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

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The magnitude of future climate change could be moderated by immediately reducing the amount of CO_2 entering the atmosphere as a result of energy generation and by adopting strategies that actively remove CO_2 from it. Biogeochemical improvement of soils by adding crushed, fast-reacting silicate rocks to croplands is one such CO_2-removal strategy. This approach has the potential to improve crop production, increase protection from pests and diseases, and restore soil fertility and structure. Managed croplands worldwide are already equipped for frequent rock dust additions to soils, making rapid adoption at scale feasible, and the potential benefits could generate financial incentives for widespread adoption in the agricultural sector. However, there are still obstacles to be surmounted. Audited field-scale assessments of the efficacy of CO_2 capture are urgently required together with detailed environmental monitoring. A cost-effective way to meet the rock requirements for CO_2 removal must be found, possibly involving the recycling of silicate waste materials. Finally, issues of public perception, trust and acceptance must also be addressed.

Rising concentrations of atmospheric CO_2, and other greenhouse gases (GHGs) 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 losses of arable top soil that exceed natural rates of soil 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 produced using 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 that the global mean temperature, already more than 1 °C above the pre-industrial level, will exceed the 1.5 °C aspirational limit set by the United Nations Paris Agreement[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 slowly amplifying climate feedbacks that include ice-sheet melt[6]. The continued response of the climate system to increased GHGs, and the practical difficulties of transitioning to carbon-free energy, makes even a more lenient 2 °C warming target[5] challenging. Consequently, effective mitigation policy needed for meeting the United Nations targets requires rapid phasing out of fossil fuel emissions and the deployment of scalable approaches for CO_2 removal (CDR) from the atmosphere with so-called negative CO_2 emissions in the second half of the twenty-first century[7–9]. The danger of sea-level rise with the 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 twenty-first Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) 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]. The aim of enhanced weathering is to accelerate the natural geological process of carbon sequestration with the production of alkaline leachate that reduces ocean acidification. It is achieved by modifying 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

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 timescales. In soils, the chemical breakdown of carbonate and silicate rocks is accelerated during aqueous reactions within the elevated CO_2 environment of the soil, releasing base

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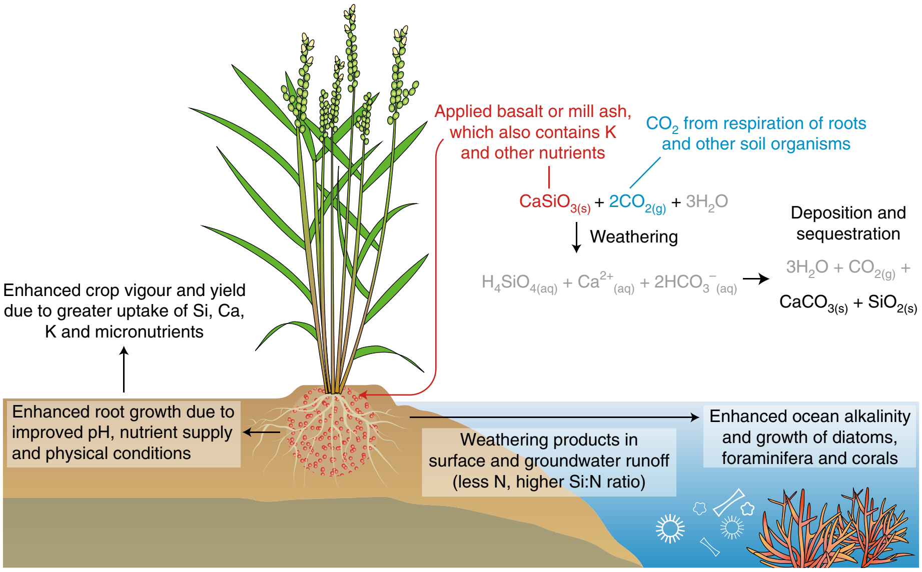

Fig. 1 | Summary of the potential effects of weathering of crushed basalt or silicate-rich wastes, such as sugarcane mill ash, applied to croplands. As silicate rocks weather, they release nutrients that can improve soil conditions and support crop production, and also generate alkaline leathate, ultimately leading to export of dissolved inorganic carbon forms to the oceans.

