012) demonstrated that, in clonal cocoa seedlings, the partial replacement of K by Na resulted in greater net photosynthesis and water use efficiency. In addition, studies indicate that the application of small doses of Na can stimulate the rooting and production of cocoa fruits, without compromising clay flocculation, soil aggregation and porosity (Erwiyono et al., 2002). These findings highlight the need for further research on the role of Na in cocoa cultivation, especially considering its presence in silicate rocks.

Silicon (Si) application to cacao can increase photosynthesis, formation of lignin, stomatal density (Fantinato et al., 2018) and protection from harmful UV-B radiation (Zanetti et al., 2023), leading to structural integrity in cacao plants. Importantly, Si content in plants is essential for disease defence (Fantinato et al., 2018) and stress resistance (Eneji et al., 2008), along with tolerance to heavy metals (Liu et al., 2020). However, cacao is often grown on highly weathered soils, and the reservoir of silicate minerals is frequently in crystalline structures with slow dissolution rates (De Tombeur et al., 2020) and plant-available Si pools can become depleted over time (De Tombeur et al., 2020). The potential of EW to increase plant-available Si remains a subject of debate. While silicate rock dust dissolution can release Si into the soil (Reynaert et al., 2023), the associated increase in soil pH may reduce Si bioavailability (Meunier et al., 2018). Si release rates vary depending on soil type, as pH influences the reactivity of different soil Si pools (Lim et al., 2023). Nonetheless, studies on basalt (Kelland et al., 2020) and wollastonite (Jariwala et al., 2022)

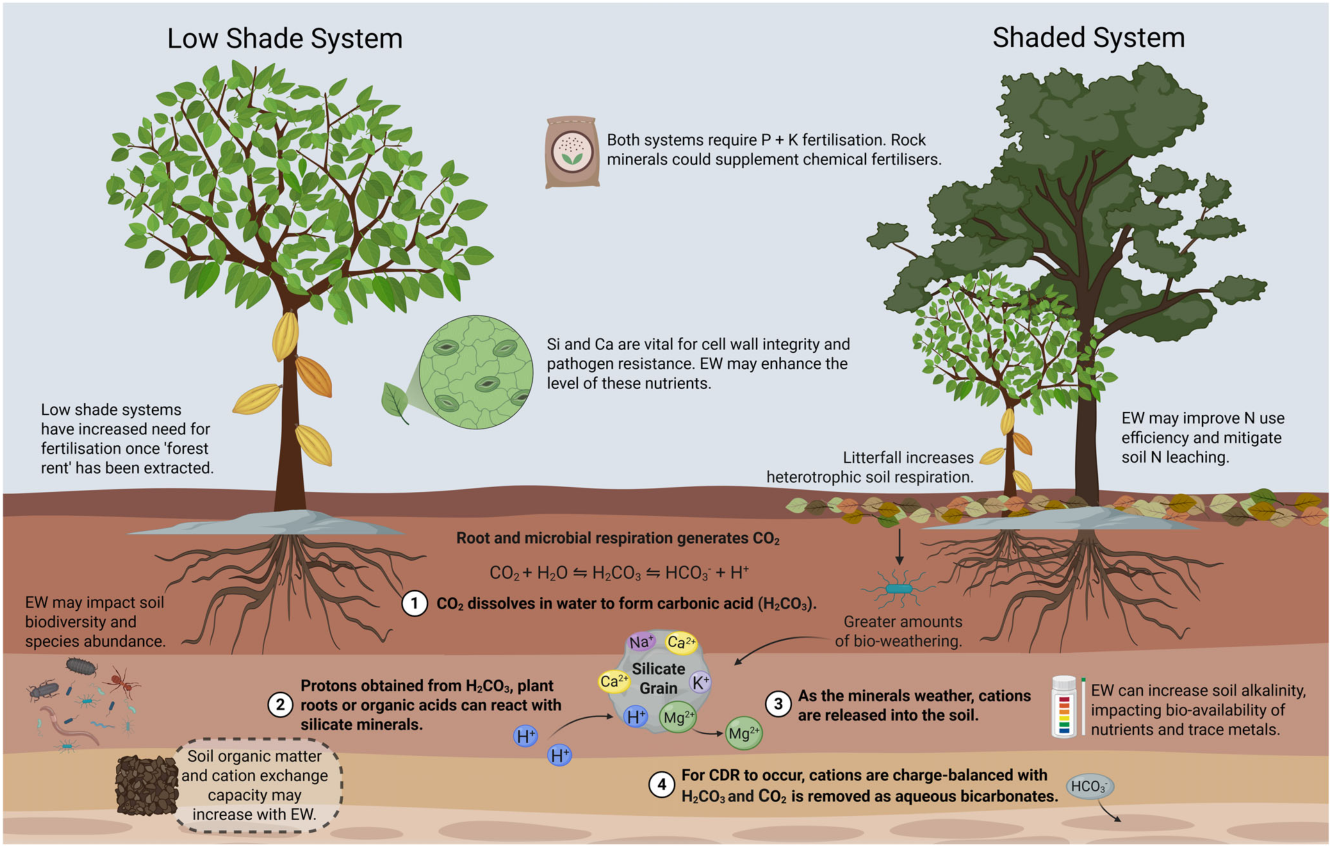

FIGURE 5 **Potential Co-benefits of Enhanced Weathering for Cacao-Agroforestry.** (Steeley, 2025).

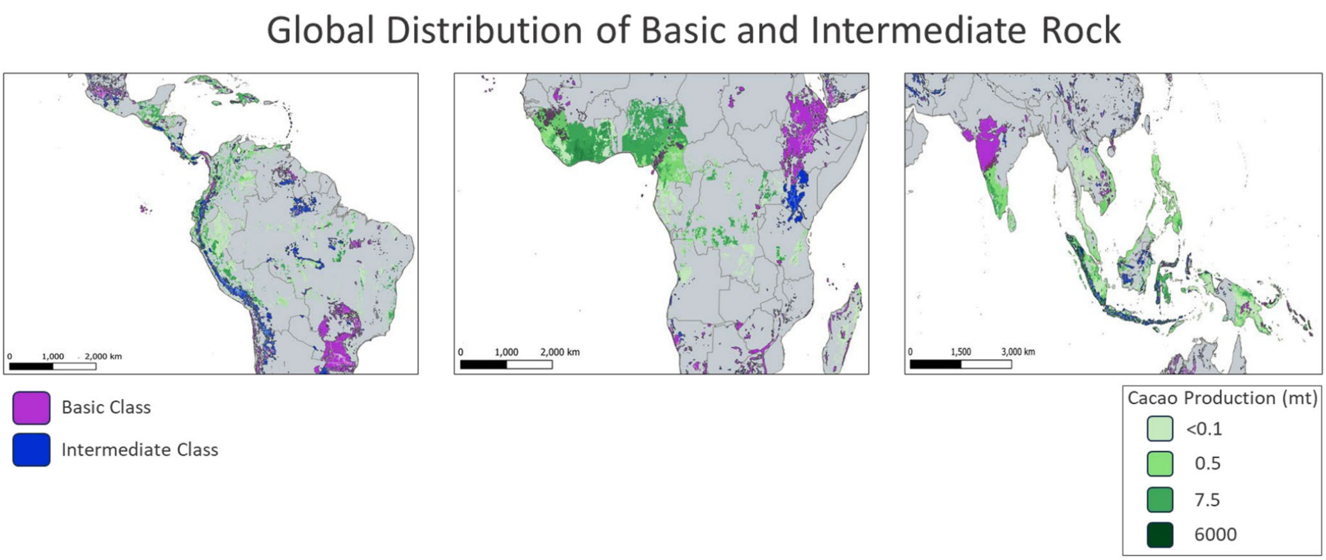

FIGURE 6 **Global lithology distribution map of Basic and Intermediate rock.** Rock sources were identified from the GLiM rock database and rock class is classified as detailed in Hartmann et al., 2013. Cacao production was retrieved from International Food Policy Research Institute (IFPRI)., 2024. Map was created in QGIS software (https://qgis.org) and with Natural Earth physical vectors (scale 1:10 m). Map does not represent all silicate rock deposits or cacao producing areas.

have demonstrated increased plant-available Si in the short term during mesocosm incubations, as pH increases are relatively limited after a single rock dust application. However, long-term trials in the US Corn Belt (Beerling et al., 2024) and Malaysia (unpublished data) show that basalt-amended crops do not benefit from increases in biomass Si, as the stable 0.5–1.0 pH unit increase in soil promotes Si adsorption into an amorphous opaline pool not immediately available to plants. These findings suggest that silicate rock weathering may offer a viable and sustainable strategy for replenishing depleted Si pools in agricultural soils.

These findings highlight the potential of EW materials in cacao cultivation, although current research has primarily focused on short-term effects, necessitating long-term studies for sustainability assessment. Variability in silicate rock composition and soil-specific interactions requires further investigation, urging comprehensive geochemical analyses. Evaluating rock dust's influence on soil microbial communities and resilience to climate change stressors is imperative. In conclusion, while previous studies have addressed the potential benefits of EW application in cacao farming, ongoing research is essential to fully understand its impact on soil health, productivity and nutrient cycling; refer to Figure 5.

