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PERSPECTIVE

Farming with crops and rocks to address global climate, food and soil security

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Limiting future climate change requires urgently decreasing CO_2 emissions through decarbonisation of energy supplies and developing approaches for carbon dioxide removal (CDR) from the atmosphere. Here, we discuss the potential for biogeochemical improvement of croplands by amending soils with crushed fast-reacting silicate rocks as a CDR strategy to address the threats of climate, food and soil security. By improving crop production and protection from pests and diseases, and restoring soil fertility and structure, this strategy could generate financial incentives for widespread adoption in the agricultural sector. Managed croplands worldwide are equipped for frequent rock dust additions to soils, making rapid adoption at scale feasible. However, audited field-scale assessments of CO_2 capture efficacy are urgently required together with detailed environmental monitoring. Recycling substantial quantities of silicate waste materials might help meet the rock requirements in a cost-effective manner. Issues of public perception, trust and acceptance must also be addressed.

Rising concentrations of atmospheric CO_2, and other greenhouse gases emitted by human activities, are already having substantial adverse climate impacts that threaten global food security[1,2]. These impacts include more intense heat waves and droughts, as well as more extreme and variable rainfall, floods, and storms fuelled by latent energy in water vapour[2]. This situation is unfolding at a time of unprecedented increase in food demand linked to dietary changes and a growing population that may reach ~11 billion by 2100, with agriculture itself a growing contributor to climate change[2,3]. Crop yields are being further compromised by arable top soil losses that exceed natural rates of formation by an order of magnitude and the depletion of nutrients, such as phosphorus (P) and potassium (K)[4]. Soil nutrient stripping is being addressed with fertilizers, but these are based on finite resources that drive price inflation[4].

Here, we examine in detail one option to help provide the required increases in yields, while reversing the negative impact of agriculture on sustainability and climate change.

Action on climate change is essential given global mean temperature, already more than 1°C above the pre-industrial level, will exceed the United Nations Paris Agreement 1.5°C aspirational limit[5] within 30 years with the recent warming rate of 0.18°C per decade[6]. Further warming is 'in the pipeline' because of Earth's present energy imbalance, thermal inertia in the ocean response, and slow amplifying climate feedbacks, including ice-sheet melt[6]. The continued response of the climate system to increased greenhouse gases, and practical difficulties of transitioning to carbon-free energy, makes even a more lenient 2°C warming target[5] challenging. Consequently, the effective mitigation policy needed for meeting the UN targets requires rapid phasing out of fossil fuel emissions and deployment of scalable approaches for carbon dioxide removal (CDR) from the atmosphere with so-called negative CO_2 emissions in the second half of the 21st century[7-9]. Danger of sea level rise with loss of productive coastal marine and agricultural ecosystems, resulting displacement of people inland, and effects of increased climate extremes, add further urgency to the need to offset CO_2 emissions[2,6].

The United Nations 21st Conference of the Parties in Paris marked a turning point in the climate change debate with the focus shifting from describing climate change to a commitment to seek innovative, sustainable solutions[10]. Enhanced weathering aims to accelerate the natural geological process of carbon sequestration with production of alkaline leachate that reduces ocean acidification. It is achieved by amending the soils of intensively managed croplands with crushed calcium (Ca) and magnesium (Mg)-bearing rocks[11-13]. Besides removing CO_2 from the atmosphere, we discuss how this strategy has the potential to also rejuvenate soils, stabilize soil organic matter, improve crop yields, conserve geological fertilizer resources, and benefit the marine environment.

Carbon capture with crops and rocks

Enhanced weathering accelerates CO_2 reactions with minerals contained in globally abundant, Mg- and/or Ca-rich rocks, a process that naturally moderates atmospheric CO_2 and stabilizes climate on geological time scales. In soils, chemical breakdown of carbonate and silicate rocks is accelerated during aqueous reactions with the elevated soil CO_2 environment, releasing base cations (Ca^{2+} and Mg^{2+}) and delivering bicarbonate (HCO_3^-), and to a lesser extent carbonate (CO_3^{2-}) anions via runoff to surface waters and eventually the ocean. Enhanced weathering, therefore, uses the oceans to store atmospheric CO_2 as these stable dissolved inorganic alkaline forms (**Figure 1**). Given the oceans worldwide store around 38,000 Pg C, >45 times the mass of C in the current atmosphere, their future storage capacity is not an issue[14]. The residence time of dissolved inorganic carbon in the global ocean is around 100,000 – 1,000,000 years, making it essentially a permanent C-storage reservoir on human timescales[15]. Silicate weathering on land can also sequester atmospheric CO_2 without involving the oceans, if soil pore water chemistry results in precipitation of secondary carbonate minerals from base cation release[15]. In this case, the precipitated carbonate becomes the sink for CO_2 rather than ocean alkalinity. Carbonate weathering on acidic agricultural soils can lead to a net CO_2 flux to air[16,17], and carbonate minerals lack silica (Si) and other plant nutrient elements. The process of carbonate weathering on land thus delivers fewer benefits to climate, soils and crops. For these reasons, we focus on enhanced silicate weathering.

By adding alkalinity to the ocean, enhanced weathering enables the oceans to store more carbon, counters the effects of ocean acidification and the ongoing decrease in $CaCO_3$ saturation state, critical issues for protecting marine biocalcifiers, such as corals and shellfish, from acidification impacts[18-20]. Untreated, such impacts are estimated to cost the global economy[21] as much as $1 trillion a year by 2100.

Like other potential large-scale CDR strategies[15,22,23], enhanced weathering is relatively immature and requires further research, development and demonstration, including across a range of crops, soil types, climates and across spatial scales (**Table 1**). Experimental and small-scale evaluation of CO_2 capture efficacy and permanency remain priority research areas to understand its future relevance and contribution. A catchment-scale one-off application of 3.5 t ha^{-1} of pelletized calcium silicate powder, wollastonite, to the 11.8 ha watershed of the Hubbard Brook Experimental Forest, New Hampshire, USA, confirmed key anticipated effects[24,25]. These included rapid (12-24 months) 50% increased delivery of weathered calcium and silica dissolved in stream water, alleviation of ecosystem acidification and decreased release of soil aluminium[25]. An upper estimate for CO_2 capture by wollastonite dissolution in the streambed during the first year of treatment, made assuming Ca^{2+} release is balanced by (bi)carbonate production, suggests a range of 110-224 g CO_2 m^{-2}, with a CO_2 capture efficiency of ~60% for the mass of wollastonite applied[26]. This upper bound, however, is not likely to be representative of CO_2 capture by weathering in the forest soil, which remains to be quantified for this experiment[26].