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 in these stable dissolved inorganic alkaline forms (Fig. 1). Given that the oceans worldwide store around 38,000 PgC, >45 times the current mass of C in atmosphere, their future storage capacity is not a limiting factor[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 the 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 most 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 alkaline leachate to the ocean, enhanced weathering enables the ocean to store more carbon, and counters the effects of ocean acidification, and the ongoing decrease in the $CaCO_3$ saturation state, critical issues for protecting marine biocalcifiers (such as corals and shellfish) from the impacts of acidification[18–20]. Untreated, such impacts are estimated to cost the global economy[21] as much as US$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 across a range of crops, soil types and climates, as well as across spatial scales (Table 1). Experimental and small-scale evaluation of CO_2 capture efficacy and permanency remain priority research areas to understand the future relevance and contribution of this strategy. 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 a rapid (12–24 months) 50% increase in the 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 by assuming Ca^{2+} release is balanced by (bi)carbonate production, suggests a range of 110–224 gCO_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 scales with existing farm equipment. Global cropland (arable, forage, fibre, fruit and so on) covers approximately 12×10^8 ha (12 million km^2)[27], and an additional $1–10 \times 10^8$ 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, for example, in North America[29] or the United Kingdom[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 of 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 tCO_2 per ton of rock dissolved[30]. However, a synthesis of published chemical analyses indicates that olivine-rich ultramafic rocks (that is, peridotites: dunite, harzburgite, lherzolite and wehrlite), contain relatively high concentrations of either chromium (Cr), nickel (Ni) or both (Fig. 2). Weathering experiments reveal a fast release of bioavailable Ni from olivine, and the 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 could, therefore, introduce harmful metals into the food chain, and the wider environment, as well as causing nutritional imbalances—thus further research is warranted[18].

Table 1 | Critical research and development needs for assessing the viability and effectiveness of enhanced weathering for CO_2 capture via silicate application to agricultural soils at scale

Approach	Goal
Sites over different crops and major soil types within major global production areas equipped with eddy-covariance to measure year round GHG emissions, and instrumented field drains to measure drainage water chemistry and flux, enabling full budgets and environmental impact assessments	Quantify net CO_2 capture and sequestration, soil GHG emissions, silicate weathering rates and fertilization of crop performance (yield, water use) under natural climate conditions that could reduce fertilizer application, costs and conserve finite P resources
Field crop trials with different major silicate sources, ideally in conjunction with the approach above	Assessment of the relative merits of different types of silicate rocks for CO_2 capture (for example, basalt, dunite)
Controlled environment tests and replicated field trials of the anticipated benefits of silicate application on crop pest and disease resistance	Determine translational opportunities for increasing crop protection and reducing pesticide usage and costs
Genetic selection for high-weathering crops through a combination of enhancement of weathering-enhancing root exudates and recruitment/associations with weathering-enhancing soil microorganisms	Identification of weathering-controlling genetic traits and selection for crop varieties with an enhanced capacity for weathering and releasing $Si(OH)_4$
Genetic selection for crop varieties that are better capable of expressing Si-induced resistance, through a combination of Si-uptake mechanisms (that is, 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 resistance
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 the practicalities of deployment on croplands
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
Geographic land-use assessment to determine where the application of silicates would be most economically and environmentally viable	Optimize enhanced weathering cost benefits with respect to individual regions
Linkage of the above into a full system model from biogeochemistry and crop yields that is capable of integration with Earth system models	Develop realistic simulation capability for understanding the Earth system response to enhanced weathering
Investigate and reflect wider public views on enhanced weathering strategies to mitigate climate change	Understand the ethical and moral concerns underlying risk perceptions of enhanced-weathering science

In contrast to ultramafic olivine-rich rocks, major continental flood basalts have lower concentrations of Ni and/or Cr (Fig. 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 the expectation that fewer environmental risks are 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 levels of ~8 (10^{-10} to 10^{-11} mol of olivine-Si per m^2 per s) are within the range of those for basalt dissolution rates at pH 4 and above expected in soils (10^{-10} to 10^{-12} mol m^{-2} s^{-1})[39].

