

Challenges and opportunities in scaling enhanced weathering for carbon dioxide removal

David J. Beerling¹✉, Christopher T. Reinhard², Rachael H. James³, Anu Khan⁴, Nick Pidgeon⁵ & Noah J. Planavsky⁶

Abstract

Terrestrial enhanced weathering (EW) on agricultural lands is a proposed carbon dioxide removal (CDR) technology involving the amendment of soils with crushed base cation-rich rocks, such as basalt. Over a quarter of a billion dollars have been raised by commercial EW start-ups across the globe, accelerating the deployment of EW at scale. In this Review, we outline the scientific knowledge and policy requirements for scaling EW. The global CDR potential of EW is 0.5–2 Gt CO₂ year by 2050. Tracking carbon as it is transferred from soils (cradle) to the oceans (grave), fully considering and quantifying lag times in CDR and developing a robust framework of monitoring, reporting and verification of CDR are all important for understanding the performance of EW deployments. Policies aimed at incentivizing responsible deployment and gaining acceptability among directly impacted communities, such as agriculture, are essential to sustainable and long-term growth of EW. High initial prices, the lack of consistent methodology for issuing carbon credits and lifecycle carbon emissions associated with a deployment are the main challenges of scaling EW through the voluntary carbon market. Future research needs to explore the co-deployment of EW and other CDR technologies and utilize long-term (>10 years) instrumented EW field trials to evaluate processes that regulate CDR efficiency and agronomic and economic co-benefits.

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¹Leverhulme Centre for Climate Change Mitigation, University of Sheffield, Sheffield, UK. ²School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA. ³School of Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton, UK. ⁴Carbon Removal Standards Initiative, Washington, DC, USA. ⁵Understanding Risk Research Group, School of Psychology, Cardiff University, Cardiff, Wales, UK. ⁶Yale Center for Natural Carbon Capture, Yale University, New Haven, CT, USA.

✉e-mail: D.J.beerling@Sheffield.ac.uk

Introduction

Atmospheric carbon dioxide removal (CDR) at scale is essential for meeting international climate goals¹. However, CDR efforts need to be compatible with major increases in food demand by 2050 to feed the increasing global population². Globally, food production accounts for >30% of anthropogenic greenhouse gas (GHG) emissions³. Increased need for food might lead to further agricultural expansion, intensive chemical fertilizer usage and continuous monocropping, degrading soils and natural ecosystems and driving GHG emissions. Therefore, achieving climate and food production goals represents a formidable challenge to humanity.

Terrestrial enhanced weathering (EW), the purposeful amendment of soils with crushed calcium-rich and magnesium-rich silicate rocks^{4,5} (Fig. 1), is an emerging CDR strategy with the potential to deliver billions of tonnes of CDR by 2050 (refs. 5,6), while improving food security and restoring soil health⁷ and mitigating ocean acidification^{8,9}. EW is straightforward to implement with existing agricultural infrastructure. Since 2020, this CDR technology has attracted

substantial worldwide commercial investment and academic interest. Currently, more than 20 commercial EW start-up companies have been established in regions such as India, Brazil, Australia, Kenya, the UK and the USA, raising over a quarter of a billion dollars (Table 1). Some of these companies already have agreements in place to supply carbon credits in the voluntary carbon market. With scientific advances and continued commercial investments, EW is emerging as a possible practical innovation for leveraging agriculture to enable positive action on climate change.

Nonetheless, challenges and knowledge gaps remain for EW to be implemented for CDR at scale in a safe, cost-effective and equitable manner¹⁰. Understanding and addressing these challenges is a pressing need, given the continued investment in EW start-up companies, involvement of non-governmental organizations and major investment in fundamental EW research. Prior work has reviewed the potential agricultural benefits of EW¹¹, but none has yet addressed barriers to scale, especially those associated with monitoring, reporting and verification (MRV), predictive modelling of CDR and policy development.

