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Author for correspondence:
David P. Edwards
e-mail: david.edwards@sheffield.ac.uk

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Global change biology

Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture

David P. Edwards[1], Felix Lim[1], Rachael H. James[2], Christopher R. Pearce[3], Julie Scholes[1], Robert P. Freckleton[1] and David J. Beerling[1]

[1]Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK
[2]Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton SO14 3ZH, UK
[3]National Oceanography Centre, University of Southampton Waterfront Campus, European Way, Southampton SO14 3ZH, UK

DPE, 0000-0001-8562-3853

Restricting future global temperature increase to 2°C or less requires the adoption of negative emissions technologies for carbon capture and storage. We review the potential for deployment of enhanced weathering (EW), via the application of crushed reactive silicate rocks (such as basalt), on over 680 million hectares of tropical agricultural and tree plantations to offset fossil fuel CO_2 emissions. Warm tropical climates and productive crops will substantially enhance weathering rates, with potential co-benefits including decreased soil acidification and increased phosphorus supply promoting higher crop yields sparing forest for conservation, and reduced cultural eutrophication. Potential pitfalls include the impacts of mining operations on deforestation, producing the energy to crush and transport silicates and the erosion of silicates into rivers and coral reefs that increases inorganic turbidity, sedimentation and pH, with unknown impacts for biodiversity. We identify nine priority research areas for untapping the potential of EW in the tropics, including effectiveness of tropical agriculture at EW for major crops in relation to particle sizes and soil types, impacts on human health, and effects on farmland, adjacent forest and stream-water biodiversity.

1. Enhanced weathering as a negative emissions strategy

The 2015 Paris Agreement on climate change recognizes that restricting future temperature increases to 1.5–2°C requires deployment of unproven negative emissions technologies (NETs) to remove CO_2 from the atmosphere. Currently, all proposed large-scale NETs have poorly developed feasibility, cost and acceptability [1] and few, if any, have had their impacts on ecosystem services or biodiversity considered [2].

Here we focus on the potential and consequences for the deployment of enhanced weathering (EW) on tropical agricultural lands by exploiting existing agricultural infrastructure. EW involves application of crushed reactive silicate rocks (particularly basalt and other mafic rocks) to vegetated landscapes to increase atmospheric CO_2 removal rates [3–5]. Natural rock weathering is regulated by climate and vegetation. CO_2 is removed by the chemical breakdown of calcium- and magnesium-rich silicate rocks and is accelerated by warm climates and vegetation rooting systems and their ubiquitous root-associating symbiotic fungi [6]. Weathered base cations and resulting bicarbonate in soils are flushed into rivers and delivered into the surface oceans, where CO_2 is stored either as dissolved inorganic carbon or permanently (on human timescales) as carbonate.