Significant potential exists for large-scale deployment of ground basalt to remove atmospheric CO_2. A maximum carbon capture potential of ~0.3 tCO_2 t^{-1} is suggested for basalt, assuming a sufficiently fine particle size for effective dissolution on decadal timescales[30]. The optimal particle size will depend on the mineralogy of the basalt, climate and biological activity, and requires further investigation and verification, but initial calculations suggest particles of 10–30 µm in 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 (that is, CO_2 costs associated with mining, grinding and spreading rocks), but suggest enhanced weathering could make a significant contribution to decarbonization strategies[8,9,23] and the ~1 Pg of CO_2 equivalent emissions (CO_2e) per year reduction needed from agriculture[41] by 2030. The 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 an adequate scale will be critical (Table 1).

A key issue affecting the efficiency of carbon capture 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 the crushing processes used, 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. This benefit will increase as future energy sources are decarbonized and the grinding process becomes more energy efficient, and by utilizing already ground waste silicate materials that were previously or are 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 using a basic rock, such as basalt, gives values of US\$52–480 tCO_2^{-1}, with grinding and transport the dominant components[30]. This cost range compares with that estimated for bioenergy with carbon capture and storage (BECCS) of US\$39–100 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

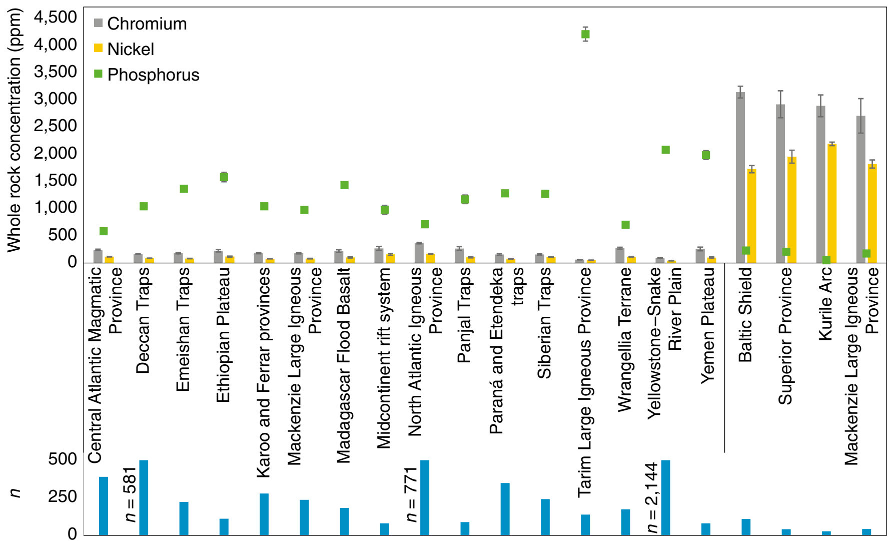

Fig. 2 | Metal and phosphorus concentrations in a range of continental flood basalts (left hand columns) and ultra-basic rocks (right hand columns). Values represent mean values and error bars indicate the standard error. The number of measurements *n* for each is given in the lower graph. Data from the Geochemistry of Rocks of the Oceans and Continents (GEOROC) database (http://georoc.mpch-mainz.gwdg.de/georoc/).