5 | FEASIBILITY

The feasibility of implementing EW practices in cacao farming depends, in part, on the proximity of farms to sources of weatherable silicate rock feedstock (e.g., basalt, gabbro, andesite, pyroxenite), as this relationship influences both transportation costs and the GHG emissions associated with material distribution (Eufrasio et al., 2022). Geographic separation introduces logistical and economic complexities for EW implementation. For instance, in a life cycle assessment of EW in São Paulo State, 990 ± 116 km was the limit for basalt transport above which the emissions associated with transport severely limit the potential capture (Lefebvre et al., 2019). By strategically utilising existing infrastructure for agricultural lime distribution and repurposing basalt waste, disruption to established practices can be minimised while reducing environmental impact. For cases where natural silicate rock deposits are located far from established cacao farms, refer to Figure 6; alternative CDR and sustainability strategies may be more appropriate. As demonstrated by Eufrasio et al. (2022), a clean energy mix and electrification of transport and rock grinding processes will improve the environmental and sustainability capacity of EW. Therefore, the CDR potential of EW on cacao farms needs to be determined holistically. Addressing these logistical tasks could support a challenging but potentially transformative solution for carbon sequestration in the cocoa industry.

6 | ADOPTION AND APPLICATION

EW could sustainably boost yields and reduce liming and fertilisation costs, with carbon credits helping to offset silicate rock application expenses and improve financial viability for farmers. However, as seen with other sustainability payment initiatives such as the Ghana Cocoa REDD+ (Reducing Emissions from Deforestation and Forest Degradation), engagement and uptake will be low if policy backing is weak and the financing does not improve living income for farmers and cover costs to transition (Dugasseh & Zandersen, 2025). Using current technologies to track CDR, monitoring and verification (MRV) processes for EW is labour-intensive, along with the physical spreading of the rock dust. Interventions to improve yield in smallholder farmers, including pest and disease management, received poor uptake when the increased production was not sufficient to cover the labour costs associated with the management practice (Scudder et al., 2022). Therefore, to increase adoption, low-cost MRV needs to be developed along with careful design of rock application rates. To minimise the machinery and labour costs associated with spreading, high rates, representing multiple applications of rock

TABLE 2 Knowledge Gaps in Enhanced Rock Weathering.

Knowledge Gap	Description
Quantifying Carbon Sequestration	Accurate measurement of carbon removal (CDR) through enhanced rock weathering (EW) remains challenging. Robust methodologies are needed to assess weathering rates, carbon storage and associated co-benefits, particularly in diverse agroforestry settings.
Biodiversity Impacts	The potential effects of EW on biodiversity within cocoa agroforestry systems, including shade trees and associated fauna, require further investigation.
Nutrient Cycling Dynamics	A deeper understanding of EW's impact on nutrient cycling, including nitrogen (N) dynamics, phosphorus (P) availability, and the release of potentially toxic elements, is crucial for optimising its application in cocoa production.
Soil & Rock Grain Microbial Interactions	The interplay between EW, soil properties and microbial communities remains poorly understood. Research is needed to determine how EW influences microbial activity, organic matter decomposition and nutrient availability.
Long-Term Effects	Most studies focus on short-term impacts. Long-term field trials are needed to assess the sustainability of EW practices and their effects on soil health, crop productivity and ecosystem services.
N_2O Emissions	The impact of EW on N_2O emissions is under-researched and could present an additional pathway to reducing cacao's climate impacts.
Socioeconomic Considerations	Research is needed to evaluate the economic feasibility and social acceptability of EW for cocoa farmers, including equitable benefit-sharing mechanisms and strategies to mitigate social and environmental risks.

dust, could be spread before the trees are planted, with further applications being targeted around the base of the tree, at the width of the canopy, where root density and therefore agronomic benefits will be highest.

Beyond logistical considerations, the application of finely crushed rock dust poses potential risks to human health, particularly for individuals directly involved in its handling and distribution. Fine particulate matter has been associated with respiratory risks, including silicosis, a condition linked to the inhalation of silica particles (Merget et al., 2002). Such risks may be higher without appropriate protective equipment, such as masks or respirators. For smallholder farmers in resource-limited settings, limited access to safety measures could increase the likelihood of adverse health outcomes. Addressing these challenges may require investment in technologies and training programs tailored to the needs of smallholder farmers, along with the provision of protective equipment, to mitigate health risks associated with rock dust application.

7 | KNOWLEDGE GAPS IN ENHANCED ROCK WEATHERING FOR COCOA AGROFORESTRY

This review highlights several critical knowledge gaps that hinder the effective implementation of EW in cocoa agroforestry systems, which are listed in Table 2.

8 | CONCLUSION

Cacao production faces complex and interlinked challenges, including low yields, poverty among smallholder farmers and substantial environmental impacts caused by land-use change and input-intensive practices. This review highlights the potential of integrated climate-smart strategies, specifically agroforestry and enhanced rock weathering, to mitigate greenhouse gas emissions, enhance soil health and improve climate resilience. However, key knowledge gaps persist regarding long-term effects, nutrient cycling and the socio-economic feasibility of these approaches. Given the multidimensional nature of these challenges, multifaceted, systemic responses are essential. The cocoa sector must adapt through scalable, evidence-based interventions that align environmental sustainability with the economic realities of smallholder farming systems.

AUTHOR CONTRIBUTIONS

I.L.S., E.S.F., D.Z.E., N.J.P and D.J.B wrote the manuscript.

ACKNOWLEDGEMENT

We acknowledge the financial support of the Biotechnology and Biological Sciences Research Council (BBSRC) and Mondelēz International, Inc. (Project Reference: 2850515). The authors would like to thank the editorial team and the anonymous reviewers for their insightful comments and suggestions, which significantly improved the manuscript. The authors would also like to thank Euripides Kantzas for his insight on GIS mapping.

CONFLICT OF INTEREST STATEMENT

D.J.B has a minority equity stake in companies (Future Forest/Undo) and is an advisory board member of The Carbon Community, a UK carbon removal charity. N.J.P. was a co-founder of the CDR company Lithos Carbon but has no remaining financial ties to the company. E.S. F is an independent contractor at the Cocoa Innovation Centre, which is part of the Southern Bahia Science and Technology Park. The remaining authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in FAOSTAT at https://www.fao.org/faostat/en/#data/QCL, reference number 44. These data were derived from the following resources available in the public domain: International Food Policy Research Institute (IFPRI). (2024). Global Spatially-Disaggregated Crop Production Statistics Data for 2020 10.7910/DVN/SWPENT.

ORCID

Isabella L. Steeley https://orcid.org/0009-0002-3544-5811
Edson S. França https://orcid.org/0009-0001-7277-3091
Dimitar Z. Epihov https://orcid.org/0000-0001-5711-5480
Noah J. Planavsky https://orcid.org/0000-0001-5849-8508
David J. Beerling https://orcid.org/0000-0003-1869-4314

REFERENCES

Agyeman-Boaten, S. Y., & Fumey, A. (2021). Effects of cocoa swollen shoot virus disease (CSSVD) on the welfare of cocoa farmers in Ghana: evidence from Chorichori community of the Sefwi Akontombra district. *SN Business & Economics*, *1*(11), 149. https://doi.org/10.1007/s43546-021-00152-8

Ahenkorah, Y., Akrofi, G. S., & Adri, A. K. (1974). The end of the first cocoa shade and manurial experiment at the Cocoa Research Institute of Ghana. *Journal of Horticultural Science*, *49*(1), 43–51. https://doi.org/10.1080/00221589.1974.11514550

Ahenkorah, Y., Halm, B. J., Appiah, M. R., Akrofi, G. S., & Yirenkyi, J. E. K. (1987). Twenty years' results from a shade and fertilizer trial on Amazon cocoa (*Theobroma cacao*) in Ghana. *Experimental Agriculture*, *23*(1), 31–39. https://doi.org/10.1017/S0014479700001101

Alemagi, D., Duguma, L., Minang, P. A., Nkeumoe, F., Feudjio, M., & Tchoundjeu, Z. (2015). Intensification of cocoa agroforestry systems as a REDD+ strategy in Cameroon: Hurdles, motivations, and challenges. *International Journal of Agricultural Sustainability*, *13*(3), 187–203. https://doi.org/10.1080/14735903.2014.940705

Amponsah-Doku, B., Daymond, A., Robinson, S., Atuah, L., & Sizmur, T. (2022). Improving soil health and closing the yield gap of cocoa production in Ghana – A review. *Scientific African*, *15*, e01075. https://doi.org/10.1016/j.sciaf.2021.e01075

Anda, M., Shamshuddin, J., & Fauziah, C. I. (2013). Increasing negative charge and nutrient contents of a highly weathered soil using basalt and rice husk to promote cocoa growth under field conditions. *Soil and Tillage Research*, *132*, 1–11. https://doi.org/10.1016/j.still.2013.04.005

Andres, C., Blaser, W. J., Dzahini-Obiatey, H. K., Ameyaw, G. A., Domfeh, O. K., Awiagah, M. A., Gattinger, A., Schneider, M., Offei, S. K., & Six, J. (2018). Agroforestry systems can mitigate the severity of cocoa swollen shoot virus disease. *Agriculture, Ecosystems & Environment*, *252*, 83–92. https://doi.org/10.1016/j.agee.2017.09.031