Given that farmers routinely apply granular fertilizers and lime, annual applications of, for example, ground basalt (an abundant, weatherable Ca- and Mg-rich rock) is feasible at large scale with existing farm equipment. Global cropland (arable, forage, fibre, fruit etc.) covers approximately 12×10^8 ha (12 million km^2)[27] and an additional 1-10 × 10^8 ha of marginal agricultural land may be available where basalt treatment could rejuvenate degraded soils[28]. Effectively, nearly 11% of the terrestrial surface is managed for crop production and this may offer an opportunity to deploy a means of carbon sequestration at scale within a decade or two. Rapid deployment of CDR strategies is an essential requirement for significantly offsetting carbon emissions in the latter half of the twenty first century to avoid CO_2 and temperatures peaking and then declining with potentially adverse ecological and economic consequences[8,23]. A first assessment might be achievable in areas of high-intensity agriculture where basalt, rock-crushing machinery, transportation infrastructure and agricultural spreaders are available, e.g., North America[29] or the UK[30].

Investigations of potential CO_2 sequestration by enhanced weathering with forested lands[12], and the oceans[31-34], have tended to focus on fast-weathering ultramafic olivine-rich rocks for which commercial mines are already in operation. Olivine comprises well over half the content by weight of ultramafic rocks, and is one of the fastest-weathering silicate minerals at $pH < 6$, potentially able to capture 0.8-0.9 t CO_2 per t of rock dissolved[30]. However, a synthesis of published chemical analyses indicates that olivine-rich ultramafic rocks (i.e., peridotite: dunite, harzburgite, iherzolite and wehrlite), contain relatively high concentrations of either chromium (Cr) or nickel (Ni) or both (**Figure 2**). Weathering experiments reveal fast release of bioavailable Ni from olivine, and suppression of plant calcium uptake, because of competition with magnesium[35]; experimental work with a soil column dosed with olivine suggested accumulation of Ni and Cr in the soil profile[36]. Widespread application of olivine to agricultural soils, therefore, could introduce harmful metals into the food chain, and the wider environment, as well as causing nutritional imbalances and warrant further research[18].

In contrast to ultramafic olivine-rich rocks, major continental flood basalts have lower concentrations of Ni and/or Cr (**Figure 2**) but significantly higher concentrations of phosphorus, suggesting their greater utility for croplands. Cultivation of crops on rich fertile soils that develop on flood basalts across continents is consistent with fewer environmental risks associated with this rock[37]. Basalt is widely recognized as producing productive soils because it weathers rapidly releasing elements essential for plant growth[38], including P, K, Ca, Mg and Fe. In terms of comparative weathering rates, olivine dissolution rates at oceanic pH~8 (10^{-10} to 10^{-11} mol olivine-Si m^{-2} s^{-1}) are within the range of those for basalt dissolution rates at pH 4 and above expected in soils (10^{-10} to 10^{-12} mol Si m^{-2} s^{-1})[39].

Significant potential exists for deployment at scale to remove atmospheric CO_2 with ground basalt. A maximum carbon capture potential of ~0.3t CO_2 t^{-1} is suggested for basalt, assuming a sufficiently fine particle size for effective dissolution on decadal time scales[30]. The actual particle size will depend upon the mineralogy of the basalt, climate and biological activity, and requires further investigation and verification, but initial calculations suggest particles of 10-30 µm diameter. On this basis, basalt applications of 10 to 50 t ha^{-1} yr^{-1} to 70×10^6 ha of the annual crops corn/soy in the corn-belt of North America could sequester 0.2–1.1 $PgCO_2$, up to 13% of the global annual agricultural emissions, in the long run[29]. Theoretical estimates of CO_2 capture and sequestration schemes involving global croplands and silicate rocks are very uncertain. Provisional estimates[22,40] suggest that amending two thirds of the most productive cropland soils (9×10^8 ha) with basalt dust at application rates of 10-30 t ha^{-1} yr^{-1} could perhaps extract 0.5-4 $PgCO_2$ yr^{-1} by 2100 depending on climate, soil and crop type. These numbers still need to account for full life cycle assessment, but suggest enhanced weathering could make a significant contribution to the negative emissions required by deep decarbonisation strategies[8,9,23] and the ~1 Pg CO_2 eq. yr^{-1} reduction from agriculture[41] by 2030. Involvement of extensive marginal lands classified as not productive, or cost-effective, for food crops, further increases the potential for offsetting anthropogenic CO_2 emissions, although these lands would tend to be less accessible. Better constraining the appropriate particle size distribution for effective dissolution of basalt grains and, ultimately, the technical potential of the approach requires integrated biogeochemical modelling of the plant-soil-atmosphere system to capture interactions between crops, rocks, soils and fertilizers (inorganic and organic)[42]. Subsequent experimental validation at adequate scale will be critical (**Table 1**).

A key issue affecting carbon capture efficiency is the energy cost associated with mining, grinding and spreading the ground rock, which could reduce the net carbon drawdown by 10-30%, depending mainly on grain size[43]. Relatively high energy costs for grinding, as influenced by rock mineralogy and crushing processes, call for innovation in the industrial sector, such as grinding and milling technology powered by renewable energy sources (solar, wind, water), to significantly increase the net CO_2 benefit. The benefit will increase as future energy sources are decarbonized, the grinding process becomes more energy efficient, and by utilizing already ground waste silicate materials previously or currently produced by the mining industry. By driving down costs for grinding in this way, carbon sequestration costs would be correspondingly cheaper.