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 yield statistics from the Food and Agriculture Organization of the United Nations 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 crop growth[12,13] and rock weathering[39] 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 of rock per year, although in practice, optimization of application rates will follow crop and soil type. These rock-dust application rates compare with the recommended liming rates for UK arable soils[48] of 0.5–10 t of lime per hectare. These are substantial amounts of rock. For context, the global aggregate industry extracts ~50 Pg of rock per year 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 them to 90% of the most productive regions to improve cost-effectiveness. This is equivalent to 75% of the agricultural land used for annual crops (6.8×10^8 ha) (Fig. 3a), and reduces the required rock mass to 7–20 Pg yr^{-1}. However, these amounts would change if deployment kept pace with the 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 that China, the USA and India are the countries with the greatest potential to sequester CO_2 in this way, with Russia and European countries, mainly Germany and France, next best placed (Fig. 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 the combustion of fossil fuels and from industry (Fig. 3c) since the pre-industrial era (1870) (565 ± 55 PgC)[51] that are driving global warming[51,52].

Demand for reactive silicate rocks could be partially met if the 7–17 Pg yr^{-1} of freshly produced plant nutrient-containing silicate mining and industrial waste materials are utilized[53], more if legacy reserves are exploited. Assuming that 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 the exploitation of basaltic reserves, and interest is growing in recycling the accumulating fine basalt dust waste (with a particle size distribution that peaks 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 the host geology, with a total accumulated waste in the USA alone of ~40 Pg between 1910 and 1980.

In addition, waste materials from industrial processes such as 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, could potentially be used for enhanced weathering[53]. Iron and steel manufacturing produces readily weatherable calcium silicate slag waste (0.4–0.5 Pg yr^{-1}), and significant global stockpiles (5.8–8.3 Pg) exist[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 byproducts 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 strategies. China, a potentially important player in enhanced weathering (Fig. 3b), is the largest steel producer in the world but only recycles 22% of its steel slag, with scope for greatly expanding this percentage[56].

Residual combustion products from some agricultural sectors produce 0.2–0.4 Pg yr^{-1} of calcium-bearing ashes, with estimated