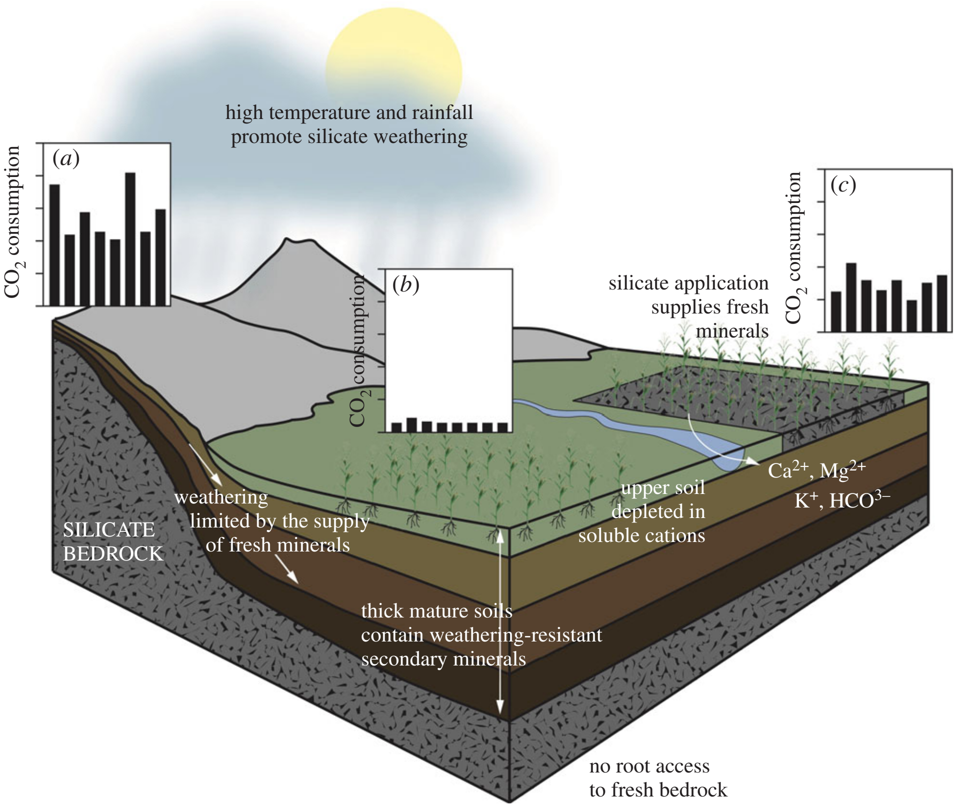

Figure 1. Schematic illustration of enhanced rock weathering for CO_2 removal in the tropics. Relative CO_2 consumption rates are graphed for eight hypothetical tropical rivers draining (*a*) highlands with limited vegetation and thin/absent soil profiles, (*b*) lowlands with thick, mature, weathering-resistant soils, and (*c*) lowlands dressed with reactive ground basalt.

Lower atmospheric CO_2 and an increased land–ocean flux of alkalinity generated by EW might help counteract ocean acidification [3,5].

In this review, we briefly introduce why the tropics are likely to be particularly effective for EW and the kinds of tropical agricultural systems that could be used. We discuss the potential positives and pitfalls of tropical EW, both within the agroecosystems themselves and on wider scales, and finish by providing a roadmap of critical outstanding research questions.

2. Why the tropics?

Silicate weathering rates depend on temperature, run-off and rate of physical erosion [7,8]. Although warm and wet tropical conditions should theoretically enhance the rate of silicate rock weathering (figure 1*a*), natural rates are often very low [9] because lowland tropical environments are predominantly characterized by thick, mature soils that undergo little physical disturbance (figure 1). Primary minerals within these soil sequences have already been altered to weathering-resistant secondary minerals depleted in the soluble cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) that support plant growth. Furthermore, areas covered with thick layers of weathered soil prevent root access to fresh bedrock, and the roots themselves stabilize the soil surface reducing erosion and lowering chemical weathering potential (figure 1*b*; [10]). Consequently, unlike other climate zones where the rate of silicate weathering is primarily controlled by kinetics, the rate of natural rock weathering in the tropics is limited by the supply of fresh mineral surfaces [7,8].

Basalts are among the most susceptible silicate rocks to weathering (e.g. [11]). Present-day CO_2 consumption from silicate weathering indicates that around 35% could be attributable to basaltic rocks, even though they constitute less than 5% of the continental area [12]. Amending tropical soils with freshly ground basalt could overcome issues associated with mineral supply and release the geochemical potential of the tropics for atmospheric CO_2 capture and storage (e.g. [5]; figure 1*c*). This will be further enhanced by the secretion of organic acids and CO_2 during respiration by roots and acidification of the rhizosphere by root-associated mycorrhizal fungi [6]. Catchment-scale studies indicate that vegetation can increase weathering rates by fivefold or more compared to adjacent barren areas [6]. These considerations make the warm, highly productive tropics ideal for using EW as means of CO_2 removal.