Aneani, F., & Ofori-Frimpong, K. (2013). An analysis of yield gap and some factors of cocoa (*Theobroma cacao*) yields in Ghana. *Sustainable Agriculture Research*, *2*(4), 117. https://doi.org/10.5539/sar.v2n4p117

Appiah, M., Ofori-Frimpong, K., & Afrifa, A. (2000). Evaluation of fertilizer application on some peasant cocoa farms in Ghana. *Ghana Journal of Agricultural Science*, *33*(2), 183–190. https://doi.org/10.4314/gjas.v33i2.1869

Araujo, Q., Ahnert, D., Loureiro, G., Faria, J., Fernandes, C., & Baligar, V. (2018). Soil quality index for cacao cropping systems. *Archives of Agronomy and Soil Science*, *64*(13), 1892–1909. https://doi.org/10.1080/03650340.2018.1467005

Armengot, L., Beltrán, M. J., Schneider, M., Simón, X., & Pérez-Neira, D. (2021). Food-energy-water nexus of different cacao production systems from a LCA approach. *Journal of Cleaner Production*, *304*, 126941. https://doi.org/10.1016/j.jclepro.2021.126941

Asare, R., Afari-Sefa, V., Osei-Owusu, Y., & Pabi, O. (2014). Cocoa agroforestry for increasing forest connectivity in a fragmented landscape in Ghana. *Agroforestry Systems*, *88*(6), 1143–1156. https://doi.org/10.1007/s10457-014-9688-3

Asomaning, E. J. A., Kwakwa, R. S., & Hutcheon, W. (1971). Physiological studies on an Amazon shade and fertilizer trial at the Cocoa Research Institute, Ghana. *Ghanaian Journal of Agricultural Science*, *4*(1), 47–64.

Baek, S. H., Kanzaki, Y., Lora, J. M., Planavsky, N., Reinhard, C. T., & Zhang, S. (2023). Impact of climate on the global capacity for enhanced rock weathering on croplands. *Earth's Future*, *11*(8), e2023EF003698. https://doi.org/10.1029/2023EF003698

Bahia, B. L., Souza-Júnior, J. O., Fernandes, L. v., & Neves, J. C. L. (2021). Reference values and diagnostic ranges to assess the degree of nutritional balance for cacao plants. *Spanish Journal of Agricultural Research*, *19*(1), e0801. https://doi.org/10.5424/sjar/2021191-17478

Baligar, V. C., & Fageria, N. K. (2005). Soil Science and Plant Nutrition Soil Aluminum Effects on Growth and Nutrition of Cacao Soil Aluminum Effects on Growth and Nutrition of Cacao. Soil Science and Plant Nutrition Soil Sci. Plant Nuti, 515.

Barron, A. R., Wurzburger, N., Bellenger, J. P., Wright, S. J., Kraepiel, A. M. L., & Hedin, L. O. (2009). Molybdenum limitation of asymbiotic nitrogen fixation in tropical forest soils. *Nature Geoscience*, *2*(1), 42–45. https://doi.org/10.1038/ngeo366

Beerling, D. J., Epihov, D. Z., Kantola, I. B., Masters, M. D., Reershemius, T., Planavsky, N. J., Reinhard, C. T., Jordan, J. S., Thorne, S. J., Weber, J., Val Martin, M., Freckleton, R. P., Hartley, S. E., James, R. H., Pearce, C. R., DeLucia, E. H., & Banwart, S. A. (2024). Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(9), e2319436121. https://doi.org/10.1073/pnas.2319436121

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J. F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9

Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., Bird, M., Kantzas, E., Taylor, L. L., Sarkar, B., Kelland, M., DeLucia, E., Kantola, I., Müller, C., Rau, G., & Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security. *Nature Plants*, *4*(3), 138–147. https://doi.org/10.1038/s41477-018-0108-y

Beg, M. S., Ahmad, S., Jan, K., & Bashir, K. (2017). Status, supply chain and processing of cocoa - A review. *Trends in Food Science & Technology*, *66*, 108–116. https://doi.org/10.1016/j.tifs.2017.06.007

Benefoh, D. T., Villamor, G. B., van Noordwijk, M., Borgemeister, C., Asante, W. A., & Asubonteng, K. O. (2018). Assessing land-use typologies and change intensities in a structurally complex Ghanaian cocoa landscape. *Applied Geography*, *99*, 109–119. https://doi.org/10.1016/j.apgeog.2018.07.027

Bensch, G., Kaestner, K., & Vance, C. (2023). Pass-through of cocoa prices along the supply chain: What's left for farmers in Côte D'Ivoire? Ruhr Economic Papers, RWI – Leibniz-Institut Für Wirtschaftsforschung, Essen, 1035. https://doi.org/10.4419/96973204

Bertagni, M. B., Calabrese, S., Cipolla, G., Noto, L. v., & Porporato, A. (2025). Advancing enhanced weathering modeling in soils: Critical comparison with experimental data. *Journal of Advances in Modeling Earth Systems*, *17*(1), e2024MS004224. https://doi.org/10.1029/2024MS004224

Bi, B., Li, G., Goll, D. S., Lin, L., Chen, H., Xu, T., Chen, Q., Li, C., Wang, X., Hao, Z., Fang, Y., Yuan, Z., & Lambers, H. (2024). Enhanced rock weathering increased soil phosphorus availability and altered root phosphorus-acquisition strategies. *Global Change Biology*, *30*(5), e17310. https://doi.org/10.1111/gcb.17310

Billings, S. A., Hirmas, D., Sullivan, P. L., Lehmeier, C. A., Bagchi, S., Min, K., Brecheisen, Z., Hauser, E., Stair, R., Flournoy, R., & de Richter, D. B. (2018). Loss of deep roots limits biogenic agents of soil development that are only partially restored by decades of forest regeneration. *Elementa: Science of the Anthropocene*, *6*, 34. https://doi.org/10.1525/elementa.287

Blanc-Betes, E., Kantola, I. B., Gomez-Casanovas, N., Hartman, M. D., Parton, W. J., Lewis, A. L., Beerling, D. J., & DeLucia, E. H. (2020). In silico assessment of the potential of basalt amendments to reduce N_2O emissions from bioenergy crops. *GCB Bioenergy*, *13*(1), 224–241. https://doi.org/10.1111/gcbb.12757

Blaser, W. J., Oppong, J., Hart, S. P., Landolt, J., Yeboah, E., & Six, J. (2018). Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nature Sustainability*, *1*(5), 234–239. https://doi.org/10.1038/s41893-018-0062-8

Bloom, P., & Inskeep, W. (1986). Factors affecting bicarbonate chemistry and iron chlorosis in soils. *Journal of Plant Nutrition*, *9*(3), 215–228. https://doi.org/10.1080/01904168609363438

Bossolani, J. W., Crusciol, C. A. C., Merloti, L. F., Moretti, L. G., Costa, N. R., Tsai, S. M., & Kuramae, E. E. (2020). Long-term lime and gypsum amendment increase nitrogen fixation and decrease nitrification and denitrification gene abundances in the rhizosphere and soil in a tropical no-till intercropping system. *Geoderma*, *375*, 114476. https://doi.org/10.1016/j.geoderma.2020.114476

Boyer, J. (1973). Cycles de la matière organique et des éléments minéraux dans une cacaoyère Camerounaise. *Café Cacao Thé*, *XVII*(1), 3–24.

Buss, W., Hasemer, H., Ferguson, S., & Borevitz, J. (2024). Stabilisation of soil organic matter with rock dust partially counteracted by plants. *Global Change Biology*, *30*(1), e17052. https://doi.org/10.1111/gcb.17052

Butler, E. E., & Engelhard, A. W. (1990). Soilborne Plant Pathogens: Management of Diseases with Macro- and Microelements. *Mycologia*, *82*(4), 538. https://doi.org/10.2307/3760036

Caicedo-Vargas, C., Pérez-Neira, D., Abad-González, J., & Gallar, D. (2022). Assessment of the environmental impact and economic performance of cacao agroforestry systems in the Ecuadorian Amazon region: An LCA approach. *Science of the Total Environment*, *849*, 157795. https://doi.org/10.1016/j.scitotenv.2022.157795

Campanella, V., Ippolito, A., & Nigro, F. (2002). Activity of calcium salts in controlling Phytophthora root rot of citrus. *Crop Protection*, *21*(9), 751–756. https://doi.org/10.1016/S0261-2194(02)00032-7

Cañarte, C., Jaimez, R., & Màrquez, V. (2023). Effects of pruning and nitrogen fertilization on flushing and pod production in cacao. *Tropical and Subtropical Agroecosystems*, *26*(1). https://doi.org/10.56369/tsaes.4421

Carmona Rojas, L. M., Gutiérrez Rodríguez, E. A., Henao Ramirez, A. M., & Urrea Trujillo, A. I. (2022). Nutrition in cacao (Theobroma cacao L.) crops: What determining factors should be considered? *Revista de la*

Facultad de Agronomía, *121*(Especial 2), 101. https://doi.org/10.24215/16699513e101