Current cost estimates are uncertain and vary widely, and better understanding the economics involved is a priority. The most detailed analysis for operational costs drawn-up for using a basic rock, such as basalt, gives values of US$52-480 tCO_2^{-1}, with comminution and transport the dominant components[30]. This cost range falls below that estimated for bioenergy with carbon capture and storage (BECCS) of $504-1296 tCO_2^{-1} (US$140-$360 tC^{-1})[22]. Deployment costs may be partially or completely offset by gains in crop productivity, and reduced requirements for lime, fertilizer, pesticide and fungicide applications, discussed later. Co-deployment of enhanced weathering with other strategies such as reforestation and afforestation, and with feedstock crops used in BECCS and biochar, could also reduce costs and significantly enhance the combined carbon sequestration potential of these methods.

Rocks for food and soil security

The amount of rock required to deploy enhanced weathering at scale is straightforward to calculate. We analysed illustrative application rates across 9 × 10^8 ha of the most productive managed lands based on FAO yield statistics for the dominant (in terms of area) annual crops[27], with the assumption that crop production is a reasonable proxy for good weathering conditions; both crops[12,13] and rock[39] weathering require sufficient warmth and water. A wide range of experimental studies also point to annual crops as accelerating basalt weathering[38,44-47] but this aspect is not considered further here. Calculated in this way, application rates of 10 to 30 t ha^{-1} yr^{-1} require 9-27 Pg rock yr^{-1}, although in practice, optimization of application rates will follow crop and soil type. These rock-dust application rates compare with recommended liming rates for UK arable soils[48] of 0.5-10 t lime ha^{-1}. For context, the global aggregate industry extracts ~50 Pg rock yr^{-1} for construction, global mining for raw mineral materials[49] extracts ~17 Pg yr^{-1} and the global cement industry extracts around 7 Pg yr^{-1} of raw material (mainly limestone, shale, and/or clay)[15]. The mass of rock distributed onto land could be reduced if applications were optimized by, for example, restricting to 90% of the most productive regions to improve cost effectiveness. This is equivalent to 75% of agricultural land for annual crops (6.8 × 10^8 ha) (**Figure 3a**), and reduces the required rock mass to 7-20 Pg rock yr^{-1}. However, these amounts would change if deployment kept pace with projected expansion of arable cropland, which is subject to population growth, dietary choices and land use practices[50].

Analysed by national crop production (area × productivity), these data indicate China, USA and India are the leading countries potentially able to sequester CO_2 in this way, with Russia and European countries, mainly Germany and France, next best placed (**Figure 3b**). Russia's relatively high agricultural productivity on moist Steppe soils, and warm summer temperatures over much of its growing region, may be conducive to CDR with enhanced weathering. These countries are the largest contributors to cumulative global CO_2 emissions from fossil fuels and industry (**Figure 3c**) since the pre-industrial era (1870) (565 ± 55 PgC)[51] that is driving global warming[51,52].

Demand for reactive silicate rocks could be partially met if the 7-17 Pg yr^{-1} freshly produced plant nutrient-containing silicate mining and industrial waste materials are utilized[53], more if legacy reserves are exploited. Assuming uncarbonated minerals and compounds remain, recycling these wastes might meet a considerable fraction of the demand given the application rates considered here. Mining of igneous rocks for construction generates an estimated 3 Pg yr^{-1} of fine grained materials, too small for use as aggregates, which may be suitable for carbon capture with crops via enhanced weathering, with a considerably lower energy penalty for grinding[53]. Increased construction and building activities in Brazil have promoted exploitation of basaltic reserves, and interest is growing in recycling accumulating fine basalt dust waste (particle size distribution peaking in the fine silt range of 10-20 µm diameter) as a natural agricultural fertilizer[54]. Mining of rocks for minerals, ores and metals produces a further 2-7 Pg yr^{-1} of overburden material that may also be suitable for CDR[53], depending on host geology, with total waste in the USA alone of ~40 Pg accumulating between 1910 and 1980.

In addition, waste materials from industrial processes including cement production and steel manufacturing may also be suitable for enhanced weathering[53]. Cement manufacture contributes ~6% of global CO_2 emissions[51], and cement-based products (mainly concrete) used for construction also contain weatherable calcium-bearing minerals. Huge quantities of construction/demolition waste (1.4-5.9 Pg yr^{-1}), often used for landfill, have potential for enhanced weathering[53]. Iron and steel manufacturing produces readily weatherable calcium silicate slag waste (0.4-0.5 Pg yr^{-1}), with the accumulation of significant global stockpiles (5.8-

8.3 Pg)[30,53]. Steel slag contains fertilizer components (CaO, SiO_2, MgO, FeO, MnO and P_2O_5) with alkaline properties for remedying soil acidity. Consequently, these industrial by-products already have a long-history of being used on farms in place of lime, increasing crop production without toxic metal contamination at the application rates used for soil pH adjustment[55], and may have scope for wider adoption in enhanced weathering. China, a potentially important player in enhanced weathering (**Figure 3b**), is the largest steel producer in the world, but only recycles 22% of its steel slag, with scope for greatly expanding this use[56].

Residual combustion products from some agricultural sectors produces 0.2-0.4 Pg yr^{-1} of calcium-bearing ashes, with estimated cumulative reserves of 4-8 Pg since 1980, suitable for enhanced weathering[53]. Globally, the sugarcane industry produces ~47 Tg ash yr^{-1}, with the Australian sugar industry[57] alone producing 1 Tg yr^{-1}, enough to apply to 10,000 ha. Mill ash is a base cation, nutrient- and silica-rich by-product of fibrous cane residue combustion that improves cane yields by up to 40% at application rates of 50-60 t ha^{-1} (dry weight)[58,59], with significant enhanced weathering potential.

Use of these mining and industrial wastes might be supplemented with substantial Ca-rich basic igneous silicate-rich rocks available as 38 × 10^8 ha (38 million km^2) of surface exposed continental flood basalts produced episodically by massive volcanic eruptions throughout Earth's history[60]. Major formations are located near to productive agricultural regions where rock might be required with estimated masses[60] sufficient for the annual requirements for enhanced weathering over many decades. For example, the USA might be served by the Central Atlantic Magmatic Province (eastern US) and the Columbia River basalts (Washington/Oregon), South America by the Paraná-Etendeka Traps and the Caribbean–Colombian Plateau, China by the Emeishan Traps, Russia by the Siberian Traps, the UK by the North Atlantic Igneous Province, western India by the Deccan Traps, and eastern India by the smaller Rajmahal Traps.