3. Potential tropical agricultural systems for enhanced weathering

We combine data from multiple sources to illustrate and compare the spatial extents and distribution of major land-use types across the tropics (figure 2). Pan-tropically, over 676 million hectares (Mha) of land were under crop production in 2010 (electronic supplementary material, table S1), indicating an extensive land area with potential for the large-scale application of EW. Tropical agriculture in each region is dominated by a few crops (figure 2): Asia dominates production of rice, oil palm, seed cotton, coconut and rubber; the Neotropics production of soya beans, sugar cane and coffee; and Africa production of sorghum, millet, cowpeas and cocoa. Given their extent and distribution, only twenty crops accounted for 548 Mha (81%) of 2010 production (electronic supplementary material, table S1).

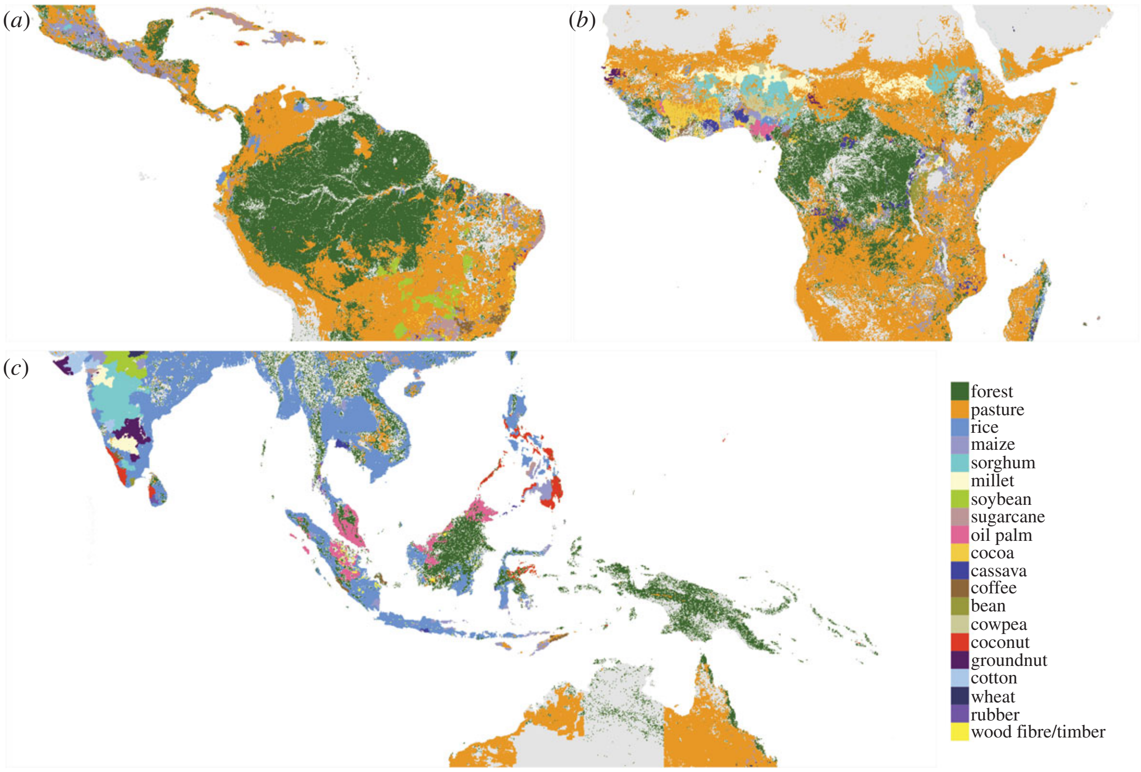

Figure 2. Extent of the 16 most frequently cultivated tropical crops, plus pasture, wood-fibre/timber plantations, rubber plantations and natural forest in (*a*) Latin America, (*b*) Africa and (*c*) Asia–Pacific. Crop and pasture distributions in 2000 (data averaged across 1997–2003) were obtained from [13] and [14]. We displayed the dominant crop of each cell (i.e. with the highest proportion; [13]) provided that harvest area exceeded 10% of the cell. Likewise, pastures were displayed if they occupied an area exceeding 10% of the cell, although any crop present (more than 10% area) was displayed over pasture. Information on the distribution of timber and wood fibre plantations was only obtained for five countries: Brazil, Cambodia, Indonesia, Malaysia and Peru via [15]. Information on the extent of forests across the tropics was obtained for 2009 [16], and includes all forest types. Each habitat was mapped at a resolution of 5 by 5 arcminutes (approximately 10 × 10 km along the equator). (Online version in colour.)