Cassano, C. R., Schroth, G., Faria, D., Delabie, J. H. C., & Bede, L. (2009). Landscape and farm scale management to enhance biodiversity conservation in the cocoa producing region of southern Bahia, Brazil. *Biodiversity and Conservation*, *18*(3), 577–603. https://doi.org/10.1007/s10531-008-9526-x

Chacón, N., Dezzeo, N., Rangel, M., & Flores, S. (2008). Seasonal changes in soil phosphorus dynamics and root mass along a flooded tropical forest gradient in the lower Orinoco River, Venezuela. *Biogeochemistry*, *87*(2), 157–168. https://doi.org/10.1007/s10533-007-9174-3

Chen, C., Hall, S. J., Coward, E., & Thompson, A. (2020). Iron-mediated organic matter decomposition in humid soils can counteract protection. *Nature Communications*, *11*(1), 2255. https://doi.org/10.1038/s41467-020-16071-5

Chepote, R. E., Sodré, G. A., Reis, E. L., Pacheco, R. G., Marrocos, P. C. L., & Valle, R. R. (2013). Recommendations for correctives and fertilizers in cocoa crop in southeastern Bahia. Technical Bulletin n. 203. Ilhéus: CEPLAC/CEPEC, p.10-43

Chiaravalloti, I., Theunissen, N., Zhang, S., Wang, J., Sun, F., Ahmed, A. A., Pihlap, E., Reinhard, C. T., & Planavsky, N. J. (2023). Mitigation of soil nitrous oxide emissions during maize production with basalt amendments. *Frontiers in Climate*, *5*, 1203043. https://doi.org/10.3389/fclim.2023.1203043

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T. C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Dwi Putra, D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C. H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., … Tscharntke, T. (2011). Combining high biodiversity with high yields in tropical agroforests. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(20), 8311–8316. https://doi.org/10.1073/pnas.1016799108

Cocoaprice - chart - historical data – news. (n.d.) Cocoa - Price - Chart - Historical Data - News. Retrieved April 24, 2024 from https://tradingeconomics.com/commodity/cocoa

Conceição, L. T., Silva, G. N., Holsback, H. M. S., Oliveira, C. d. F., Marcante, N. C., Martins, É. d. S., Santos, F. L. d. S., & Santos, E. F. (2022). Potential of basalt dust to improve soil fertility and crop nutrition. *Journal of Agriculture and Food Research*, *10*, 100443. https://doi.org/10.1016/j.jafr.2022.100443

De Almeida Leite, R., Martins da Costa, E., Cabral Michel, D., do Amaral Leite, A., de Oliveira-Longatti, S. M., de Lima, W., Konstantinidis, K. T., & de Souza Moreira, F. M. (2024). Genomic insights into organic acid production and plant growth promotion by different species of phosphate-solubilizing bacteria. *World Journal of Microbiology and Biotechnology*, *40*(10), 311. https://doi.org/10.1007/s11274-024-04119-3

De Tombeur, F., Turner, B. L., Laliberté, E., Lambers, H., Mahy, G., Faucon, M. P., Zemunik, G., & Cornelis, J. T. (2020). Plants sustain the terrestrial silicon cycle during ecosystem retrogression. *Science*, *369*(6508), 1245–1248. https://doi.org/10.1126/SCIENCE.ABC0393

Devau, N., le Cadre, E., Hinsinger, P., Jaillard, B., & Gérard, F. (2009). Soil pH controls the environmental availability of phosphorus: Experimental and mechanistic modelling approaches. *Applied Geochemistry*, *24*(11), 2163–2174. https://doi.org/10.1016/j.apgeochem.2009.09.020

Dietzen, C., & Rosing, M. T. (2023). Quantification of CO2 uptake by enhanced weathering of silicate minerals applied to acidic soils. *International Journal of Greenhouse Gas Control*, *125*, 103872. https://doi.org/10.1016/j.ijggc.2023.103872

Doe, E. K., Attua, E. M., Dogbatse, J. A., & Fosu-Mensah, B. Y. (2022). Assessing the condition and capability of soils in cocoa districts of Ghana using geovisualization. *Soil Security*, *7*, 100058. https://doi.org/10.1016/j.soisec.2022.100058

Dugasseh, F. A., & Zandersen, M. (2025). Farmer perceptions of REDD+ livelihood interventions as incentive mechanism for reducing deforestation in the Juabuso-Bia cocoa forest landscape. *Forest Policy and Economics*, *175*, 103494. https://doi.org/10.1016/j.forpol.2025.103494

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

Edwards, D. P., Lim, F., James, R. H., Pearce, C. R., Scholes, J., Freckleton, R. P., & Beerling, D. J. (2017). Climate change mitigation: Potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. *Biology Letters*, *13*(4), 20160715. https://doi.org/10.1098/rsbl.2016.0715

Eneji, A. E., Inanaga, S., Muranaka, S., Li, J., Hattori, T., An, P., & Tsuji, W. (2008). Growth and nutrient use in four grasses under drought stress as mediated by silicon fertilizers. *Journal of Plant Nutrition*, *31*(2), 355–365. https://doi.org/10.1080/01904160801894913

Epihov, D. Z., Batterman, S. A., Hedin, L. O., Leake, J. R., Smith, L. M., & Beerling, D. J. (2017). N2-fixing tropical legume evolution: A contributor to enhanced weathering through the Cenozoic? *Proceedings of the Royal Society B: Biological Sciences*, *284*(1860), 20170370. https://doi.org/10.1098/rspb.2017.0370

Epihov, D. Z., Saltonstall, K., Batterman, S. A., Hedin, L. O., Hall, J. S., van Breugel, M., Leake, J. R., & Beerling, D. J. (2021). Legume–microbiome interactions unlock mineral nutrients in regrowing tropical forests. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(11), e2022241118. https://doi.org/10.1073/pnas.2022241118

Epstein, E., & Bloom, A. J. (2004). *Mineral Nutrition of Plants: Principles and Perspective*. Sinauer Associates.

Erwiyono, R., Baon, J. B., Kaspani, U., Sulistyaningsih, N., & Sukarno, G. (2002). KCl on cocoa on soil physical properties and roots. Pelita Perkebunan. ISSN 0215-0212 2002 v. 18(1) p. 22-30 2 ill., 4 tables; 9. [Portuguese]

Eufrasio, R. M., Kantzas, E. P., Edwards, N. R., Holden, P. B., Pollitt, H., Mercure, J. F., Koh, S. C. L., & Beerling, D. J. (2022). Environmental and health impacts of atmospheric CO2 removal by enhanced rock weathering depend on nations' energy mix. *Communications Earth & Environment*, *3*(1), 106. https://doi.org/10.1038/s43247-022-00436-3

Fang, Q., Lu, A., Hong, H., Kuzyakov, Y., Algeo, T. J., Zhao, L., Olshansky, Y., Moravec, B., Barrientes, D. M., & Chorover, J. (2023). Mineral weathering is linked to microbial priming in the critical zone. *Nature Communications*, *14*(1), 345. https://doi.org/10.1038/s41467-022-35671-x

Fantinato, D. E., Zanetti, L. v., Aguilar, M. A. G., Souza, C. A. S., Cuzzuol, G. R. F., Gama, V. N., & Milanez, C. R. D. (2018). Effects of silicon on biochemical and physiological aspects in *Theobroma cacao* under inoculation with *Moniliophthora perniciosa*. *Revista de Ciências Agrárias*, *41*(3), 841–848. https://doi.org/10.19084/rca18064

Faostat. (2024). Crops and livestock products. Retrieved January 06, 2025 from https://www.fao.org/faostat/en/#data/QCL

Ferreira, D. F., Darling, A., Jarrett, C., Atagana, P. J., Sandjo, P. R., Taedoumg, H., Welch, A. J., Rebelo, H., & Powell, L. L. (2023). Not all farms are created equal: Shady African cocoa farms promote a richer bat fauna. *Biological Conservation*, *284*, 110191. https://doi.org/10.1016/j.biocon.2023.110191

Forbes, S. J., & Northfield, T. D. (2017). Increased pollinator habitat enhances cacao fruit set and predator conservation. *Ecological Applications*, *27*(3), 887–899. https://doi.org/10.1002/eap.1491

Fujii, K. (2014). Soil acidification and adaptations of plants and microorganisms in Bornean tropical forests. *Ecological Research*, *29*(3), 371–381. https://doi.org/10.1007/s11284-014-1144-3

Gama-Rodrigues, E. F., Gama-Rodrigues, A. C., & Nair, P. K. R. (2011). Soil Carbon Sequestration in Cacao Agroforestry Systems: A Case Study from Bahia, Brazil. 85–99. https://doi.org/10.1007/978-94-007-1630-8_5

Gateau-Rey, L., Tanner, E. V. J., Rapidel, B., Marelli, J. P., & Royaert, S. (2018). Climate change could threaten cocoa production: Effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. *PLoS ONE*, *13*(7), e0200454. https://doi.org/10.1371/journal.pone.0200454

Gattward, J. N., Almeida, A. A. F., Souza, J. O., Gomes, F. P., & Kronzucker, H. J. (2012). Sodium-potassium synergism in *Theobroma cacao*: Stimulation of photosynthesis, water-use efficiency and mineral nutrition. *Physiologia Plantarum*, *146*(3), 350–362. https://doi.org/10.1111/j.1399-3054.2012.01621.x