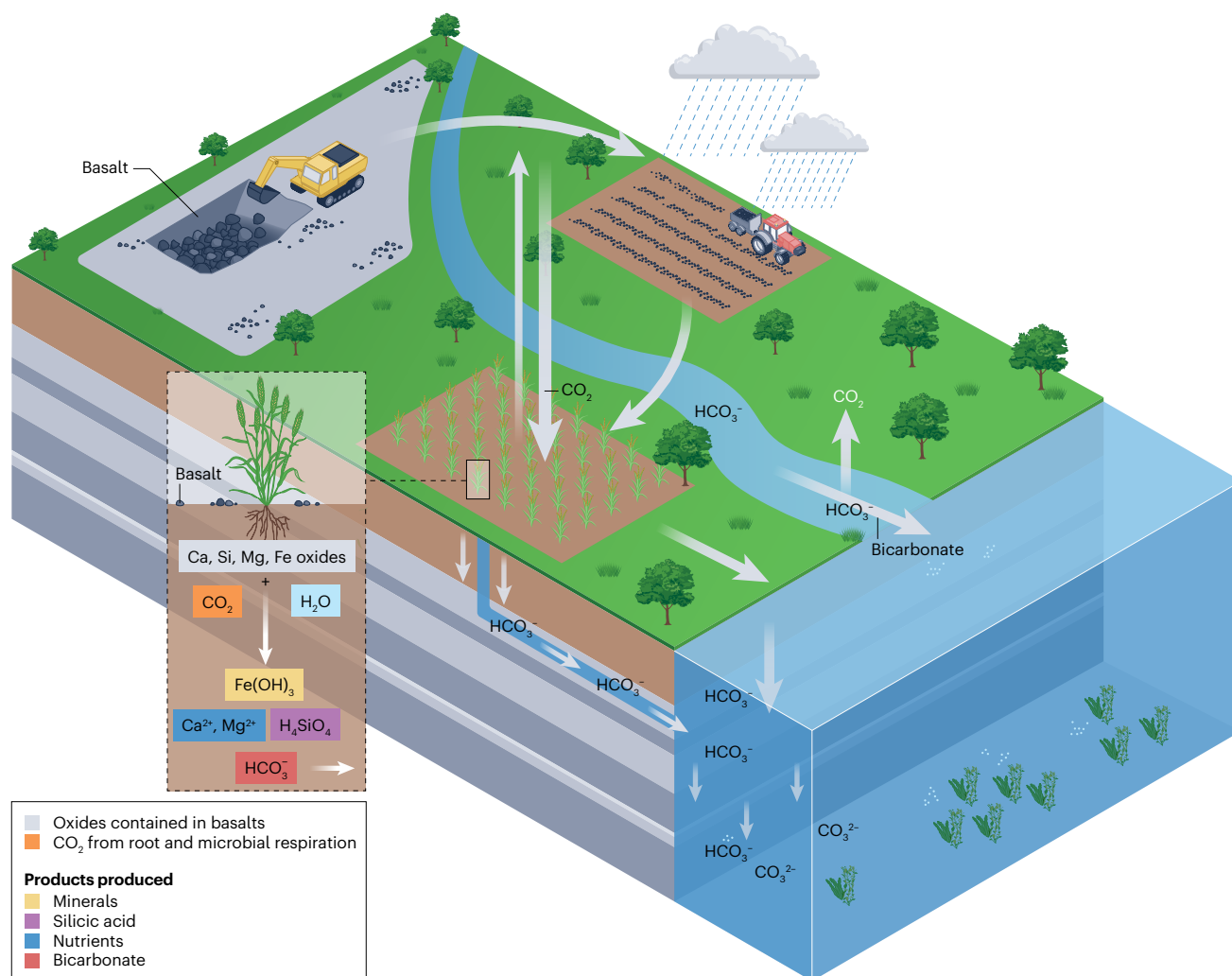


Fig. 1 | Overview of enhanced weathering of crushed basalt rock on agricultural lands. Enhanced weathering involves rock extraction and transportation, application of basalt to fields, biogeochemical processes in soils, inland waters and coastal oceans. Inset: basalt is weathered by reaction with

water and CO₂, producing new minerals, silicic acid, nutrients that support plant growth. Bicarbonate ions (HCO₃⁻) make their way to the sea, achieving long-term carbon storage.

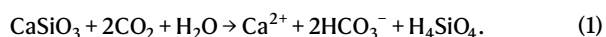
In this Review, we discuss the challenges and opportunities of implementing EW with crushed silicate rocks at scale. First, we outline mechanisms of EW, tracking carbon removal across the soil profile, groundwater and river systems and the coastal ocean and highlighting the crucial role of a system-wide numerical modelling framework for robust carbon accounting. We then discuss the carbon sequestration potential of EW, the potential environmental benefits and negative impacts. We further identify barriers to upscaling EW and outline policies that could incentivize deployment, facilitate up-scaling and build public and stakeholder trust based on lessons learnt from other negative emissions technologies. Finally, we emphasize the need for long-term EW field trials and pathways for stacking EW deployment with other CDR technologies, such as afforestation and biochar, in future research. Crushed silicate rocks, such as basalt, are the focus of this Review, because they are most commonly adopted in academic and commercial sector activities (Table 1). Although carbonate-rich feedstocks might also be used for EW purposes^{12,13}, this approach is not considered here.

Mechanisms of EW

EW feedstocks include olivine, wollastonite and basalt. Basalt, primarily composed of oxides of silicon, iron, aluminium, magnesium and calcium, is mostly widely used (Table 1) because it is abundant and widely distributed globally, with relatively high concentrations of plant-essential nutrients. After being applied to soils, crushed basalt is weathered to produce new minerals, silicic acid, nutrients, mobile cations (Ca^{2+} and Mg^{2+}) and bicarbonate ions (HCO_3^-). HCO_3^- will experience a series of biogeochemical processes (Fig. 2), with potential of being converted back to CO_2 , before reaching the sea for long-term storage.

Weathering and carbon removal

Weathering occurs when carbonic acid (H_2CO_3) in rainwater, produced from the dissolution of atmospheric CO_2 , reacts with silicate minerals in rocks and soils (equation (1)), consuming H^+ ions and releasing base cations such as Ca^{2+} and Mg^{2+} into solution. Release of base cations increases the alkalinity of the soil solution (its capacity to neutralize acid) because H_2CO_3 is converted to negatively charged carbon species (principally HCO_3^- , with some CO_3^{2-}). The weathering products (base cations, HCO_3^- and silicic acid) are then transported through soils to rivers and subsequently to the ocean, where the carbon species are securely stored for >100,000 years (refs. 14,15):



Some of the HCO_3^- ions produced via equation (1) might, in some circumstances, subsequently precipitate as carbonate minerals within soils and rivers^{14–18} (equation (2)). As carbonate precipitation re-releases half of the CO_2 captured by weathering of silicate minerals, carbonate mineralization halves the amount of CDR. Although soil carbonate can be stable on timescales of >10,000 years^{17,18}, in an EW setting, stability is highly dependent on water availability: carbonate that precipitates during drier periods might redissolve when it is wet.



Characterizing the chemical and mineralogical composition of the mineral feedstocks before application to agricultural lands is important to understand potential and rate of CDR. Silicate minerals with high proportions of base cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+) have the highest CDR potential. For example, weathering of 1 tonne of olivine (Mg_2SiO_4)

Table 1 | Enhanced weathering companies^a

EW companies	Operational nation(s)	Silicate rock	Capital raised (million dollars)	Notes
Undo	Canada, Australia, UK	Basalt, wollastonite	11.9	Plus \$5 million X Prize, third runner up
Lithos Carbon	USA	Basalt	63.4	Plus \$57 million (Frontier)
Eion	USA	Olivine	16	Plus \$33 million (Frontier)
InPlanet	Brazil	Basalt	5.84	
Terradot	Brazil		58.2	Plus \$27 million (Frontier)
Silicate Carbon	Ireland, USA	Recycled concrete, basalt	0.2	
Carbonaught	Australia, USA	Basalt	4.8	
Mati Carbon	India, Tanzania, Zambia		1.2	Plus \$50 million X-Prize winner
MetalPlant	Albania	Serpentine with metal recovery	3.7	
Everest Carbon	India	Wollastonite, basalt	3	EW instrumentation
Silica Earth	Mexico	Basalt	ND	
ZeroEx	Germany		0.095	
Flux Carbon	Kenya, Cameroon		ND	
Andes Bio	USA	Native soil silicates	38	Microbial EW acceleration
Verde Agritech	Brazil	Basalt	26.1	
Alt Carbon	India		12	Plus \$0.5 million (Frontier)
Reverce	Germany, Greece		7	
Rock Flour	Denmark, Ghana	Glacial rock flour	ND	
Carbony	Austria	Basalt	3.7	
ClimeRock	France		0.131	
Varaha	India		12.7	
Total			268	173