Targeting these dominant crops for EW could maximize its effectiveness and efficiency. Additionally, substantial tree plantations of *Eucalyptus*, *Acacia*, etc. for paper-pulp and softwood exist in Brazil (7.3 Mha) and Indonesia (2.6 Mha) that might be used for EW (figure 2). EW might also have a role within forest restoration projects. Extensive tropical restoration required for re-establishing lost biomass carbon sinks [17] might be deployed for EW to further enhance carbon sequestration.

Crops (e.g. soya bean, sugar cane, oil palm), tree and rubber plantations grown intensively by large- to medium-scale agribusiness have the road and employment infrastructural capacity required for spreading crushed silicates, with many already applying crushed limestone, as agricultural lime, and fertilizer [18]. By contrast, small-scale farmers, especially those practising shifting (slash-and-burn) agriculture, will likely lack sufficient resources to apply crushed rocks. These practices make up a substantial component of all tropical farming: shifting agriculture spans an estimated 258 Mha, with approximately 6–19% farmed annually; the remainder is naturally regenerating as forest [19]. However, these systems are transitioning to more permanent and mechanized farming with inputs, including via small-holders selling or leasing farmland for monoculture conversion [20]. Further, improvements to road networks in such areas aimed at reducing yield gaps [21] would aid the delivery of crushed silicates. Thus, over time, much of these systems will probably become suitable for EW.

4. Potential positives

(a) Improved productivity and reduced CO_2 emissions from agriculture

Silicate rocks contain P, Mg, K and Ca, which are limiting nutrients for plant growth, thus their release via EW can fertilize crops [5]. There is a long history of amending soils with ground silicate rocks to improve crop yields, especially in highly weathered tropical soils in Africa and Brazil [22,23]. For example, cocoa plants applied with basalt (5 or 10 t ha^{-1}) had higher concentrations of K (1.4-fold), Mg (10-fold) and Ca (1.7-fold) than untreated controls [24]; after 24 months, treated plants were 50% taller and 60% thicker-stemmed than controls [24]. In many cases, silicate rocks are likely to be applied in combination with fertilizer and/or manure. In Mauritius, addition of 60–250 t basalt ha^{-1}, in combination with standard N, P, K fertilizer treatments, increased yields by 29% over five successive crops and by 17% over three successive crops in two different sets of replicated trials compared with plots receiving fertilizer only and no basalt addition [25], indicating a positive interaction between basalt and fertilizer.

EW also releases silica into the soil and is taken up as silicic acid by major tropical crops, including rice, oil palm, sugar cane, maize and sorghum [3,26,27], helping to confer resistance to economically important pests and diseases [3,26,27] via mechanical cell wall strengthening (deposition of silicon within tissues) and defence priming

[28,29]. Silicon can improve water-use efficiency by lowering leaf transpiration rates, potentially increasing crop resilience to drought [3]. Application of silicate rocks for EW might therefore contribute to improving food security in drought-threatened areas and reduce the use and costs of pesticides.

Application of crushed basalt increases pH on highly weathered tropical soils [24], and helps mitigate soil acidification in agricultural regions more generally [30] and production constraints in crops established on acidic soils (e.g. heavy metal toxicity in plants [24], including oil palm on drained peatlands in Southeast Asia [31]). EW effects on soil pH broadly mirror those of liming agricultural soils to reduce acidification [32]. Substituting silicate EW for liming averts CO_2 emitted when lime reacts with soil water and during its production [32].