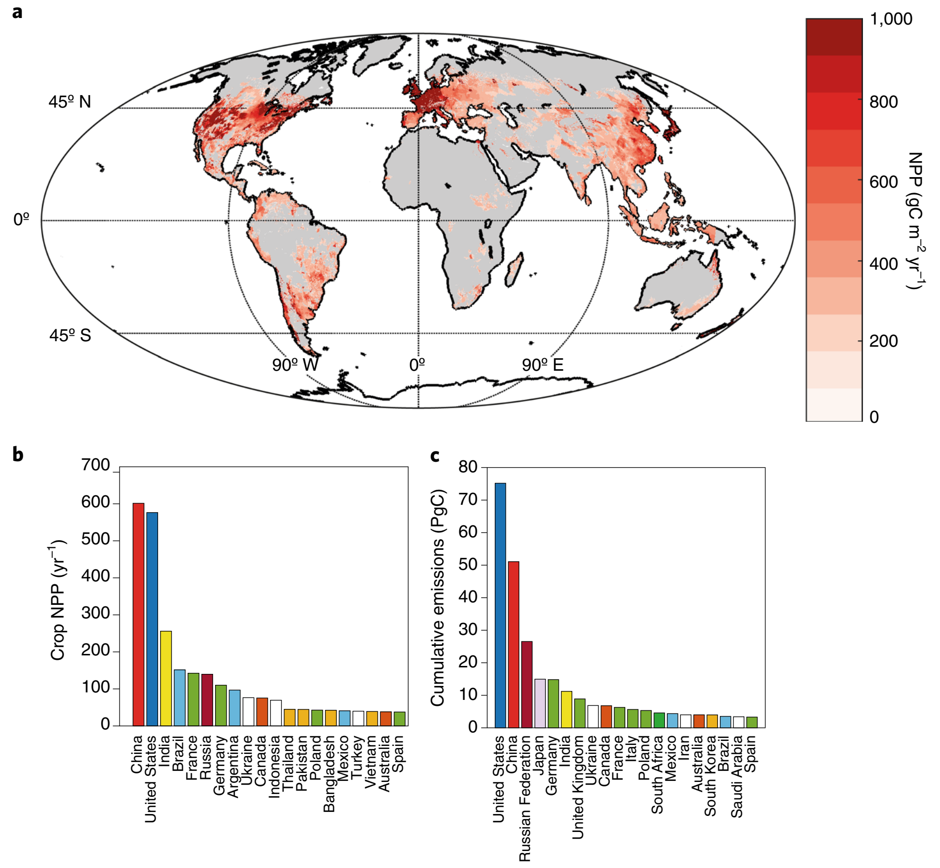

Fig. 3 | Net primary production of annual crops and cumulative CO_2 emissions by nation. a, The most productive 75% of annual croplands, based on a reanalysis of 10 × 10 km latitude–longitude resolution data for the year 2000, where net primary production (NPP) was calculated by converting FAO yield data[27]. **b**, The top 20 arable crop producing countries, ranked by NPP. **c**, Cumulative CO_2 emissions from all sources for the period 1959–2015 by country. CO_2 data from the Global Carbon Atlas (http://globalcarbonatlas.org).

cumulative reserves of 4–8 Pg since 1980 that are suitable for enhanced weathering[53]. Globally, the sugarcane industry produces ~47 Tg of ash per year, 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 byproduct 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 via 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 of enhanced weathering over many decades. For example, the USA might be served by the Central Atlantic Magmatic Province (eastern USA) 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 probably have further economic benefit due to their ability to help replenish eroded soil and enhance soil organic carbon (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 versus 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 continues to outpace 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 to reverse diminishing SOC stocks and decelerate 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 the weathering of silicates could further increase SOC retention through a range of organo–mineral interactions, including adsorption reactions and the physical protection of organic matter produced by decomposing organisms, which help to build soil while improving quality[67]. Increasing SOC in the rooting zone benefits crop yields in diverse agricultural soils of the tropics and subtropics[68]. Operating across timescales from years to several decades, these effects, and others associated with an increasing mineral surface area available to trap soil carbon[69], could help rebuild soils and slow 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 at COP21 as part of the UNFCCC[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 still uncertain.

Enhanced weathering strategies not only capture carbon but could also help to restore soils and resupply impoverished reserves of trace elements that are 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 are seriously depleting plant-available Si in soils[73,74]. In the USA, for example, crop harvesting removes 19 Mt of Si annually[75]. Annual depletion of soil Si by continuous intensive farming, coupled with the 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

Modifying 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 the prospects of 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 harvests 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 US$43 billion a year to Brazil's economy and US$1.5 billion a year in export earnings for Australia, suggesting that 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 that processed calcium silicate slag acts 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 alkaline leachate as they weather, silicate rocks reduce the soil acidification caused by overuse of ammonium and elemental sulfur fertilizers, urea, the 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 (for example, levels of aluminium and manganese) and increases P availability, especially in highly weathered acidic tropical soils, where metal oxides strongly bind to 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 fertilizers 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 including 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 (such as 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 fertilizers, especially single super phosphate, has generated toxicity in agricultural soils worldwide[92].

Benefits for crop protection against biotic threats from silicate weathering arise from the production of soluble silicic acid, which is readily taken up by plants, thereby improving stem strength and increasing resistance to pests and diseases in major temperate (soybean and wheat, for example)[29] and tropical (sugarcane, maize, rice and oil palm)[21] crops. Greenhouse and field trials have shown that Si augments the host plant resistance to disease and actively suppresses diseases by influencing the 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 to 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]. The strengthening of cells walls 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 US$7 billion annually[100].

Genetic assessment of crop attributes, for example the 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 (such as the uptake and accumulation of silica) in response to silicate rock/agro-mineral fertilization could be achieved through conventional