EW, enhanced weathering; ND, no data. ^aAs of May 2025.

can remove up to 1.2 tonnes of CO_2 , whereas weathering of 1 tonne of albite ($\text{NaAlSi}_3\text{O}_8$) removes <0.17 tonnes CO_2 (ref. 19). Olivine is also relatively fast-weathering ($10^{-10} \text{ mol m}^{-2} \text{ s}^{-1}$)¹⁹, whereas albite weathers slowly ($10^{-12} \text{ mol m}^{-2} \text{ s}^{-1}$) at pH -5, with the complete dissolution of small grains (diameter -50 μm) taking hundreds of years²⁰. Silicate feedstocks often contain trace quantities of secondary carbonate minerals²¹ that can weather rapidly as well, with only half the CDR potential of silicates though (discussed subsequently).

Temperature, water flux, particle size of mineral feedstocks and biological factors also affect EW-CDR performance. EW of silicate rocks

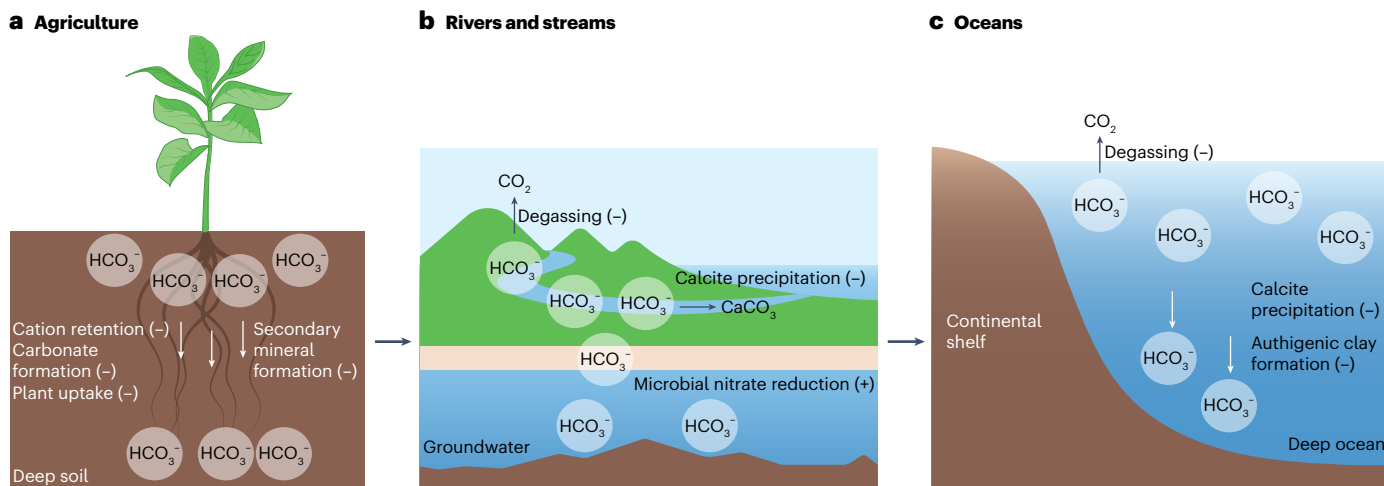
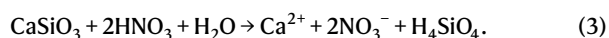


Fig. 2 | Downstream processes that affect carbon dioxide removal efficiency. **a**, Processes in soil that increase (positive signs) or decrease (negative signs) carbon dioxide removal efficiency of enhanced weathering. **b**, As in part **a**, but for processes in rivers and streams (top) and in groundwater (bottom). **c**, As in part **a**,

but for oceanic processes. Biogeochemical processes occurring during transport of bicarbonate ions (HCO_3^-) from soils to the ocean can lead to transient or permanent losses of alkalinity produced via weathering, lowering carbon dioxide removal efficiency.

will be most effective where temperature and the vertical water flux through the soil profile are high, allowing dissolution to proceed under far-from-equilibrium conditions^{22,23}. Grinding rock to small particle sizes can help overcome kinetic constraints on silicate mineral dissolution, although comminution also releases CO_2 (ref. 24). However, the effects of particle size might be small, relative to other parameters such as runoff and temperature^{24–26} and flow pathways through soils^{26,27}. Crops and soil microorganisms are also crucially important drivers. The physical breakdown and chemical dissolution of minerals (bioweathering) via rhizosphere processes also accelerate EW^{5,16}.

In soils, weathering can be driven by sulfuric acid or nitric acids (equation (3)), as well as weak organic acids derived from decomposition of organic material, reducing the efficiency of CDR²⁸. Thus, non-carbonic acid weathering does not contribute directly to and lead to extra carbon export from soils; it will, nevertheless, in many cases reduce acid-driven CO_2 evasion from rivers.



Tracking and measuring carbon uptake in soils

Quantifying CDR via EW presents a challenge because cropland environments are diverse and dynamic and weathering is a long-term process, whose full effects might not be realized for years. CDR rates measured in the field can be highly variable, ranging from 0 to up to -5 tonnes CO_2 ha^{-1} for annual application of -50 tonnes ha^{-1} crushed silicate rock^{29,30}. Such a high variance is partly related to differences in quantification methodologies. CDR rates are mainly measured by three approaches: aqueous alkalinity, CO_2 gas exchange and base cations in soils. These three-phase measurements are complementary and can be used for benchmarking EW reactive transport models. Development of robust and cost-effective protocols for quantifying CDR is essential to unlock financing and facilitate large-scale EW deployment.

At the catchment scale, CDR can be quantified directly by combining measurements of alkalinity and other carbon system parameters

in soil solutions with measurements of discharge^{31,32}. This approach accounts for CDR losses within the soil system (for example, clay formation and uptake by plants), as well as the effects of non-carbonic acid weathering. However, the approach is challenging to use in typical EW settings that are rarely hydrologically isolated and thus require extensive (and therefore expensive) monitoring to capture temporal and spatial variations in solute fluxes. Most CDR estimates based on this approach rely on isolated (point-based) aqueous measurements within the soil (lysimeters) and thus might not capture the spatial and temporal variability of waters percolating through a field.