(b) Land sparing

Expansion of tropical agricultural area continues at high rates (102 Mha from 2000 to 2010; electronic supplementary material, table S1), mainly via deforestation (e.g. [31]). If application of silicate rocks improves crop yields, food demand might be met on reduced land area, resulting in less deforestation and/or more natural forest regeneration on abandoned marginal farms. The Green Revolution in Asia and Latin America was land and greenhouse gas emissions sparing [33], suggesting increased yields produced by EW could offer further land savings. Absence of effective market regulation and land planning, however, may cause perverse outcomes of higher-yielding, cheap tropical crops, including further deforestation [34].

(c) Reduced risk of phytoplankton blooms in rivers and reefs

Fertilizers applied at high doses and incorrect times of year in tropical farmland are frequently eroded (washed away), and deposited into rivers and nearby oceans, causing large phytoplankton blooms [35], including toxic blue-green algae. Threat of eutrophication is dependent on Si : N and Si : P ratios in run-off water [36,37]. Cultural eutrophication occurs when high N and P but low Si cause algal blooms. EW of silicate rocks will likely generate high Si : P and Si : N ratios in run-off, increasing diatoms that remove nutrients from the water, preventing cultural eutrophication and instead supporting diverse and productive food webs [37]. This could be a significant benefit for polluted riverine, reef and oceanic ecosystems downstream of major areas of tropical agricultural production, while increased diatom production could increase CO_2 drawdown in the oceans [4,38].

5. Potential pitfalls

(a) Greenhouse gas emissions from grinding and transport

Global analyses indicate that energy costs (i.e. CO_2 emissions) associated with mining, grinding and spreading rock dust could decrease efficiency of CO_2 sequestration by EW by 10–25%, depending on grain size [39]. However, this cost will likely decline as the world transitions to decarbonized energy sources. Increased transportation of crushed rock would increase NO_x emissions. In 16 Mha of oil palm plantations, which are high isoprene emitters, this could raise ground-level ozone (O_3) to harmful levels for plant and human health [40].

(b) Yield quality

Potentially toxic elements contained in some silicate minerals could become bioavailable under EW, reducing yields or accumulating in the food chain [3], with human health issues. In particular, high nickel and chromium content in olivine would be problematic in agriculture and in association with asbestos-related minerals in major mines [5]. EW with basalt appears the pragmatic choice for application in tropical agriculture to avoid unintended negative consequences [5]. The trade-off is that, theoretically at least, basalt is less effective than olivine for CO_2 capture (e.g. approximately 0.3 $tCO_2\,t^{-1}$ basalt versus 0.8 $tCO_2\,t^{-1}$ olivine [41]). Ancillary benefits of basalt for crop production, soil improvement and suppression of greenhouse gas emissions that are less likely to accrue from olivine and the lack of heavy metal toxicity would lower the practical barriers to take-up by farmers in tropical agroecosystems.

(c) Biodiversity impacts within plantations and adjacent forest

Tropical farmland has wildlife that provides important ecosystem services for humans, including pollination and pest control. How these species will respond to silicate application is unknown. In particular, increasing pH could have negative consequences for species adapted to low pH soils, which are widespread in tropical regions, especially in peatlands. Forest edges are affected by environmental changes (e.g. increased wind, higher nutrient loads) that penetrate tens to hundreds of metres into forest interiors [42]. How far crushed silicates penetrate into forest from farmland and what the consequences would be for biodiversity adapted to nutrient-poor and acidic mature soils are uncertain. If consequences were negative then this would be a major concern, given that 25% of the Amazon and Congo and 91% Brazilian Atlantic forest is within 1 km of farmland edge [43].

(d) Reduced water quality in rivers and reefs

If unweathered silicates are washed into rivers, perhaps during intense tropical rainstorms, increased inorganic turbidity and sedimentation might follow, reducing reproduction and recruitment in river fish populations [44]. Higher sediment loads and inorganic turbidity cause coral mortality and reductions in reef diversity and depth limit [45]. There are thus potentially severe negative implications for local fisheries and conservation, although such losses would need to be weighed against any benefits gained from reduced organic turbidity (i.e. lower eutrophication, see §4c above). Increased water pH might also negatively impact riverine plants and animals, especially in naturally acidic drainages (e.g. peatlands).