Adding crushed silicates to soils, whether residues or purposely mined, will likely have further economic benefit arising from their ability to help replenish eroded soil, and enhance SOC content, both serious global concerns threatening food security[61,62]. Erosion rates from cropland soils outpace natural rates of formation by a factor of ten (average ~6 t ha^{-1} yr^{-1} loss vs. 0.6-0.8 t ha^{-1} yr^{-1} formation), limiting agricultural sustainability[61]. Erosion rates in US cropland soils, while declining some 50% over the past 30 years, still range from ~3 to ~13 t ha^{-1} yr^{-1}, depending on agricultural practices[61]. In the European Union[63], soil erosion rates over 12.7 % of arable land exceed 5 t ha^{-1} yr^{-1}. Depending on management practices, this situation is likely to worsen with climate change. Increased variations in rainfall patterns and intensity will make soils more susceptible to erosion. If agricultural soil erosion outpaces rates of soil formation, new methods will be needed to sustain and protect soils[61], which have suffered global losses of 133 PgC from the original carbon stocks in the top 2 m over the past two centuries[62].

Enhanced weathering might help reverse diminishing SOC stocks and retard soil erosion. Cation release from basalt weathering increases the cation exchange capacity of soils and nutrient availability[64,65] and could improve SOC sequestration by resulting in higher inputs of organic carbon from roots and mycorrhizal fungi, which themselves promote soil aggregate formation and SOC stability[66]. Increased formation of clay minerals from weathering of silicates could further increase SOC retention through a range of organo-mineral interactions, including adsorption reactions and physical protection of organic matter from decomposing organisms, which help build soil while improving quality[67]. Increasing SOC in the rooting zone benefits crop yields in diverse agricultural soils of the tropics and sub-tropics[68]. Operating across timescales from years to several decades, these effects, and others associated with increasing mineral surface area available to trap soil carbon[69], could help rebuild soils and retard erosion. It may, therefore, contribute to increasing soil organic matter stocks, the goal of the '4 per 1000 Initiative: Soils for Food Security and Climate', proposed under the Agenda for Action of the 21st session of the United Nations Framework Convention on Climate Change[70]. At present, however, the long-term effects of applying pulverized silicate rocks on the organic carbon content of agricultural soils is not understood and requires further research. Over time, adding crushed rocks to soils will change their porosity, and other factors governing hydrology, with feedbacks on crop performance, trace gas emissions, and the diversity and functioning of soil organisms, that are currently uncertain.

Enhanced weathering strategies not only capture carbon but could also help restore soils and resupply impoverished reserves of trace elements important for human nutrition[71] and crop production[72]. Seven out of the top ten crops ranked according to global production data (sugarcane, rice, wheat, barley, sugar beet, soybean, and tomatoes) are classified as Si accumulators (> 1%)[65] and intensive cultivation and repeated removal of harvested products from the field is seriously depleting plant available Si in soils[73,74]. In the US, for example, crop harvesting removes 19 million tonnes of Si annually[75]. Annual depletion of soil Si by continuous intensive farming, coupled with low solubility of soil Si, has led to calls for the development of viable Si-fertilization practices in the near future to increase plant available pools and maintain crop yields[75-77]. Dissolution of crushed silicates, or Si-containing mining and industrial wastes, releases Si, replenishing the plant available form. The fate and transformation of enhanced weathering derived Si in the soil-plant continuum, and its long-term biogeochemical cycling[78], warrant future research in the context of mitigating Si-related yield constraints on agricultural crop production.

Crop production and protection

Amending soils with ground Ca/Mg-rich silicate rocks can improve crop yields and has a long history of being practiced on a small scale, especially in highly weathered tropical soils in Africa, Brazil[79,80], Malaysia[81,82] and Mauritius[83], as well as rejuvenating lateritic soils and promoting tree establishment in Europe[84,85]. Consequently, enhanced weathering of crushed silicates has a number of proven and expected benefits for temperate and tropical croplands that could improve its prospects for large-scale deployment[21,29]. Sugarcane trials with crushed basalt applications in excess of 20 t ha^{-1} in combination with standard NPK fertilizer treatments increased yields by up to 30% over five successive crops on the highly weathered soils of Mauritius compared with plots receiving fertilizer and no basalt addition[83]. Sugarcane, grown extensively on acidic, nutrient-poor highly weathered soils, generates approximately $43 billion a year to Brazil's economy and $1.5 billion a year in export earnings for Australia, suggesting such effects could offer significant economic incentives for the industry to adopt the practice more widely.

Few field and experimental studies have explicitly investigated basalt treatments on temperate croplands to test directly the effects on yields and soil properties but numerous field and greenhouse studies have documented the benefits of applying silicates and modified silicate wastes to crop production across the USA. This practice extends back to 1871 when the first patent for using Si-rich slag as a fertilizer was granted[75]. Consequently, decades of research has established processed Ca-silicate slag as an effective liming material and Si-fertilizer, without yet recognizing its CO_2 capture potential. Studies include field trials in Florida and Louisiana, where silicate slag applications increased sugarcane, maize and rice production and elsewhere in New Jersey where silicate slag increased yields of a wide range of crops including winter wheat, oats, cabbage and corn, with residual benefits continuing up to 3-4 years after the last application[75].

By generating alkalinity as they weather, silicate rocks reduce soil acidification caused by overuse of ammonium and elemental sulphur fertilizers, urea, growth of nitrogen-fixing legumes and repeated crop harvesting. Acidification of agricultural soils is a worldwide problem and reversing it improves nutrient uptake, root growth and crop yields. Neutralizing acidic soils also reduces metal toxicity (e.g., aluminium and manganese) and increases P availability, especially in highly weathered acidic tropical soils, where metal oxides strongly bind remaining P reserves[64]. Plant-induced weathering of basalt supplies trace amounts of P in the form of calcium phosphate, the primary source of P in most ecosystems and fertilizers, and adds plant-essential trace nutrients. For example, most of the nutrient-mined tropical soils in developing countries[4] are deficient in K, and crushed silicate rocks applied as slow-release K fertilisers can help sustain profitable crop production while achieving the primary goal of carbon sequestration[86].