Measurements of CO_2 gas exchange across the soil–air interface arguably provide the most direct measure of CO_2 removal fluxes. However, existing methods are still prohibitively expensive on anything other than research plots. As with soil waters, the sampling densities needed to accurately capture CDR flux at the field scale are poorly understood. Eddy covariance towers provide a spatially integrated analysis of carbon fluxes, but distinguishing a CDR signal from background fluxes is difficult³³. Gas flux measurements also do not account for changes in acid export from the system, which affect downstream carbon fluxes.

Measurements of mobile base cation loss from soils are used extensively to quantify long-term chemical weathering rates³⁴, which, in turn, can be used to estimate the potential CDR^{30,35}. In contrast to aqueous and gas phase measurements, soil-based approaches provide time-integrated estimates of potential CDR. It is also known how to accurately capture the chemistry of a field through soil sampling³⁶. Measuring soil chemistry is relatively inexpensive and millions of solid-phase measurements are already being made in conventional agriculture, providing a possible path to decrease EW monitoring costs. However, cation losses from EW feedstocks can be difficult to detect in some soils³⁷, especially on relatively short (annual) timescales. Furthermore, soil-based measurements only track the initial release of cations and do not include secondary processes that might modify cation (and thus alkalinity) fluxes. In this regard, aqueous and gas-based approaches are advantageous, as they integrate alkalinity and carbon fluxes from the soil system and account for permanent or transient

alkalinity loss through secondary mineral formation, biomass uptake and sorption on soil cation exchange sites.

Downstream processes and removal efficiency

Biogeochemical processes within soils and groundwaters during transport of soil waters to the ocean, and processes within the ocean, can lead to transient or permanent losses of alkalinity produced via weathering, lowering CDR efficiency downstream from where weathering occurred (Fig. 2). Alkalinity loss might occur directly, for example, through uptake of base cations by plants or by secondary minerals, or indirectly, for example, through increased respiration of soil organic carbon (SOC) in response to increased soil pH³⁸.

The impact of these processes on CDR efficiency is an active area of EW research and remains uncertain. For example, EW field trials over 4 years that directly quantify cation uptake by biomass suggest that this effect is small, ~4.5% for CDR removal in maize and soybean and ~1.1% for miscanthus³⁰. Precipitation of secondary silicate and carbonate minerals will lower CDR by trapping base cations in insoluble products. As mineral precipitation is likely to be spatially and temporally separated from feedstock deployment (for example, taking place deep in the soil profile, or only during relatively dry periods), measuring its effect on

CDR efficiency remains a challenge. In the following paragraphs, processes that might induce alkalinity losses in different environmental settings are discussed in detail.

Soils. Base cations released via weathering can be exchanged for acidic cations (H^+ and Al^{3+}) on soil cation exchange sites on clays and organic matter, and this reaction could drive CO_2 evasion and reduce CDR (Fig. 3). As sorbed base cations will re-enter the soil solution after dissolution of the applied EW feedstock is complete, the reduction in CDR is only temporary, although the time lag between uptake and release can be long (years to decades)³⁹.

The extent to which alkalinity is charge balanced by HCO_3^- (and CO_3^{2-}) is dependent on the pH and pCO_2 (partial pressure of CO_2) of the soil solution. In high pH soils (more than ~6.3)⁴⁰, almost all cations released by weathering are charge balanced by HCO_3^- . However, for soils with pH below, for example, ~5.2 (ref. 40) and containing sulfide minerals and/or heavily amended with nitrogen-based fertilizers, base cations might also be released by charge balance with nitrate or sulfate. Strong acid weathering can still lead to CO_2 reductions, albeit by decreasing acid-driven soil or river CO_2 evasion rather than increased bicarbonate export.