Gillman, G. P. (1980). The Effect of Crushed Basalt Scoria on the Cation Exchange Properties of a Highly Weathered Soil. *Soil Science Society of America Journal*, *44*(3), 465–468. https://doi.org/10.2136/sssaj1980.03615995004400030005x

Goulding, K. W. T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use and Management*, *32*(3), 390–399. https://doi.org/10.1111/sum.12270

Green, H., Larsen, P., Liu, Y., & Nelson, P. N. (2024). Carbon dioxide removal via weathering of sugarcane mill ash under different soil conditions. *Applied Geochemistry*, *165*, 105940. https://doi.org/10.1016/j.apgeochem.2024.105940

Guo, F., Sun, H., Yang, J., Zhang, L., Mu, Y., Wang, Y., & Wu, F. (2023). Improving food security and farmland carbon sequestration in China through enhanced rock weathering: Field evidence and potential assessment in different humid regions. *Science of the Total Environment*, *903*, 166118. https://doi.org/10.1016/j.scitotenv.2023.166118

Haque, F., Khalidy, R., Chiang, Y. W., & Santos, R. M. (2023). Constraining the capacity of global croplands to CO2 drawdown via mineral weathering. *ACS Earth and Space Chemistry*, *7*(7), 1294–1305. https://doi.org/10.1021/acsearthspacechem.2c00374

Hartmann, J., West, A. J., Renforth, P., Köhler, P., de La Rocha, C. L., Wolf-Gladrow, D. A., Dürr, H. H., & Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, *51*(2), 113–149. https://doi.org/10.1002/rog.20004

Hashimoto, S., Tanaka, N., Kume, T., Yoshifuji, N., Hotta, N., Tanaka, K., & Suzuki, M. (2007). Seasonality of vertically partitioned soil CO2 production in temperate and tropical forest. *Journal of Forest Research*, *12*(3), 209–221. https://doi.org/10.1007/s10310-007-0009-9

Haynes, R. J. (1983). Soil acidification induced by leguminous crops. *Grass and Forage Science*, *38*, 1–11. https://doi.org/10.1111/j.1365-2494.1983.tb01614.x

Hinsinger, P., Plassard, C., Tang, C., & Jaillard, B. (2003). Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: A review. *Plant and Soil*, *248*, 43–59. https://doi.org/10.1023/A:1022371130939

Holden, F. J., Davies, K., Bird, M. I., Hume, R., Green, H., Beerling, D. J., & Nelson, P. N. (2024). In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. *Science of the Total Environment*, *955*, 176568. https://doi.org/10.1016/j.scitotenv.2024.176568

Horizon Grand View Research. (2023). Cocoa Beans Market Size, Share & Trends Analysis Report By Product (Cocoa Butter, Cocoa Powder, Cocoa Liquor), By Application, By Distribution Channel, By Region, And Segment Forecasts, 2024–2030. GVR-3-68038-087-3. Retrieved from https://www.grandviewresearch.com/industry-analysis/cocoa-beans-market

Igawa, T. K., Toledo, P. M., & Anjos, L. J. S. (2022). Climate change could reduce and spatially reconfigure cocoa cultivation in the Brazilian Amazon by 2050. *PLoS ONE*, *17*(1 January), e0262729. https://doi.org/10.1371/journal.pone.0262729

International Food Policy Research Institute (IFPRI). (2024). Global Spatially-Disaggregated Crop Production Statistics Data for 2020 Version 1.0.0. Harvard Dataverse. Version 3. https://doi.org/10.7910/DVN/SWPENT

IPCC. (2022). *Climate Change 2022 - Mitigation of Climate Change - Working Group III*. Cambridge University Press.

Isaac, M. E., Harmand, J. M., Lesueur, D., & Lelon, J. (2011). Tree age and soil phosphorus conditions influence N2-fixation rates and soil N dynamics in natural populations of Acacia senegal. *Forest Ecology and Management*, *261*(3), 582–588. https://doi.org/10.1016/j.foreco.2010.11.011

Ishfaq, M., Wang, Y., Yan, M., Wang, Z., Wu, L., Li, C., & Li, X. (2022). Physiological Essence of Magnesium in Plants and Its Widespread Deficiency in the Farming System of China. *Frontiers in Plant Science*, *13*, 802274. https://doi.org/10.3389/fpls.2022.802274

Jariwala, H., Haque, F., Vanderburgt, S., Santos, R. M., & Chiang, Y. W. (2022). Mineral–Soil–Plant–Nutrient Synergisms of Enhanced Weathering for Agriculture: Short-Term Investigations Using Fast-Weathering Wollastonite Skarn. *Frontiers in Plant Science*, *13*, 929457. https://doi.org/10.3389/fpls.2022.929457

Jarrett, C., Smith, T. B., Claire, T. T. R., Ferreira, D. F., Tchoumbou, M., Elikwo, M. N. F., Wolfe, J., Brzeski, K., Welch, A. J., Hanna, R., & Powell, L. L. (2021). Bird communities in African cocoa agroforestry are diverse but lack specialized insectivores. *Journal of Applied Ecology*, *58*(6), 1237–1247. https://doi.org/10.1111/1365-2664.13864

Jerden, J., Mejbel, M., Filho, A. N. Z., Carroll, M., & Campe, J. (2024). The impact of geochemical and life-cycle variables on carbon dioxide removal by enhanced rock weathering: Development and application of the Stella ERW model. *Applied Geochemistry*, *167*, 106002. https://doi.org/10.1016/j.apgeochem.2024.106002

Kaba, J. S., Asare, A. Y., Andoh, H., Kwashie, G. K. S., & Abunyewa, A. A. (2022). Toward sustainable cocoa (*Theobroma cacao* L) production: The role of potassium fertilizer in cocoa seedlings drought recovery and survival. *International Journal of Fruit Science*, *22*(1), 618–627. https://doi.org/10.1080/15538362.2022.2092932

Kalischek, N., Lang, N., Renier, C., Daudt, R. C., Addoah, T., Thompson, W., Blaser-Hart, W. J., Garrett, R., Schindler, K., & Wegner, J. D. (2023). Cocoa plantations are associated with deforestation in Côte d'Ivoire and Ghana. *Nature Food*, *4*(5), 384–393. https://doi.org/10.1038/s43016-023-00751-8

Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M. G., Lomas, M. R., Cotton, T. E. A., Kemp, S. J., James, R. H., Pearce, C. R., Hartley, S. E., Hodson, M. E., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2020). Increased yield and CO2 sequestration potential with the C4 cereal *Sorghum bicolor* cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*, *26*(6), 3658–3676. https://doi.org/10.1111/gcb.15089

Kenfack Essougong, U. P., Slingerland, M., Mathé, S., Vanhove, W., Tata Ngome, I., Boudes, P., Giller, K. E., Woittiez, L. S., & Leeuwis, C. (2020). Farmers' perceptions as a driver of agricultural practices: Understanding soil fertility management practices in cocoa agroforestry systems in Cameroon. *Human Ecology*, *48*, 709–720. https://doi.org/10.1007/s10745-020-00190-0

Knapp, W. J., & Tipper, E. T. (2022). The efficacy of enhancing carbonate weathering for carbon dioxide sequestration. *Frontiers in Climate*, *4*, 928215. https://doi.org/10.3389/fclim.2022.928215

Konstantas, A., Jeswani, H. K., Stamford, L., & Azapagic, A. (2018). Environmental impacts of chocolate production and consumption in the UK. *Food Research International*, *106*, 1012–1025. https://doi.org/10.1016/j.foodres.2018.02.042

Kump, L. R., Brantley, S. L., & Arthur, M. A. (2000). Chemical weathering, atmospheric CO2, and climate. *Annual Review of Earth and Planetary Sciences*, *28*, 611–667. https://doi.org/10.1146/annurev.earth.28.1.611

Lander, T. A., Atta-Boateng, A., Toledo-Hernández, M., Wood, A., Malhi, Y., Solé, M., Tscharntke, T., & Wanger, T. C. (2025). Global chocolate supply is limited by low pollination and high temperatures. *Communications Earth & Environment*, *6*(1), 97. https://doi.org/10.1038/s43247-025-02072-z

Larkin, C. S., Andrews, G. M., Pearce, C. R., Yeong, K. L., Beerling, D. J., Bellamy, J., Benedick, S., Freckleton, R. P., Goring-Harford, H., Sadekar, S., & James, R. H. (2022). Quantification of CO2 removal in a large-scale enhanced weathering field trial on an oil palm plantation in Sabah, Malaysia. *Frontiers in Climate*, *4*, 959229. https://doi.org/10.3389/fclim.2022.959229

Lefebvre, D., Goglio, P., Williams, A., Manning, D. A. C., de Azevedo, A. C., Bergmann, M., Meersmans, J., & Smith, P. (2019). Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *Journal of Cleaner Production*, *233*, 468–481. https://doi.org/10.1016/j.jclepro.2019.06.099

Lei, K., Bucka, F. B., Teixeira, P. P. C., Buegger, F., Just, C., & Kögel-Knabner, I. (2025). Balancing Organic and Inorganic Carbon Dynamics in Enhanced Rock Weathering: Implications for Carbon Sequestration. *Global Change Biology*, *31*(4), e70186. https://doi.org/10.1111/gcb.70186