Although not regarded as an essential element for plant growth, Si benefits productivity by enhancing the resilience of plants against abiotic stresses include drought, salinity and heat[72,87], all of which are expected to worsen with future climate change and sea-level rise[2]. Simultaneous increases in plant available Si in soils amended with silicates reduces the uptake of heavy metals (e.g., cadmium arsenic and lead) in the edible parts of agricultural crops[88-92]. Increased silica uptake from the soil is a competitive inhibitor of arsenic uptake in rice, for example, which is a widespread human health issue in southeast Asia[91]. Cadmium uptake in wheat is also reduced, and this is an important issue where prolonged application of fertilisers, especially single super phosphate, has generated toxicity in agricultural soils worldwide[92].

Benefits for crop protection against biotic threats from silicate weathering arise from production of soluble silicic acid that is readily taken up by plants, thereby improving stem strength and increasing resistance to pests and diseases in major temperate (e.g., soybean, wheat)[29] and tropical (e.g., sugarcane, maize, rice, oil palm)[21] crops. Greenhouse and field trials have shown Si augments host plant resistance to disease and actively suppresses diseases by influencing incubation period, latent period, lesion number and lesion size[75]. Staple cereal crops, such as rice, maize and barley, are major silica accumulators, with silicic acid transporters responsible for uptake into the root cortex and transfer to the xylem[93,94]. Silicic acid uptake acts by priming the defence pathways, for example, jasmonic acid (JA)-dependent plant immunity, and strengthens cell walls in leaves and roots[95]. This multi-mechanistic mode of action offers durable and broad-spectrum protection against a wide range of insect herbivores and pathogens.

Accordingly, Si-induced resistance offers tangible opportunities to protect temperate crops and tropical cereals against emerging and enduring pests, an increasing number of which are becoming resistant to pesticides. For example, the recent large-scale invasion of the fall armyworm (Spodoptera frugiperda) in Africa reduced maize production. However, Si-treated maize may restrict the spread of this invasive pest by significantly decreasing fecundity[96]. Si-induced resistance against phloem-feeding Hemiptera pests may also reduce the spread of major viral diseases that are transmitted by these insects, such as maize streak virus, the most damaging viral disease for this crop in Africa[97]. Cell wall strengthening and JA dependent defence pathways are involved in resistance against the parasitic weed Striga[98,99], which causes devastating losses of yields of rain-fed rice, maize, sorghum and millet in sub-Saharan Africa, costing the African economy over seven billion US$ annually[100].

Genetic assessment of crop attributes, e.g., capacity to recruit and associate with mycorrhizal fungi, could accelerate development of new, faster weathering, crop varieties.

Selection for new cereal varieties with increased performance (e.g., uptake and accumulation of silica) in response to silicate rock/agro-mineral fertilization could be achieved through conventional breeding and/or using gene editing techniques to modify elite varieties (e.g., CRISPR-Cas9). Engineering crop varieties that are effectively able to exploit soil amended with crushed silicate rocks would potentially deliver significant benefits by improving nutrient supply to fertilize production and increasing protection against pests and diseases as well as promoting weathering to raise pH, cation exchange capacity and increase soil organic carbon capture. However, such potential benefits require demonstration in replicated field trials (**Table 1**).

A further co-benefit may arise from agricultural application of crushed silicate rocks to soils suppressing emissions of the powerful and long-lived greenhouse gas N_2O and avert CO_2 emissions by liming. Liming with $CaCO_3$ can release CO_2 when it is applied to acidic soils (pH <6) typical of agricultural lands[16,17,101]; in the USA, liming contributes 2% of agricultural greenhouse gas emissions[16]. In contrast, silicate weathering consistently consumes CO_2 to produce bicarbonate and carbonate ions. By increasing soil pH as they weather, silicates may also reduce emissions of N_2O, as found with liming[102]. Preliminary tests with a replicated field experiment support this suggestion with the soil N_2O flux from heavily fertilized maize plots decreasing by ~50% with the application 10 kg m^{-2} of pulverized basalt with no effect on soil respiration[103]. Basalt-treated arable fields may, thus, lower the current substantial global soil-atmosphere flux from croplands[104] of 4-5 Tg N_2O-N yr^{-1} as a by-product of weathering.

In summary, potential ancillary benefits of CO_2 capture with rocks and agriculture include fertilization of yields and reduced use and cost of fertilizers, including those with finite geological reserves (rock phosphate)[4], neutralizing soil acidification, suppressing/averting soil greenhouse gas (N_2O and CO_2) emissions, restoration of micro-nutrients important for human nutrition, and replacement of soils lost by erosion (**Figures 1** and **4**). Additionally, increased crop protection from insect herbivores and pathogens, and avoidance of toxic metal uptake, resulting from release and uptake of silica, could decrease pesticide use and cost and improve yields, further safeguarding food security (**Figure 4**).

Environmental impacts

Development of widespread mining, grinding and spreading operations will likely have negative environmental and ecological impacts, especially if linked to tropical deforestation near areas of high biodiversity value that would require careful management[21]. However, the severity of the threat to biodiversity and local ecology would depend on the extent to which silicate waste materials are utilized thereby reducing the need for mining operations. Judicious selection of source materials, such as basalt instead of faster-weathering but Ni- and Cr-enriched ultramafic rock types, for example, minimizes dangers of toxic metal contamination (**Figure 2**). Avoiding inhalation of dust particles during mining, grinding and spreading will be important because these can cause silicosis. Additionally, particles washing into rivers, and ultimately the oceans, might cause increased turbidity, sedimentation and pH changes, with unknown impacts for marine biodiversity and function[21].

In addition to downstream alkalinity addition (discussed earlier), enhanced silicate weathering can be expected to increase dissolved silica fluxes to rivers and oceans. This may partially help mitigate effects of N and P in runoff from agricultural regions. Increased Si:N and/or Si:P ratios in runoff reaching coastal waters from soils amended with silicates might favour the growth of diatoms over problematic non-siliceous algae that produce toxins, red tides (dinoflagellate blooms), foam (Phaeocystis blooms) and scum (cyanobacterial blooms)[105,106]. Such a changed nutrient balance could also beneficially preserve or increase downstream food web and fisheries production because diatoms are the preferred diet of pelagic and benthic grazers, mostly copepods and bivalves[105,106], and increase marine biological CO_2 drawdown and storage[12,18], with economic benefits in particular regions. For example, the Great Barrier Reef is adjacent to the main sugarcane growing regions in Australia, where adding crushed basalt to soils may not only enhance sugarcane production, but also improve runoff and ground water chemistry while countering ocean acidity via alkalinity addition. However, the hypothesized benefits and impacts of land-based enhanced weathering on aquatic food webs have yet to be proven and require further research.