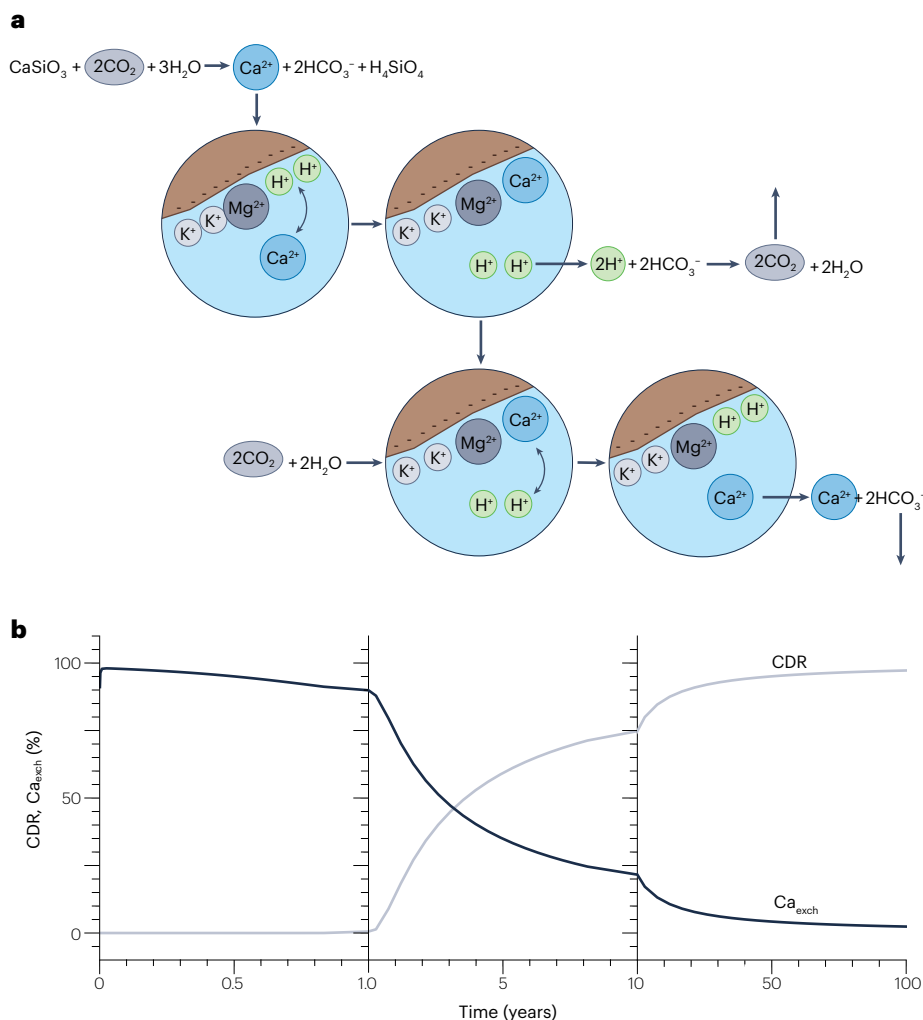


Fig. 3 | The impact of soil cation exchange on the time dynamics of carbon removal. **a**, Base cations, such as Ca^{2+} , released from enhanced weathering feedstock are charge balanced by production of bicarbonate (HCO_3^-), but some fraction of the base cations released will replace exchangeable acidity (H^+) on soil exchange sites. This release of exchangeable acidity consumes HCO_3^- , reversing a portion of the initial carbon removal. However, the base cations will eventually be cycled off the soil exchange complex, regaining some of the initial carbon removal. **b**, Simulations from a soil reaction-transport model for a site in the southeastern USA show the fraction of calcium released from basalt feedstock that is stored on the soil exchange complex (Ca_{exch}) and carbon dioxide removal (CDR) as a percentage of overall CDR potential over time. Cation exchange lags delay CDR delivery, and the lags vary spatially³⁹, depending on background and target soil pH, fluid fluxes and soil composition. Parts **a** and **b** are reprinted and adapted from ref. 39, respectively, CC BY 4.0.

Alkalinity, dissolved inorganic carbon and base cation fluxes from the upper soil can potentially be altered by a range of processes downstream of a deployment region. For instance, formation of secondary mineral phases can occur in deeper groundwater systems during transit to streams and rivers⁴¹. If these phases redissolve, they will have negligible net effect on overall carbon and alkalinity throughput, but if secondary phase formation is permanent, it should be viewed as a permanent loss of alkalinity and a reduction in CDR potential overall. Developing empirical constraints on the factors controlling these processes in field deployments of EW is a critical task for future work.

Groundwater. In agricultural regions, extensive microbial nitrate reduction can occur in soils and groundwaters, which produces alkalinity (Fig. 2a,b). Cations from weathering that are charged balanced with nitrate in upper soils can also become charge balanced by HCO_3^- formation through downstream nitrate reduction. Although rates are variable, it is common for a large fraction of exported nitrogen to undergo denitrification during short-range transport⁴². Nitrate reduction or uptake, both of which produce alkalinity, will continue in the ocean, with strong feedback proximal to riverine nitrate inputs⁴³. The source of organic matter for nitrate reduction matters, and it is important to understand whether a given treatment mobilizes an otherwise recalcitrant pool of organic matter relative to the counterfactual case⁴⁴. Regardless, the fate of nitrate produced in agricultural systems and its impact on integrated charge balance across timescales have not been incorporated into existing EW frameworks.

Rivers and streams. Once delivered to river and stream systems, the re-equilibration of the carbonate system as waters of differing chemistry mix can potentially drive CO_2 degassing without base cation loss (Fig. 2b). Development of robust frameworks for quantifying this effect is at an early stage, but existing evidence suggests that its magnitude is generally relatively small^{10,45}. Regardless, if CO_2 degassing occurs without base cation loss, the remaining base cations will most likely be charge balanced by HCO_3^- production before being transported into the ocean interior. In this case, any CO_2 degassing and associated reduction in CDR efficiency would be transient. Secondary mineral formation can also potentially remove alkalinity and base cations in river and stream systems⁴⁶, thus reducing CDR efficiency. The effect, however, is expected to be minor, because secondary carbonates will likely be redissolved either as bedload transits along the transport continuum or when delivered to shallow marine sediments.

Oceans and sediments. The coastal ocean is the final filter that carbon must make it through to be considered removed permanently (geological timescales) (Fig. 2c). Many of the same processes discussed earlier apply here as well – re-equilibration of the carbonate system as fluid mix could drive CO_2 degassing (or uptake) depending on the chemistry of the background surface ocean⁴⁷, and secondary clay or carbonate formation can remove base cations and reduce CDR efficiency.

Authigenic clay formation in marine systems – the so-called reverse weathering – removes base cations, consumes HCO_3^- and releases CO_2 , essentially reversing the biogeochemical impacts of silicate weathering. Reverse weathering is a widespread process in marine sediments and represents a major component of Earth's long-term carbon cycle^{48,49}. However, this process is driven by remobilization of biogenic silica in a relatively closed system⁵⁰. It is not yet clear whether the solute impacts of EW would be of a sufficient magnitude to drive growth in the rates of reverse weathering relative to the counterfactual,

even with large-scale deployment. Secondary carbonate formation could potentially occur in localized regions of elevated carbonate saturation state upon solute flushing into coastal marine systems, but much or all of the secondary carbonates might redissolve in the aerobic zone of shallow marine sediments⁵¹.

Several processes can alter solute fluxes after initial CDR in the field, but the key question is whether base cations are permanently removed during solute transport to the ocean. Permanent base cation removal should be considered a true reduction in overall CDR efficiency, and it will be important to forge better empirical and theoretical constraints on the processes driving permanent base cation removal. Transient CO_2 degassing and/or transient base cation removal (for example, through redissolution of secondary carbonate), however, should not lead to substantive reductions in overall CDR efficiency.

Carbon sequestration potential

Understanding the CDR potential of EW with agriculture is important for assessing its possible role in assisting global and national net-zero GHG emission goals^{10,25,52}. The estimation of CDR potential and rates and the MRV of CDR via EW will largely rely on predictive modelling approaches, given the likely costs of field measurements at scale. In this section, the modelling approaches and their resultant estimates are discussed in detail.