Leuschner, C., Moser, G., Hertel, D., Erasmi, S., Leitner, D., Culmsee, H., Schuldt, B., & Schwendenmann, L. (2013). Conversion of tropical moist forest into cacao agroforest: Consequences for carbon pools and annual C sequestration. *Agroforestry Systems*, *87*(5), 1173–1187. https://doi.org/10.1007/s10457-013-9628-7

Levy, C. R., Almaraz, M., Beerling, D. J., Raymond, P., Reinhard, C. T., Suhrhoff, T. J., & Taylor, L. (2024). Enhanced rock weathering for carbon removal–monitoring and mitigating potential environmental impacts on agricultural land. *Environmental Science & Technology*, *58*(39), 17215–17226. https://doi.org/10.1021/acs.est.4c02368

Li, C., & Ji, H. (2016). Chemical weathering and the role of sulfuric and nitric acids in carbonate weathering: Isotopes (13C, 15N, 34S, and 18O) and chemical constraints. *Journal of Geophysical Research: Biogeosciences*, *121*(5), 1288–1305. https://doi.org/10.1002/2015JG003121

Lim, A. G., Pokrovsky, O. S., Cornu, S., & Meunier, J. D. (2023). Release of labile Si from forest and agricultural soils. *Catena*, *229*, 107211. https://doi.org/10.1016/j.catena.2023.107211

Liu, X., Yin, L., Deng, X., Gong, D., Du, S., Wang Zhang, Z. (2020). Combined application of silicon and nitric oxide jointly alleviated cadmium accumulation and toxicity in maize. *Journal of Hazardous Materials*, 395. https://doi.org/10.1016/j.jhazmat.2020.122679

Loerting, T., & Bernard, J. (2010). Aqueous carbonic acid (H2CO3). *ChemPhysChem*, *11*(11), 2305–2309. https://doi.org/10.1002/cphc.201000220

Lubis, S. T., Putra, E. T. S., & Kurniasih, B. (2022). Anatomical characteristics of cocoa plant roots as affected by the levels of calcium fertilization. *Ilmu Pertanian (Agricultural Science)*, *7*(2), 68. https://doi.org/10.22146/ipas.69842

Luna, M., & Barcellos-Paula, L. (2024). Structured Equations to Assess the Socioeconomic and Business Factors Influencing the Financial Sustainability of Traditional Amazonian Chakra in the Ecuadorian Amazon. *Sustainability*, *16*(6), 2480. https://doi.org/10.3390/su16062480

Maney, C., Sassen, M., & Hill, S. L. L. (2022). Modelling biodiversity responses to land use in areas of cocoa cultivation. *Agriculture, Ecosystems and Environment*, *324*, 107712. https://doi.org/10.1016/j.agee.2021.107712

Manning, D. A. C., Baptista, J., Sanchez Limon, M., & Brandt, K. (2017). Testing the ability of plants to access potassium from framework silicate minerals. *Science of the Total Environment*, *574*, 476–481. https://doi.org/10.1016/j.scitotenv.2016.09.086

Marrocos, P. C. L., Guilherme, G. A. H., de Araujo, Q. R., Sodré, G. A., Ahnert, D., & Baligar, V. C. (2020). Mineral nutrient ratios and cacao productivity. *Journal of Plant Nutrition*, *43*(15), 2368–2382. https://doi.org/10.1080/01904167.2020.1771582

McDermott, F., Bryson, M., Magee, R., & van Acken, D. (2024). Enhanced weathering for CO2 removal using carbonate-rich crushed returned concrete; a pilot study from SE Ireland. *Applied Geochemistry*, *169*, 106056. https://doi.org/10.1016/j.apgeochem.2024.106056

Mengel, K. (1980). Potassium Requirements of Crops. Worblaufen-Bern, Switzerland.

Merget, R., Bauer, T., Küpper, H., Philippou, S., Bauer, H., Breitstadt, R., & Bruening, T. (2002). Health hazards due to the inhalation of amorphous silica. *Archives of Toxicology*, *75*(11), 625–634. https://doi.org/10.1007/s002040100266

Meunier, J. D., Sandhya, K., Prakash, N. B., Borschneck, D., & Dussouillez, P. (2018). pH as a proxy for estimating plant-available Si? A case study in rice fields in Karnataka (South India). *Plant and Soil*, *432*(1–2), 143–155. https://doi.org/10.1007/s11104-018-3758-7

Miharza, T., Wijayanto, N., Roshetko, J. M., & Siregar, I. Z. (2023). Carbon stocks and footprints of smallholder cacao systems in Polewali Mandar, West Sulawesi. *Frontiers in Environmental Science*, *11*, 680984. https://doi.org/10.3389/fenvs.2023.680984

Moosdorf, N., Renforth, P., & Hartmann, J. (2014). Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science & Technology*, *48*(9), 4809–4816. https://doi.org/10.1021/es4052022

Mosca, S., Benedetti, P., Guerriero, E., & Rotatori, M. (2014). Assessment of nitrous oxide emission from cement plants: Real data measured with both Fourier transform infrared and nondispersive infrared techniques. *Journal of the Air & Waste Management Association*, *64*(11), 1270–1278. https://doi.org/10.1080/10962247.2014.936986

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., da Motta, R. S., Armijo, E., Castello, L., Brando, P., Hansen, M. C., McGrath-Horn, M., Carvalho, O., & Hess, L. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, *344*(6188), 1118–1123. https://doi.org/10.1126/science.1248525

Neves Cavalcante, P. J. d. C., Michel, R. F. M., Moreau, M. S., de Queiroz Paiva, A., Freitas Noronha, R. H., & Silva, T. M. (2023). Spectral evaluation of cocoa: A methodological proposal for its management and application of the cabruca decree. *Floresta e Ambiente*, *30*(1), e20220050. https://doi.org/10.1590/2179-8087-FLORAM-2022-0050

Ng, J. F., Ahmed, O. H., Jalloh, M. B., Omar, L., Kwan, Y. M., Musah, A. A., & Poong, K. H. (2022). Soil Nutrient Retention and pH Buffering Capacity Are Enhanced by Calciprill and Sodium Silicate. *Agronomy*, *12*(1), 219. https://doi.org/10.3390/agronomy12010219

Nguyen, H., Schoenau, J. J., Nguyen, D., van Rees, K., & Boehm, M. (2002). Effects of long-term nitrogen, phosphorus, and potassium fertilization on cassava yield and plant nutrient composition in North Vietnam. *Journal of Plant Nutrition*, *25*(3), 425–442. https://doi.org/10.1081/PLN-120003374

Niether, W., Armengot, L., Andres, C., Schneider, M., & Gerold, G. (2018). Shade trees and tree pruning alter throughfall and microclimate in cocoa (Theobroma cacao L.) production systems. *Annals of Forest Science*, *75*(2), 38. https://doi.org/10.1007/s13595-018-0723-9

Nishio, T., & Fujimoto, T. (1990). Kinetics of nitrification of various amounts of ammonium added to soils. *Soil Biology and Biochemistry*, *22*(1), 51–55. https://doi.org/10.1016/0038-0717(90)90059-9

Ntiamoah, A., & Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: Life cycle assessment approach. *Journal of Cleaner Production*, *16*(16), 1735–1740. https://doi.org/10.1016/j.jclepro.2007.11.004

Oh, N. H., & Raymond, P. A. (2006). Contribution of agricultural liming to riverine bicarbonate export and CO2 sequestration in the Ohio River basin. *Global Biogeochemical Cycles*, *20*(3), 2005GB002565. https://doi.org/10.1029/2005GB002565

Oliveira, L. C., Hankerson, S. J., Dietz, J. M., & Raboy, B. E. (2010). Key tree species for the golden-headed lion tamarin and implications for shade-cocoa management in southern Bahia, Brazil. *Animal Conservation*, *13*(1), 60–70. https://doi.org/10.1111/j.1469-1795.2009.00296.x

Omokaro, G. O., Michael, I., Abamba, E. E., Bakare, A., Igbe, A. O., Otokpa, E. I., Ofulue, C. J., & Okpro, O. F. (2025). Assessment of micronutrient and heavy metal contamination in soils near refuse dumpsites in Ughelli North, Delta State, Nigeria. *EQA*, *65*, 78–85. https://doi.org/10.6092/issn.2281-4485/20213

Ortiz-R, O. O., Gallardo, R. A. V., & Rangel, J. M. R. (2014). Applying life cycle management of Colombian cocoa production. *Food Science and Technology*, *34*(1), 62–68. https://doi.org/10.1590/S0101-20612014005000006

Parra-Paitan, C., & Verburg, P. H. (2022). Accounting for land use changes beyond the farm-level in sustainability assessments: The impact of cocoa production. *Science of the Total Environment*, *825*, 154032. https://doi.org/10.1016/j.scitotenv.2022.154032

Perez-Fodich, A., & Derry, L. A. (2019). Organic acids and high soil CO2 drive intense chemical weathering of Hawaiian basalts: Insights from reactive transport models. *Geochimica et Cosmochimica Acta*, *249*, 173–198. https://doi.org/10.1016/j.gca.2019.01.027