Outlook

Effective climate change mitigation requires an expanding portfolio of actions for extracting and sequestering CO_2 alongside urgent reduction of CO_2 emissions[2,6-9,107], as highlighted by the United Nations Environment Programme[108]. In our analysis, nations that contributed most to the problem have the potential to be big players in mitigation by addressing the substantial engineering challenge of developing an operational enhanced weathering industry (**Figure 3**). The challenge may be suited to international cooperation between nations, including provision of assets needed for implementation in developing countries. However, like the extensive deployment of any CDR approach, enhanced weathering not only has to be evaluated and proven in field-scale trials, with CO_2 sequestration potential better understood, but also has to be socially and environmentally acceptable. This requires extensive, detailed, risk assessment, public participation and transparency[109-110].

Adapting agricultural practices to manage soils, alongside reforestation efforts, for atmospheric carbon removal could help slow the rate of climate change, if combined with near-term emission reductions[2,6,107,108]. Continued high emissions, on the other hand, may force society to consider more expensive industrial-scale carbon clean-up operations to stabilize climate[6]. Methods of CO_2 extraction, like BECCS and direct air capture (DAC) of CO_2, require large-scale infrastructure development and investment with substantial energy and resource demands and potential land-use conflicts threatening global food security[6,8,23]. Spurring investment and bringing down costs of CDR options (e.g., BECCS and DAC), requires some form of market linked to the price of carbon. Investment incentives for enhanced weathering are potentially broader and include increased yields, improved soils, reduced agrochemical costs, improved runoff water quality in environmentally sensitive areas, and potential benefits to marine life.

We conclude that substituting a weatherable silicate rock, such as basalt, or silicate waste, for limestone, and increasing application rates over those used in conventional liming operations, may offer a pragmatic, rapidly deployable global carbon cycle intervention strategy. More broadly, if proven effective, and undertaken carefully to minimise undesirable impacts, enhanced weathering may have untapped potential for addressing the United Nations Sustainable Development Goals (SDGs) adopted by 193 countries in 2015[111]. For example, we highlight how sequestering CO_2 constitutes action on climate change (SDG 13), restoring soils and promoting sustainable agriculture contributes to zero hunger (SDG 2), helping protect the oceans from acidification conserves global resources in life below water (SDG 14), reducing agrochemical usage and recycling wastes helps with sustainable consumption and production (SDG 12), and improving agricultural production and restoring degraded soils contributes to land sparing (SDG 15) (**Figure 4**). However, there is an urgent need to address unanswered technical and social questions and develop rigorous audited testing in the field where the full elemental cycles can be closed, efficacy of CO_2 capture quantified, and the risks, benefits, socio-economics, techno-economics, and ethics assessed (**Table 1**).

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Contributions

D.J.B. conceived the study and wrote the first draft of the manuscript, with input on sections and addition of appropriate references from all authors. E.K., L.L.T. and M.K. undertook data analysis.

Competing Interests

The authors declare no competing interests.

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Figure legends

Figure 1. Summary of potential effects of applying crushed basalt or silicate-rich wastes, such as sugarcane mill ash, on crop productivity, nutrient use efficiency, water quality and CO_2 capture and sequestration, due to weathering.

Figure 2. Metal and phosphorus concentrations in a range of continental flood basalts (CFB) and ultra-basic rocks (peridotites). Values means ± s.e., measurement n for each is given in the lower graph. Data obtained from GEOROC (Geochemistry of Rocks of the Oceans and Continents) database maintained by the Max Planck Institute for Chemistry in Mainz (http://georoc.mpch-mainz.gwdg.de/georoc/)

Figure 3. (**a**) Calculated 75% of the most productive annual croplands, based on a reanalysis of 10 km × 10 km latitude-longitude resolution data for the year 2000, where crop net primary production (NPP) was calculated by converting FAO yield data[27], (**b**) ranked top 20 arable crop producing countries and (**c**) cumulative CO_2 emissions from all sources by country. CO_2 data from the Global Carbon Atlas: http://globalcarbonatlas.org

Figure 4. Enhanced weathering could address the 21st Century threats to society of climate, food and soil security.