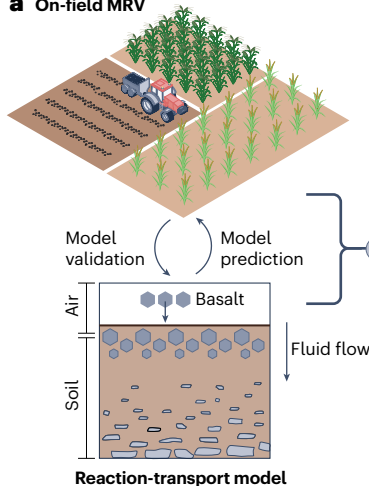
Modelling of EW

Numerical modelling frameworks can be used for various purposes, including acquiring better mechanistic understanding of a discrete EW process, predicting downstream impacts, refining systems optimization at the project or regional scale or as a cost reduction measure for supplier-based MRV on a voluntary market. Indeed, suppliers, regulators and policymakers will likely increasingly leverage modelling tools in MRV. In parallel, academics and technical specialists will continue to develop, validate and refine modelling tools that can be used for more robust prediction of CDR rates, lifecycle impacts and technoeconomics^{10,24,26}. It is thus critically important that the right framework for evaluating and validating models is established now, as large-scale field trial data are growing rapidly and might become accessible to various stakeholders.

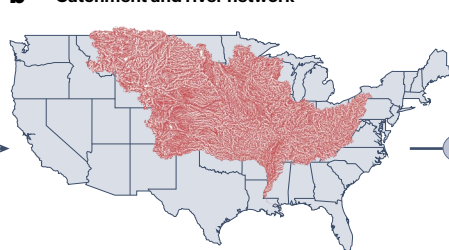
The inclusion of the biogeochemistry of carbon removal and nutrient cycling in models is essential for credible analysis of CDR potential and costs. Full assessment of CDR rates requires a cradle-to-grave EW modelling analysis of four discrete domains¹⁰ (Fig. 4): shallow soil horizons that feedstock is applied to and in which initial cation release and carbon removal occur; deeper flow paths that link shallow soil horizons with groundwater reservoirs and/or stream and river systems; river and stream systems; the coastal ocean. Only after carbon is removed in soil and has transited through these domains can it be confidently said to be stored for geological timescales. Accurate MRV needs to include these four domains. For MRV at the river and stream scale, integrating all upstream domains will be needed.

Although reaction-transport models for simulating shallow soil and deeper flow paths exist, some of which have been in use for decades⁵³, few have been designed or tested with EW. For example, most of these models do not by default include many of the key mechanisms and parameters required to accurately represent the EW process, including particle-size-distribution tracking, comprehensive cation exchange and charge balance accounting, various soil mixing regimes that reflect those used in managed lands, and analytical frameworks for mimicking soil chemistry and agronomic measurements. Existing

a On-field MRV



b Catchment and river network



c Ocean storage

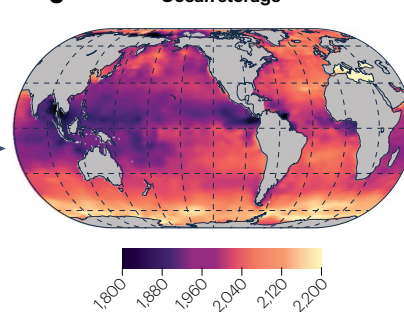


Fig. 4 | The cradle-to-grave framework for tracking carbon flow. **a**, Feedstock dissolution and carbon removal must be tracked through robust on-field monitoring, reporting and verification (MRV). These data can potentially be used to validate predictive reaction-transport models for upper soil and deeper flow paths. **b**, Once transported from the site of weathering to surface waters, carbon

and alkalinity must be tracked through river and stream systems across scales from experimental site to catchment. **c**, Map shows dissolved inorganic carbon concentrations ($\mu\text{mol kg}^{-1}$) in the oceans¹¹². Carbon and alkalinity can be recycled (and carbon potentially released) after delivery to the surface ocean before being permanently stored in the ocean interior.

models that include these processes^{5,10,26,54,55} lack benchmarking against each other or validating with empirical data.

Similarly, current stream and river reaction-transport modelling packages are not well designed for capturing carbon flow and environmental impacts of large-scale EW. Efforts to develop and validate stream and river carbonate chemistry models that can be operationalized at the regional scale are ongoing^{45,56}. Mechanistic improvements in their representations of carbonate mineral formation and dissolution and the impacts of alkalinity perturbations on baseline stream and river metabolism are particularly needed. In relatively well-instrumented regions such as the USA – which features the US Geological Survey gauging network of 3,560 stations – there is a path towards empirical validation of developing models and progressively more sophisticated iterations of existing and built-for-purpose models. However, the validation and application of models to regions with limited and sparse data will be challenging, hindering EW application in these regions.

Carbon loss through degassing in coastal oceans appears to be a relatively minor flux⁹, but this result has not been confirmed with high-resolution models of ocean biogeochemistry. Potential impacts of EW solutes beyond bicarbonate and alkalinity – micronutrients and macronutrients – represent a key target for future research. Several existing ocean biogeochemistry modules are suitable for evaluating these impacts if forced with realistic solute fluxes from upstream empirical measurements or model results, provided that local carbonate system impacts are not extreme. Transparent model–model intercomparison (for example, the [RockMIP project](#)) and data-model validation are important, and a full consideration of environmental impacts is required. Overall, carbon loss in coastal ocean systems is likely to be a less important source of uncertainty than carbon flow through shallow soils and other terrestrial aquatic systems^{47,56} in EW modelling.

Deployment of EW at scale will require robust and demonstrable predictive models in CDR projections to boost academic and public confidence. Advancing the state-of-the-art should become possible by assessing EW model performance against observational data sets

from field trials with rigorous criteria for acceptability and applicability. Furthermore, as the number of EW field trials and commercial deployments increases, it raises the prospect of generating large data sets representative of thousands of hectares. This situation will create opportunities for exploiting artificial intelligence and machine learning to enhance model performance. Although there have been steps forward in modelling carbon leakage in rivers and the oceans^{10,45,56}, modelling of the lower soil column is lacking and is an obvious target for future work.