Pérez-Neira, D., Copena, D., Armengot, L., & Simón, X. (2020). Transportation can cancel out the ecological advantages of producing organic cacao: The carbon footprint of the globalized agrifood system of ecuadorian chocolate. *Journal of Environmental Management*, *276*, 111306. https://doi.org/10.1016/j.jenvman.2020.111306

Pérez-Neira, D., Schneider, M., & Armengot, L. (2020). Crop-diversification and organic management increase the energy efficiency of cacao plantations. *Agricultural Systems*, *177*, 102711. https://doi.org/10.1016/j.agsy.2019.102711

Pierre, W. H., & Banwart, W. L. (1973). Excess-base and excess-base/nitrogen ratio of various crop species and parts of plants 1. *Agronomy Journal*, *65*, 91–96. https://doi.org/10.2134/agronj1973.00021962006500010028x

Plata, L. G., Ramos, C. G., Silva Oliveira, M. L., & Silva Oliveira, L. F. (2021). Release kinetics of multi-nutrients from volcanic rock mining by-products: Evidences for their use as a soil remineralizer. *Journal of Cleaner Production*, *279*, 123668. https://doi.org/10.1016/j.jclepro.2020.123668

Pokrovsky, O. S., Golubev, S. v., Schott, J., & Castillo, A. (2009). Calcite, dolomite and magnesite dissolution kinetics in aqueous solutions at acid to circumneutral pH, 25 to 150 °C and 1 to 55 atm pCO2: New constraints on CO2 sequestration in sedimentary basins. *Chemical Geology*, *265*(1–2), 20–32. https://doi.org/10.1016/j.chemgeo.2009.01.013

Poschenrieder, C., Fernández, J. A., Rubio, L., Pérez, L., Terés, J., & Barceló, J. (2018). Transport and use of bicarbonate in plants: Current knowledge and challenges ahead. *International Journal of Molecular Sciences*, *19*(5), 1352. https://doi.org/10.3390/ijms19051352

Presidncia da Repblica. (2013). LAW No. 12,890, OF DECEMBER 10, 2013. Retrieved April 15, 2024 from https://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/l12890.htm

Quan, Z., Huang, B., Lu, C., Shi, Y., Chen, X., Zhang, H., & Fang, Y. (2016). The fate of fertilizer nitrogen in a high nitrate accumulated agricultural soil. *Scientific Reports*, *5*, 21539. https://doi.org/10.1038/srep21539

Ramtahal, G., Umaharan, P., Hanuman, A., Davis, C., & Ali, L. (2019). The effectiveness of soil amendments, biochar and lime, in mitigating cadmium bioaccumulation in Theobroma cacao L. *Science of the Total Environment*, *693*, 133563. https://doi.org/10.1016/j.scitotenv.2019.07.369

Reganold, J. P., & Harsh, J. B. (1985). Expressing cation exchange capacity in milliequivalents per 100 grams and in SI units 1. *Journal of Agronomic Education*, *14*(2), 84–90. https://doi.org/10.2134/jae1985.0084

Reitsma, R., Parrish, J. D., & Mclarney, W. (2001). The role of cacao plantations in maintaining forest avian diversity in southeastern Costa Rica. *Agroforestry Systems*, *53*, 185–193. https://doi.org/10.1023/A:1013328621106

Renforth, P. (2019). The negative emission potential of alkaline materials. *Nature Communications*, *10*(1), 1401. https://doi.org/10.1038/s41467-019-09475-5

Reynaert, S., Vienne, A., de Boeck, H. J., D'Hose, T., Janssens, I., Nijs, I., Portillo-Estrada, M., Verbruggen, E., Vicca, S., & Poblador, S. (2023). Basalt addition improves the performance of young grassland monocultures under more persistent weather featuring longer dry and wet spells. *Agricultural and Forest Meteorology*, *340*, 109610. https://doi.org/10.1016/j.agrformet.2023.109610

Ruf, F. O. (2011). The myth of complex cocoa agroforests: The case of Ghana. *Human Ecology*, *39*(3), 373–388. https://doi.org/10.1007/s10745-011-9392-0

Ryan, P. C., Santis, A., Vanderkloot, E., Bhatti, M., Caddle, S., Ellis, M., Grimes, A., Silverman, S., Soderstrom, E., Stone, C., Takoudes, A., Tulay, P., & Wright, S. (2024). The potential for carbon dioxide removal by enhanced rock weathering in the tropics: An evaluation of Costa Rica. *Science of the Total Environment*, *927*, 172053. https://doi.org/10.1016/j.scitotenv.2024.172053

Saj, S., Durot, C., Mvondo Sakouma, K., Tayo Gamo, K., & Avana-Tientcheu, M. L. (2017). Contribution of associated trees to long-term species conservation, carbon storage and sustainability: A functional analysis of tree communities in cacao plantations of Central Cameroon. *International Journal of Agricultural Sustainability*, *15*(3), 282–302. https://doi.org/10.1080/14735903.2017.1311764

Sandim, A. d. S., Büll, L. T., Furim, A. R., Lima, G. d. S., & Garcia, J. L. N. (2014). Phosphorus availability in oxidic soils treated with lime and silicate applications. *Revista Brasileira de Ciência do Solo*, *38*(4), 1215–1222. https://doi.org/10.1590/S0100-06832014000400018

Sassen, M., van Soesbergen, A., Arnell, A. P., & Scott, E. (2022). Patterns of (future) environmental risks from cocoa expansion and intensification in West Africa call for context specific responses. *Land Use Policy*, *119*, 106142. https://doi.org/10.1016/j.landusepol.2022.106142

Schroth, G., Garcia, E., Griscom, B. W., Teixeira, W. G., & Barros, L. P. (2016). Commodity production as restoration driver in the Brazilian Amazon? Pasture re-agro-forestation with cocoa (*Theobroma cacao*) in southern Pará. *Sustainability Science*, *11*(2), 277–293. https://doi.org/10.1007/s11625-015-0330-8

Schroth, G., Läderach, P., Martinez-Valle, A. I., Bunn, C., & Jassogne, L. (2016). Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. *Science of the Total Environment*, *556*, 231–241. https://doi.org/10.1016/j.scitotenv.2016.03.024

Schuiling, R. D., & Krijgsman, P. (2006). Enhanced weathering: An effective and cheap tool to sequester CO 2. *Climatic Change*, *74*(1–3), 349–354. https://doi.org/10.1007/s10584-005-3485-y

Scudder, M., Wampe, N., Waviki, Z., Applegate, G., & Herbohn, J. (2022). Smallholder cocoa agroforestry systems; is increased yield worth the labour and capital inputs? *Agricultural Systems*, *196*, 103350. https://doi.org/10.1016/j.agsy.2021.103350

Seefeldt, L. C., Hoffman, B. M., & Dean, D. R. (2009). Mechanism of Mo-dependent nitrogenase. *Annual Review of Biochemistry*, *78*, 701– 722. https://doi.org/10.1146/annurev.biochem.78.070907.103812

Shamshuddin, J., Anda, M., Fauziah, C. I., & Omar, S. S. R. (2011). Growth of cocoa planted on highly weathered soil as affected by application of basalt and/or compost. *Communications in Soil Science and Plant Analysis*, *42*(22), 2751–2766. https://doi.org/10.1080/00103624.2011.622822

Shamshuddin, J., Panhwar, Q. A., Roslan, I., Fauziah, C. I., Naher, U. A., & Hakeem, K. R. (2015). Sustaining cocoa production on Oxisols in Malaysia. In *Crop Production and Global Environmental Issues* (pp. 169–180). Springer International Publishing. https://doi.org/10.1007/978-3-319-23162-4_7

Slessarev, E. W., Chadwick, O. A., Sokol, N. W., Nuccio, E. E., & Pett-Ridge, J. (2022). Rock weathering controls the potential for soil carbon storage at a continental scale. *Biogeochemistry*, *157*(1), 1–13. https://doi.org/10.1007/s10533-021-00859-8

Snoeck, D., Afrifa, A. A., Ofori-Frimpong, K., Boateng, E., & Abekoe, M. K. (2010). Mapping fertilizer recommendations for cocoa production in

Ghana using soil diagnostic and GIS tools. *West Africa Journal of Applied Ecology*, *17*, 97–108.