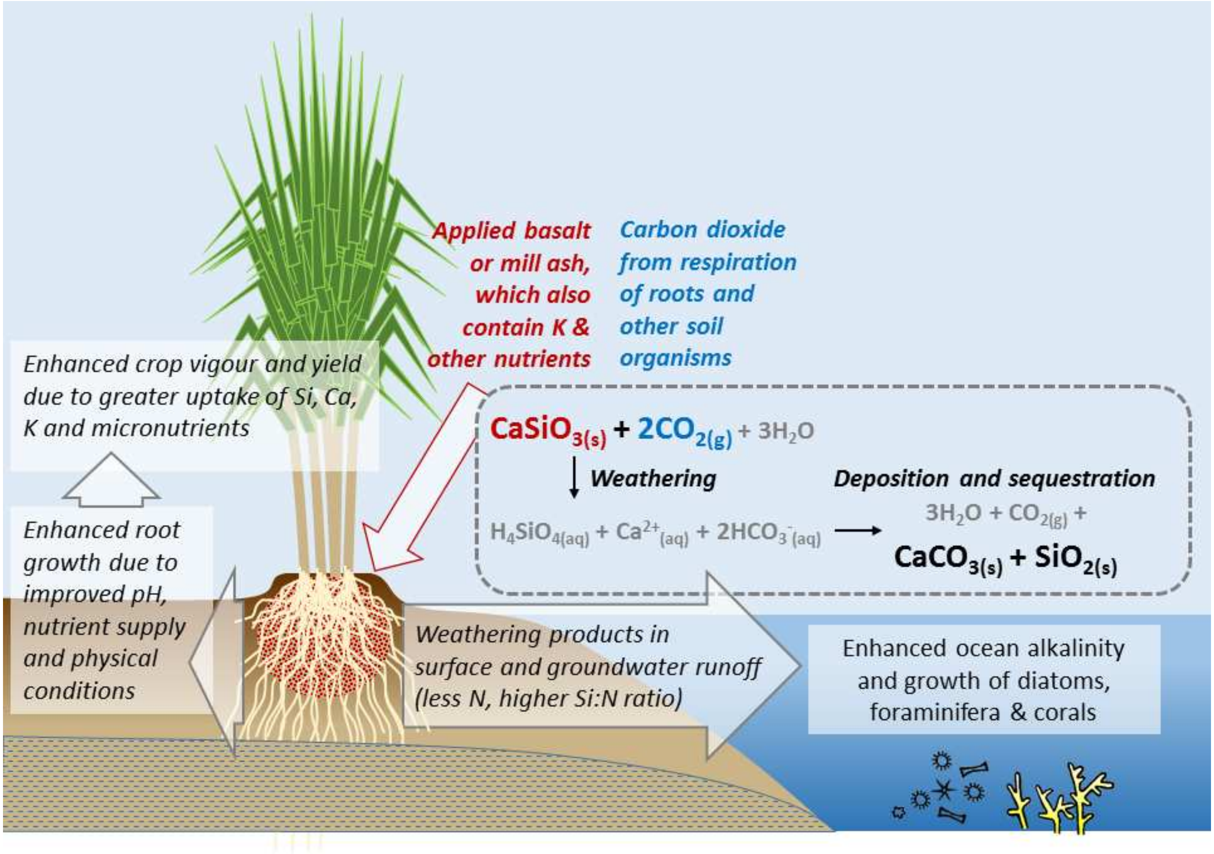


Figure 1

(Beerling et al.)

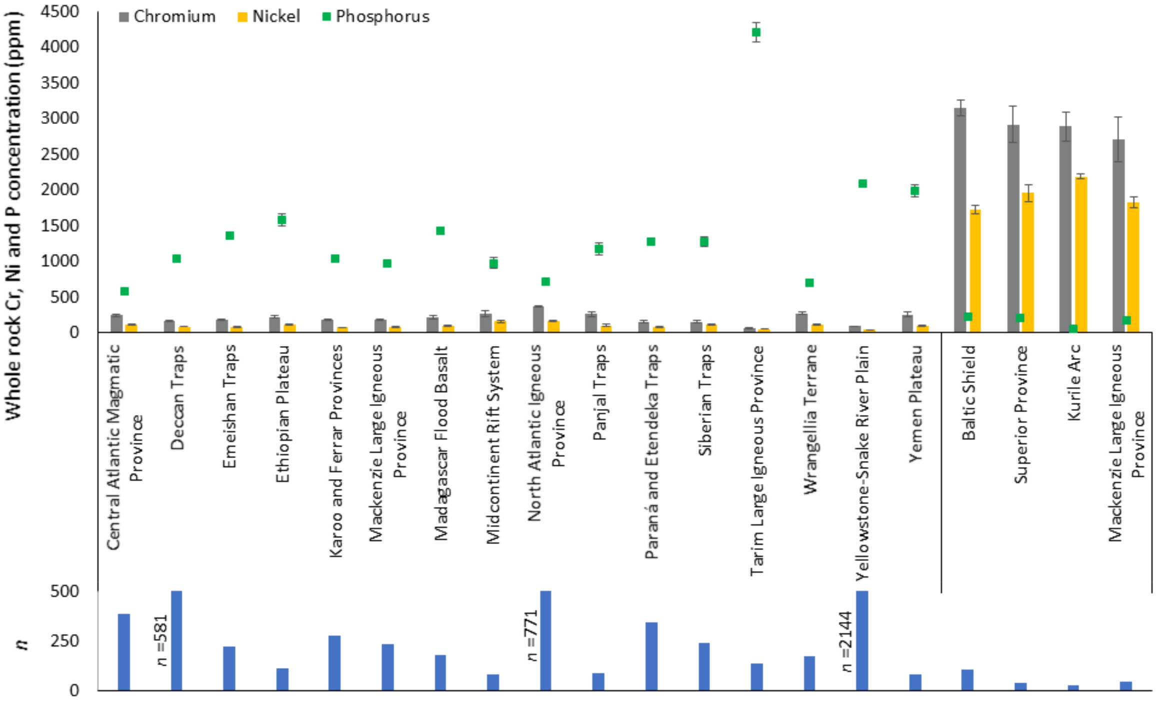
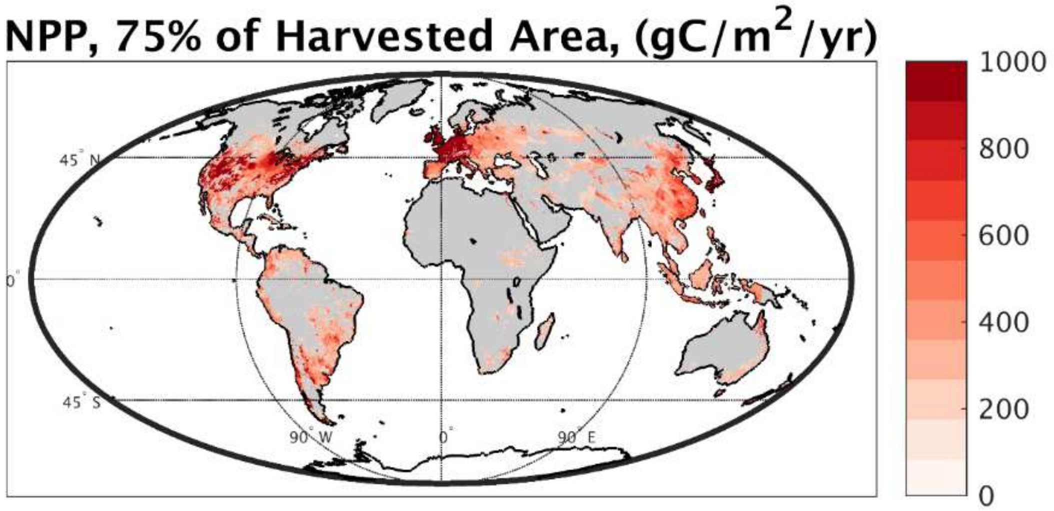
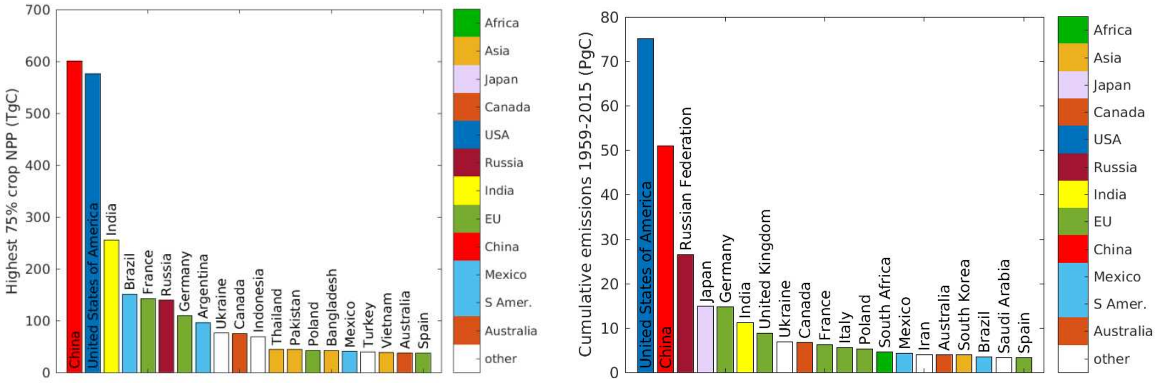