Estimates of CDR potential of EW

The CDR potential of EW is estimated based on models. Initial estimates tended to be global and determined simply as a function of fixed particle size, EW rates, land area deployed, application rate and number of years deployed. Later work involved more detailed geochemical modelling but from the maximum potential CO_2 drawdown perspective irrespective of land use, practicality, costs and resource constraints^{6,8,24,57}. EW rates through the soil profile can now be more realistically estimated using 1D reactive transport geochemical models that account for many critical processes and incorporate real-world implementation of field data such as particle size distribution^{5,26,55}, climate and nitrogen fertilizer usage^{10,26}.

Availability of suitable feedstock^{5,24–26}, proximity to agricultural lands, cropland area^{5,10,25,26} and water availability are major constraints on CDR delivery by EW and have been used to estimate CDR potential of different regions. Major agricultural nations collectively have the potential to remove net 0.5–2 Gt CO_2 per year with EW deployment⁵ by 2050 (Table 2). Lower national CDR potentials for EW have been suggested based on a simplified calculation without direct modelling of weathering processes or accounting for spatial variability in climate and soils⁵⁸. If the upper range of CDR could sustain over five decades, EW could save up to 12% of the remaining cumulative carbon emission budget that gives a 66% probability of limiting global warming to $<2^\circ\text{C}$ above the pre-industrial average temperature⁵⁹. Therefore, EW should

Table 2 | Carbon dioxide removal potential of enhanced weathering on the agricultural land worldwide

Regions	CDR potential (Gt CO ₂ per year) ^a	CDR potential (Gt CO ₂ per year) ^b
China	0.13–0.53 (0.28–0.4) ^c	0.011
USA	0.11–0.42 (0.25–0.5) ^d	0.078
India	0.15–0.49	0.27
Brazil	0.041–0.17	0.04 (South America)
Indonesia	0.017–0.067	NA
Canada	0.022–0.06	
Mexico	0.013–0.06	
Thailand	NA	0.032
Africa		0.071
France	0.017–0.067	NA
Germany	0.012–0.05	
Italy	0.0007–0.029	
Spain	0.012–0.035	
Poland	0.0085–0.025	
Austria		
UK	0.008–0.035 ^e	
Australia	NA	0.017
Total	0.54–2.0	0.52

CDR, carbon dioxide removal; NA, not available. ^aAbout 10–55% of cropland enhanced weathering (EW) deployment, 40 tonne ha⁻¹ per year basalt application rate, 2040–2050, decadal average. Net CDR values, after accounting for secondary carbon emissions⁵. ^bAbout 70% of cropland EW deployment, 10 tonne ha⁻¹ per year basalt application rate, 2006–2080 average. Gross CDR values, not accounting for secondary carbon emissions¹¹. ^cAbout 25–50 tonne ha⁻¹ per year basalt application rate. Net CDR values, after accounting for secondary carbon emissions. ^dTime-varying cropland EW deployment, 40 tonne ha⁻¹ per year basalt application by 2070. Net CDR values, after accounting for secondary carbon emissions¹⁰. ^eTime-varying cropland EW deployment, 40 tonne ha⁻¹ per year basalt application, 2020–2070 average. Net CDR values, after accounting for secondary carbon emissions²⁶.

be considered as a critical part of a negative emissions portfolio – not a single solution.

USA, India and China, the three major fossil fuel CO₂ emitters, have the highest CDR potential owing to large agricultural land areas and warm climate. Notably, the USA^{5,10} and China⁶⁰ might have the capacity to remove 0.5 Gt CO₂ per year if EW was widely adopted (Table 2). In the USA, upscaling of EW mainly across the Corn Belt states¹⁰ could provide 16–30% of the nation's greenhouse gas removal requirements for net-zero by 2050, with carbon removal costs decreasing from US\$ 200–250 tCO₂ in 2030 to US\$ 100–150 tCO₂ by 2050.

Regions in the Global South, including Indonesia and Brazil, have relatively high CDR potential owing to their warm, seasonally wet climates that support high EW rates and widespread croplands co-located with basalt deposits (Table 1). This location benefit reduces rock dust transportation distances and, combined with lower labour and fuel costs, tends to reduce the price of net CO₂ removal relative to developed nations.

Modelling attention is also now transitioning towards developing detailed national CDR estimates for EW deployment, constrained by resources, and integrating with models of the other carbon removal pathways (for example, rivers and oceans) to give whole system assessment of CDR potential (Fig. 2) and costs¹⁰. This crucial endeavour allows regions

to more realistically determine the relative contribution EW might make to national net-zero goals as part of a portfolio of CDR strategies.

Co-benefits and monitoring requirements

Applications of crushed silicate rocks to agricultural landscapes could have important implications for global food security, thus requiring rigorous environmental monitoring. This section outlines evidence of the environmental impacts and examines the monitoring requirements.

Agricultural benefits

EW applications with silicates improve agricultural production and soil health⁷. Intensification of agricultural practices over time leads to soil degradation through acidification, depletion of plant-essential micronutrients and macronutrients, loss of soil organic matter and physical erosion that limits crop yields. Application of crushed silicates with EW could reverse these effects^{7,10}, as evidenced from multiyear large-scale EW field trials in the US Corn Belt with crushed basalt^{30,33}. Brazil has a long history of using various crushed silicate rocks in agricultural practices to improve soils and crop production and to facilitate sustainability and the autonomy of farmers⁶¹, which strengthens the case for EW agricultural benefits.

Weathering products include alkalinity that reverses soil acidity and inorganic nutrients, including phosphorus (P), potassium (K) and silicon that are important for maintaining or increasing yields. These effects, repeatedly seen in EW field trials and mesocosm experiments in controlled environments¹¹, can reduce P and K fertilizer usage and thus generate economic savings, partially offsetting EW deployment costs²⁶. Reducing P and K fertilizer use is important given price volatility and predicted P and K supply issues^{62,63} in the future.

EW can also decrease nitrous oxide (N₂O) emissions^{64,65} by increasing soil pH. This emission reduction represents an important benefit given the limited options for tackling agricultural N₂O emissions⁶⁶. Reductions in soil emissions of N₂O can also lead to reductions in soil nitric oxide (NO) emissions. For example, EW implementation in the US Corn Belt is estimated to reduce soil NO emissions by up to 30%, leading to temporary reductions in near-surface spring–summer time ozone concentrations, with benefits for crop production and ecosystem and human health¹⁰. Simulated soil trace gas emission responses to EW await empirical evaluation with detailed on-site measurements from EW field trials.