(e) Mining and infrastructural expansion

Although silicates are a waste product from mining and steel and iron production [46], if applied pan-tropically then new or larger mines could be required. For instance, rock application to 670 Mha of tropical cropland at 10 $t\,ha^{-1}\,yr^{-1}$ would require 6.7 Pg of rock per year, and at 50 $t\,ha^{-1}\,yr^{-1}$

would need 33.5 Pg annually [5]. By comparison, global silicate production is 7-17 Pg [46] and global aggregate production is 40 Pg [47,48]. Mine creation is environmentally destructive, driving deforestation across the tropics and often occurring within or near to areas of high biodiversity value [49]. Development and expansion of road and rail infrastructure for mining can increase access to biodiverse and remote ecosystems [49], which combined with employment opportunities, encourage population immigration, land clearing for agriculture and hunting [49].

6. Future directions

We highlight nine major outstanding questions, indicating the need for further research on EW and clear protocols and regulations for any pan-tropical roll-out.

(1) *How effective is tropical agriculture at enhanced rock weathering?* Effectiveness of tropical agricultural systems at EW is a critical unknown and requires replicated pot experiments under field conditions for different key crops (figure 2; electronic supplementary material, table S1), soil types, application rates and particle sizes. Resolving effective particle sizes that can be adopted in tropical agriculture will be critical because of the high energy costs associated with grinding rocks to fine particle sizes (less than 10 μm diameter) [39]. Once these questions have been addressed, field-scale trials are required to understand additional effects of catchment topography, drainage and soils on EW rates and to evaluate biogeochemical models. This information is critical for informing accurate spatial projections of pan-tropical carbon capture for EW in agriculture.

(2) *What are the long-term effects of EW on farms and neighbouring forest?* We need to quantify a range of processes at catchment scales before and after the application of silicate for multiple years (Shao *et al*. [50] added silicate (wollastonite) to the Hubbard brook catchment and found effects lasting over a decade). These should include rates of weathering, as well as impacts on yield, sediment and chemical run-off into streams, and biodiversity within plantations. Application rates for crushed silicates required for carbon capture are uncertain (e.g. approximately 10–50 $t\ ha^{-1}\ yr^{-1}$ [5]) and could be higher than current estimates. In practice, application rates would be optimized for crop type, prevailing climate and soil, but will likely exceed those used for liming. On widespread highly weathered oxisols in the tropics, annual liming rates to obtain 90% of maximum yield (i.e. maximum economic rate) can reach 9 $t\ ha^{-1}$ for soya bean, 8 $t\ ha^{-1}$ for corn, 6 $t\ ha^{-1}$ for cotton and 3.8 $t\ ha^{-1}$ for sugarcane [51], with usual application rates for Brazilian soy of approximately 4–6 $t\ ha^{-1}\ yr^{-1}$ [18]. A key question is what happens to the unweathered materials: if they accumulate in farmland or wash into rivers, then we need to understand the implications for major biogeochemical processes and biodiversity. Precision application methods might be necessary to optimize rates of application and EW while minimizing any harmful biological effects.

Adopting farm catchments in proximity to natural forest will enable monitoring of silicates' penetration into adjacent forest, including if/how they affect plant growth, interactions between species and biodiversity conservation value. If edge effects of EW are severe, then research should identify which forest patches have sufficiently high conservation value to require protection, and in those cases, silicates should only be applied at a minimum distance from forest edge.