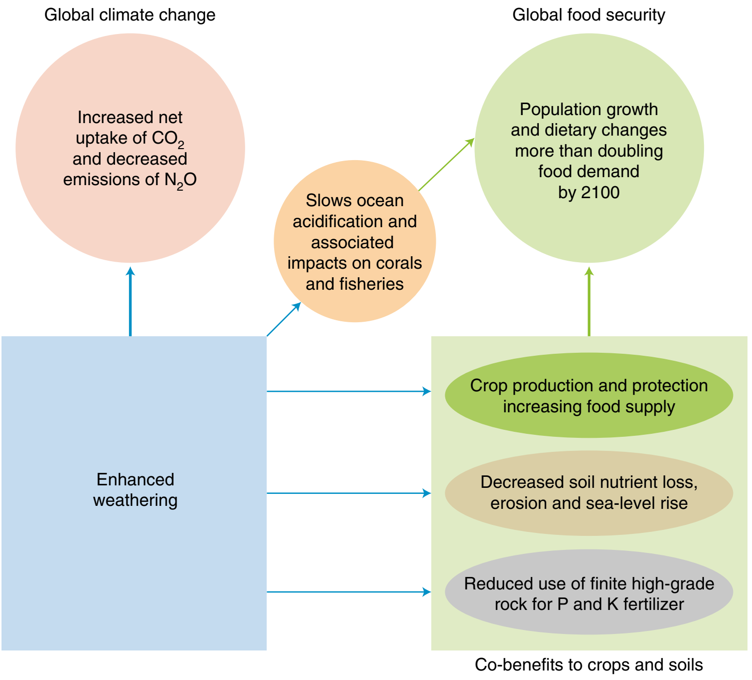

Fig. 4 | Enhanced weathering could address twenty-first century threats to climate, food and soil security. Schematic pathways illustrating how enhanced rock weathering could ameliorate climate change by reducing greenhouse gas emissions, help avert ocean acidification, and benefit croplands and soils.

breeding and/or using gene-editing techniques to modify elite varieties (for example, CRISPR–Cas9). Engineering crop varieties that are effectively able to exploit soil enriched 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 and cation exchange capacity, and increase SOC capture. However, such potential benefits require assessment in replicated field trials (Table 1).

A further co-benefit may arise from the agricultural application of crushed silicate rocks to soils suppressing emissions of the powerful and long-lived GHG N_2O and averting CO_2 emissions due to liming. Liming with $CaCO_3$ can release CO_2 when it is applied to the acidic soils ($pH < 6$) typical of agricultural lands[16,17,101]; in the USA, liming contributes 2% of agricultural GHG 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 conventionally fertilized maize plots decreasing by ~50% with the application of 10 kg m^{-2} of pulverized basalt and no concurrent effects 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 yr^{-1} of nitrogen as N_2O as a byproduct of weathering.

In summary, potential ancillary benefits of CO_2 capture with rocks and agriculture include: the 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 GHG (N_2O and CO_2) emissions; restoration of micro-nutrients important for human nutrition; and replacement of soils lost by erosion (Figs. 1 and 4). Additionally, increased crop protection from insect herbivores and pathogens, and the avoidance of toxic metal uptake, resulting from the release and uptake of silica, could decrease pesticide use and cost and improve yields, further safeguarding food security (Fig. 4).

Environmental impacts

The development of widespread mining, grinding and spreading operations would likely have negative environmental and ecological impacts—especially if linked to tropical deforestation near areas of high biodiversity value—and 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 the dangers of toxic metal contamination (Fig. 2). Avoiding inhalation of dust particles during mining, grinding and spreading will be important because these particles 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 to mitigate the 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 the addition of alkaline leachate. 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 reductions 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 (Fig. 3). The challenge may be suited to international cooperation between nations, including the provision of assets needed for implementation in developing countries. However, as for the extensive deployment of any CDR approach, enhanced weathering has not only to be evaluated and proven in field-scale trials, with the 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 the climate[6]. Methods of CO_2 extraction such as 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 that may threaten global food security[6,8,23]. Generating investment and bringing down the costs of CDR options (BECCS and DAC, for example), 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 minimize 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, 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) (Fig. 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, the efficacy of CO_2 capture quantified and the risks, benefits, socio-economics, techno-economics and ethics assessed (Table 1).

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Author contributions

D.J.B. wrote the first draft of the manuscript, with contributions from J.R.L., S.P.L. and J.H. All authors provided input on sections and the addition of appropriate references in later drafts. E.K., L.L.T. and M.K. undertook data analysis.

Competing interests

The authors declare no competing interests.

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