Figure 2

(Beerling et al.)

(a) Net primary production (NPP) of 75% of the harvestable area of global cropland




(b) Agricultural production by nation

(c) Cumulative CO_2 emissions by nation

Figure 3

(Beerling et al.)

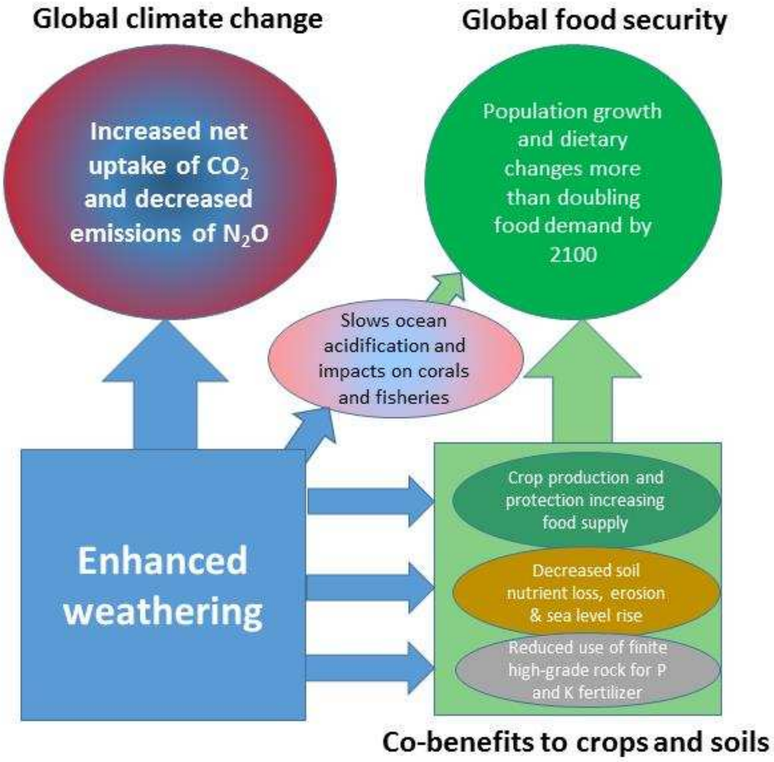


Figure 4

(Beerling et al.)

Table 1. Critical R&D needs for assessing the viability and effectivness of enhanced weathering (EW) for CO_2 capture via silicate application to agricultural soils at scale.

	Approach	**Goal**
1	Sites over different crops and major soil types within major global production areas, equiped with eddy-covariance to measure year round GHG emissions and instrumented field drains to measure drainage water chemistry and flux, allowing full budgets and environmental impact assessments.	Quantify net CO_2 capture and sequestration, silicate weathering rates and fertilization of crop performance (yield, water-use) under natural climate conditions that could reduce fertilzer application, costs and conserve finite P resouces.
2	Field crop trials with different major silicate sources, ideally in conjunction with 1 above.	Assessment of relative merits of different types of silicate rocks for CO_2 capture (e.g., basalt, dunite)
3	Controlled environment tests and replicated field trials of anticipated benefits of silicate applications on crop pest and disease resistance.	Determine translational opportunities for increasing crop protection and reducing pesticide usage and costs.
4	Genetic selection for high-weathering crops through a combination of enhanced exudation of weathering-enhancing root exudates and recruitment/associations with weathering-enhancing soil microbes.	Identification of weathering-controlling genetic traits and select for crop varieties with an enhanced capacity for weathering and releasing $Si(OH)_4$.
5	Genetic selection for crop varieties that are better capable of expressing Si-induced resistance, through a combination of Si-uptake mechanisms (i.e. Si transporters) and Si-responsive priming of JA-dependent immunity.	Characterization of the genetic basis of Si uptake, Si-induced cell wall defence and Si-induced immune priming to select for crop varieties with an increased capacity for Si-induced resistance.
6	Assessment of regional farm services capability to store, handle and spread silicates, coupled with past agronomic experience in spreading lime and silicate rich slags	Determine practicalities of deployment on croplands.
7	A full life-cycle economic/energy analysis of the cost-benefits of mining, grinding and spreading silicates, with and without carbon credits	Quantify costs and energy penalty of deployment across different scales.
8	Geographic land use assessment to determine where application of silicates would be most economically and environmentally viable	Optimize EW cost-benefits with respect to individual regions.
9	Linkage of the above into a full system model from biogeochemistry and crop yields, capable of intergration with Earth system models.	Develop realistic simulation capability for understanding Earth system response to EW
10	Investigate and reflect wider public views on EW strategies to mitigate climate change.	Understand ethical and moral concerns underlying risk perceptions of EW science