(3) *What is the effect of EW on tropical agriculture yields?* Using pot (*1*) and catchment-scale (*2*) experiments, we need to investigate how crop yield is affected by EW and investigate yield quality to determine the grades of silicate rocks that do not risk bioaccumulation of toxic metals. Is the fertilizer effect sufficient to allow farmers to reduce (or cease) application of commercially produced fertilizers? These data will allow assessment of economic costs and benefits of EW to farmers, and determine when and for which crops yield benefits are sufficient to promote adoption by agriculture.

Additional co-benefits of EW need to be understood given that they might incentivise widespread adoption. These include the benefits of increasing soil pH of widespread highly weathered acidic tropical soils, and increased plant resistance to pests, diseases and drought. Each could reduce or remove the necessity for liming, pesticides and fungicides, and increase crop yields with drought.

(4) *How does EW affect hydrological cycles, rivers and coral reefs?* By increasing plant water-use efficiency or changing sand-silt-clay fractions, EW might alter local hydrologic cycles, and this should be modelled [3]. We also need to understand fluxes into rivers and coral reefs from treated catchments to quantify likely effects on sedimentation, turbidity, pH and enhanced Si : N and Si : P ratios. This will identify the net balance between the potential positives of reduced ocean acidification and cultural eutrophication versus the negatives of poorer water quality. By sampling biodiversity within streams of catchment studies (*2*), any local-scale impacts would provide an early warning system to larger river- or reef-scale impacts.

(5) *How to minimize human health risks with silicate application?* At small particle sizes, there are health risks for workers crushing or spreading silicates, including silicosis and other respiratory diseases [5]. Especially in areas where agriculture is not managed by agribusiness, this would require a pan-tropical investment in education, safety equipment and protocols. Additionally, application in tropical dry seasons could lead to large quantities of silicates being eroded by wind with potential issues for local population settlements.

(6) *Can EW link with large-scale tropical reforestation programmes?* As in (*1*), we need to understand optimal grain size and application of EW in large-scale reforestation systems and how that affects growth and carbon sequestration across a range of tree species with differing mycorrhizal associations and soil types. We also need to understand whether it would be cost-efficient to apply EW to reforestation, given a lack of long-term manpower and transport networks, and impacts on biodiversity and ecosystem services.

(7) *Will there be unintended mining and transport impacts of EW and how can they be prevented or mitigated?* We need to understand the mass of silicate rock required for tropic-wide application of EW and whether existing mines and infrastructure can meet this demand. If they cannot, then we must predict likely sources of silicates and resulting on- and off-mine consequences for deforestation, biodiversity loss and socioeconomic change. Investors in 'conservation mining' to reduce climate change via EW must then demand strict environmental standards to prevent such on- and off-mine impacts.

(8) *Will the carbon savings from EW outweigh the carbon costs of producing and applying silicates?* In (*1*) we highlight a need to understand the optimal particle size and application quantities to maximize EW and thus CO_2 sequestration rates, plus CO_2 emissions savings from avoided liming. This needs to be balanced against the energy costs of mining, grinding, transporting and spreading via a full life cycle assessment analysis across the tropics and different crop types. A related issue will likely be the need to innovate and develop new high-efficiency low-carbon emitting grinding technologies, including adopting solar energy in tropical regions.

(9) *What role might carbon markets play in incentivising roll-out of EW?* We need to calculate the carbon market cost ($\$t^{-1}$ CO_2) to subsidize silicate application across a range of crop types and socioeconomic (e.g. labour cost) and geographical (distance to market, etc.) scenarios to make EW no net cost or profitable to farmers. This will entail understanding and modelling the full range of economic costs and profits of EW, combined with net carbon budgets from (*8*).

7. Conclusion

EW is a promising NET option that could deliver significant co-benefits to tropical agriculture and coastal ocean ecosystems. However, major issues remain regarding the potential effectiveness of EW and the associated benefits and pitfalls of the related operation for tropical agroecosystems and natural habitats. If empirical evidence from field studies and carbon cycle modelling demonstrates a significant capacity of pan-tropical agroecosystems for net long-term carbon sequestration, then these benefits to humanity will need balancing against negative impacts on biodiversity and ecosystem services.

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