Snoeck, D., Koko, L., Joffre, J., Bastide, P., & Jagoret, P. (2016). Cacao Nutrition and Fertilization. 155–202. https://doi.org/10.1007/978-3-319-26777-7_4

Soilueang, P., Chromkaew, Y., Mawan, N., Wicharuck, S., Kullachonphuri, S., Buachun, S., Wu, Y. T., Chen, Y., Iamsaard, K., & Khongdee, N. (2025). Temporal Dynamics of Soil Carbon Stocks and Mineralization Rates in Coffea arabica Agroforestry Systems. *Agriculture (Basel)*, *15*(1), 14. https://doi.org/10.3390/agriculture15010014

Sokol, N. W., Sohng, J., Moreland, K., Slessarev, E., Goertzen, H., Schmidt, R., Samaddar, S., Holzer, I., Almaraz, M., Geoghegan, E., Houlton, B., Montañez, I., Pett-Ridge, J., & Scow, K. (2024). Reduced accrual of mineral-associated organic matter after two years of enhanced rock weathering in cropland soils, though no net losses of soil organic carbon. *Biogeochemistry*, *167*, 989–1005. https://doi.org/10.1007/s10533-024-01160-0

Souza, J. O., Sodre, G. A., & Neves, J. C. L. (2018). *Soil fertility, acidity correction and fertilization recommendation for cocoa trees. Cocoa: cultivation, research and innovation* (pp. 333–377). Editus. https://doi.org/10.7476/9786586213188

Steeley, I. (2025). Figure created in Biorender. https://BioRender.com/b78p896

Sun, C., Yao, Z., Wang, Q., Guo, L., & Shen, X. (2023). Theoretical study on the organic acid promoted dissolution mechanism of forsterite mineral. *Applied Surface Science*, *614*, 156063. https://doi.org/10.1016/j.apsusc.2022.156063

Tadu, Z., & Djiéto-Lordon, C. (2014). Ant diversity in different cocoa agroforest habitats in the Centre Region of Cameroon. *African Entomology*, *22*(2), 388–404. https://doi.org/10.4001/003.022.0219

Taiz, L., Zeiger, E., Møller, I., & Murphy, A. (2014). Plant Physiology and Development.

Taylor, L. L., Driscoll, C. T., Groffman, P. M., Rau, G. H., Blum, J. D., & Beerling, D. J. (2021). Increased carbon capture by a silicate-treated forested watershed affected by acid deposition. *Biogeosciences*, *18*(1), 169–188. https://doi.org/10.5194/bg-18-169-2021

Te Pas, E. E. E. M., Chang, E., Marklein, A. R., Comans, R. N. J., & Hagens, M. (2025). Accounting for retarded weathering products in comparing methods for quantifying carbon dioxide removal in a short-term enhanced weathering study. *Frontiers in Climate*, *6*, 1524998. https://doi.org/10.3389/fclim.2024.1524998

Tittonell, P., & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research*, *143*, 76–90. https://doi.org/10.1016/j.fcr.2012.10.007

Val Martin, M., Blanc-Betes, E., Fung, K. M., Kantzas, E. P., Kantola, I. B., Chiaravalloti, I., Taylor, L. L., Emmons, L. K., Wieder, W. R., Planavsky, N. J., Masters, M. D., Delucia, E. H., Tai, A. P. K., & Beerling, D. J. (2023). Improving nitrogen cycling in a land surface model (CLM5) to quantify soil N_2O, NO, and NH_3 emissions from enhanced rock weathering with croplands. *Geoscientific Model Development*, *16*(20), 5783–5801. https://doi.org/10.5194/gmd-16-5783-2023

Van Stkveninck, R. K. M. (1965). The significance of calcium on the apparent permeability of cell membranes and the effects of substitution with other divalent ions. *Physiologia Plantarum*, *18*(1), 54–69. https://doi.org/10.1111/j.1399-3054.1965.tb06869.x

Van Vliet, J. A., Slingerland, M. A., Waarts, Y. R., & Giller, K. E. (2021). A living income for cocoa producers in Côte d'Ivoire and Ghana? *Frontiers in Sustainable Food Systems*, *5*, 732831. https://doi.org/10.3389/fsufs.2021.732831

Vervuurt, W., Slingerland, M. A., Pronk, A. A., & van Bussel, L. G. J. (2022). Modelling greenhouse gas emissions of cacao production in the Republic of Côte d'Ivoire. *Agroforestry Systems*, *96*(2), 417–434. https://doi.org/10.1007/s10457-022-00729-8

Vienne, A., Poblador, S., Portillo-Estrada, M., Hartmann, J., Ijiehon, S., Wade, P., & Vicca, S. (2022). Enhanced weathering using basalt rock powder: Carbon sequestration, co-benefits and risks in a mesocosm study with *Solanum tuberosum*. *Frontiers in Climate*, *4*, 869456. https://doi.org/10.3389/fclim.2022.869456

Villalaz-Pérez, J. A., Casanoves, F., Villarreal-Núñez, J. E., Santo-Pineda, A., Gutiérrez-Lezcano, A., & Merino, A. (2024). Cadmium concentration in cocoa beans produced in agroforestry systems of small producers in Panama. *Spanish Journal of Agricultural Research*, *22*(1), e0301. https://doi.org/10.5424/sjar/2024221-20405

Wang, R., Wang, Y., Zhang, Z., Pan, H., Lan, L., Huang, R., Deng, X., & Peng, Y. (2023). Effects of Exponential N Application on Soil Exchangeable Base Cations and the Growth and Nutrient Contents of Clonal Chinese Fir Seedlings. *Plants*, *12*(4), 851. https://doi.org/10.3390/plants12040851

Welch, S. A., & Ullman, W. J. (1993). The effect of organic acids on plagioclase dissolution rates and stoichiometry. *Geochimica et Cosmochimica Acta*, *57*(12), 2725–2736. https://doi.org/10.1016/0016-7037(93)90386-B

Wen, H., Sullivan, P. L., Macpherson, G. L., Billings, S. A., & Li, L. (2020). Deepening roots can enhance carbonate weathering. https://doi.org/10.5194/bg-2020-180

Weng, Z., Li, G., Sale, P., & Tang, C. (2022). Application of calcium nitrate with phosphorus promotes rhizosphere alkalization in acid subsoil. *European Journal of Soil Science*, *73*(1), e13153. https://doi.org/10.1111/ejss.13153

Wessel, M. (1971). Fertilizer requirements of cacao (Theobroma cacao L.) in south-western Nigeria. In Communication of the Department of Agricultural Research, (Issue no 61).

Wiltshire, J., Wynn, S., Clarke, J., Chambers, B., Cottrill, B., Drakes, D., Gittins, J., Nicholson, C., Phillips, K., Thorman, R., Tiffin, D., Walker, O., Tucker, G., Thorn, R., Green, A., Fendler, A., Williams, A., Bellamy, P., Audsley, E., & Foster, C. (2008). Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food (Technical Annex to final report on Defra Project No. FO0404)

Xu, T., Yuan, Z., Vicca, S., Goll, D. S., Li, G., Lin, L., Chen, H., Bi, B., Chen, Q., Li, C., Wang, X., Wang, C., Hao, Z., Fang, Y., & Beerling, D. J. (2024). Enhanced silicate weathering accelerates forest carbon sequestration by stimulating the soil mineral carbon pump. *Global Change Biology*, *30*(8), e17464. https://doi.org/10.1111/gcb.17464

Yan, Y., Dong, X., Li, R., Zhang, Y., Yan, S., Guan, X., Yang, Q., Chen, L., Fang, Y., Zhang, W., & Wang, S. (2023). Wollastonite addition stimulates soil organic carbon mineralization: Evidences from 12 land-use types in subtropical China. *Catena*, *225*, 107031. https://doi.org/10.1016/j.catena.2023.107031

Yao, Y. C. A., Jean, C. N. J., Kpangui, B., & Vroh, T. A. B. (2015). Farming practices, diversity and utilizations of associated species of cocoa plantations in a forest-savannah transition zone, Center Côte d'Ivoire. *Global Journal of Wood Science, Forestry and Wildlife*, *3*(3), 94–100. http://www.globalscienceresearchjournals.org/

Youssef, R. A., & Chino, M. (1989). Root-induced changes in the rhizosphere of plants. I. pH changes in relation to the bulk soil. *Soil Science and Plant Nutrition*, *35*(3), 461–468. https://doi.org/10.1080/00380768.1989.10434779

Zanetti, L. V., Werner, E. T., Cuzzuol, G. R. F., & Milanez, C. R. D. (2023). Silicon in cacao plants exposed to UV-B radiation. *Pesquisa Agropecuária Brasileira*, *58*, e03083. https://doi.org/10.1590/S1678-3921.pab2023.v58.03083

Zarrillo, S., Gaikwad, N., Lanaud, C., Powis, T., Viot, C., Lesur, I., Fouet, O., Argout, X., Guichoux, E., Salin, F., Solorzano, R. L., Bouchez, O., Vignes, H., Severts, P., Hurtado, J., Yepez, A., Grivetti, L., Blake, M., & Valdez, F. (2018). The use and domestication of *Theobroma cacao* during the mid-Holocene in the upper Amazon. *Nature Ecology &*

Evolution, *2*(12), 1879–1888. https://doi.org/10.1038/s41559-018-0697-x

Zhang, S., Planavsky, N. J., Katchinoff, J., Raymond, P. A., Kanzaki, Y., Reershemius, T., & Reinhard, C. T. (2022). River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering. *Limnology and Oceanography*, *67*(S2), S148–S157. https://doi.org/10.1002/lno.12244

Zuidema, P. A., Leffelaar, P. A., Gerritsma, W., Mommer, L., & Anten, N. P. R. (2005). A physiological production model for cocoa (*Theobroma cacao*): Model presentation, validation and application. *Agricultural Systems*, *84*(2), 195–225. https://doi.org/10.1016/j.agsy.2004.06.015

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Steeley, I. L., França, E. S., Epihov, D. Z., Planavsky, N. J., & Beerling, D. J. (2025). Agroforestry and enhanced rock weathering: A dual strategy for sustainable cacao. *Plants, People, Planet*, 1–18. https://doi.org/10.1002/ppp3.70097