Impacts and monitoring requirements

Deployment of EW with basalt could have negative effects on the plant–soil–water environment and require monitoring⁶⁷. Potential accumulation of trace metals released by weathering of basalt (and other potential silicate feedstocks) in soils and edible portions of crops has been raised as a possible concern of repeated EW practices over time⁶⁸. However, the biogeochemistry of trace metals in plant–soil systems is complex, and metal solubility decreases with increased pH, precipitation of secondary minerals and adsorption onto cation exchange surfaces, such as clays and organic matter. Additionally, application of crushed basalt can increase soil aggregate formation, potentially reducing solubility of trace metals⁶⁹. No marked changes in soil metal concentrations have been observed in many EW field trials, including those running for years³⁰ and using high loadings of crushed basalt (100 tonnes ha⁻¹)¹⁶.

Accumulating data for crops from field trials and mesocosm experiments also show limited evidence or no evidence for increased trace metal accumulation. For example, in corn kernels and soybeans after 4 years of basalt treatment in the Corn Belt³⁰ and in rice grains, arsenic

and cadmium were reduced probably because of increased soil pH following wollastonite application^{70,71}. However, there were small increases in nickel in spring oats after a year with basalt⁷². Continued monitoring of these trace metals is essential to understand the long-term effects.

Some possible EW feedstocks, notably ultramafic rocks or olivine sands, can contain relatively high concentrations of chromium (Cr) (up to 0.2 wt% of the rock) with the potential to release hexavalent⁷³ Cr during weathering under highly oxidizing conditions. However, hexavalent Cr production has not been observed in any EW trial deployment with basalt, and it is not clear how mobile Cr will be over time in the soil system. Nevertheless, given the important health impacts of hexavalent Cr, targeted monitoring of this species should be part of EW deployment plans.

In freshwater systems, extensive EW deployment can offset the acidification of inland waters resulting from historical sulfur dioxide emissions during industrialization and widespread fertilizer usage, reducing the negative impacts on the biosphere¹⁰. However, direct alkalinity changes could have uncertain impacts on downstream ecosystems, thus requiring monitoring. The primary impacts of large-scale EW deployment include elevated base cation concentrations and carbonate saturation states^{8,9}, especially near river mouths, and changes in the abundance of certain nutrients and trace elements. Scaling EW requires (re)investment in long-term river monitoring networks.

EW could also potentially incentivize land-use change. For example, sale of EW credits on a voluntary market could be used to reduce or subsidize the cost of increasing soil pH after conversion of forests or rangeland to agricultural lands, potentially increasing the carbon intensity of agricultural production. Therefore, strict requirements regarding land-use history in EW deployments are essential to prevent adverse impacts on land use.

Scaling EW through carbon credits

Voluntary carbon market and government procurement of carbon removal are likely to grow substantially in future⁷⁴. EW could meet an important fraction of this demand while addressing the permanence concern arising from other forms of CDR, such as via land management. However, issues associated with carbon accounting, governance and environmental impacts must be addressed to ensure the credibility of EW carbon credits.

Learning from the existing carbon markets

Carbon credits, which are used to offset emissions generated along the value chain of the corporation, need vigorous validation based on cradle-to-grave accounting. Over half of the 2,000 largest publicly traded companies in the world have made public net-zero commitments⁷⁵. In the voluntary carbon market, corporations purchase carbon credits to offset emissions and meet the commitments. Rigorous offsetting claims require cradle-to-grave accounting of all lifecycle emissions associated with a CDR deployment and tracking of carbon losses (reversals) over large spatial and temporal scales (Cascade Climate)¹⁰. For EW, emissions need to include those from quarrying, grinding, transporting material and all carbon losses downstream of the field.

Overestimation of carbon removal and climate benefits is a well-documented shortcoming of the voluntary carbon market. Major credit types – including reduced deforestation and regenerative agriculture – have notably overestimated climate benefits owing to unrealistic baselines, inaccurate leakage estimates and over-reliance on poorly validated models. Systematic assessment of past carbon crediting projects, covering 20% of total credits issued in the voluntary carbon market, found that only 16% of the projects represented real emission

reduction⁷⁶. Therefore, there is an obvious need to learn from the early stages and shortcomings of existing carbon markets.

EW should learn from the volatile market for SOC credits. Efforts to quantify the SOC benefits of agricultural practices such as no-till and cover cropping led to the creation of SOC crediting methodologies and credit generation. However, there is scientific uncertainty associated with in-field empirical and modelled SOC quantification⁷⁷, and crediting methodologies vary widely, with the potential for over-crediting⁷⁸. These issues have led to the volatility in the price of and demand for SOC credits, discouraging farmer's participation⁷⁹. The most obvious lessons learnt from critiques of SOC crediting are to avoid an over-reliance on models before robust validation and that data and model transparency are essential to build trust in a practice.

A takeaway from the most strident criticisms of early carbon markets is that the voluntary carbon market might be a fundamentally flawed financing path for practices – such as EW – that have a range of co-benefits but where precisely quantify carbon fluxes might be difficult. Carbon accounting at the regional scale, rather than field or project level⁸⁰, is one of the important steps towards accurate quantification of carbon fluxes. EW scaling not only needs government support but also strict rules learnt from these early employments.

Barriers to upscaling EW

Achieving global, climate-relevant scale CDR with EW through the voluntary carbon market faces several challenges. The voluntary carbon market is small compared with the global need for emissions mitigation⁸¹. In 2023, 164 million carbon credits were retired, at a total market value of US\$1 billion. For comparison, global energy emissions reached a record high of 37.4 billion tonnes of CO₂ equivalent in the same year. EW credit purchases were a trivial fraction (<1%) of all carbon credit purchases and most were from five entities (according to CDR.fyi).

EW is, even in the best case, far from being cost-competitive. The cost of EW purchases ranging from US\$300 tonne⁻¹ to US\$420 tonne⁻¹ (Frontier Climate) is much higher than the typical carbon credit prices of US\$5–15 tonne⁻¹ (World Bank). Scaling EW through carbon markets requires mechanisms to differentiate and appropriately price credits based on key climate impact parameters, including duration of carbon storage and reversal risk (Cambridge)⁸⁰. However, the EW community has not yet been able to demonstrate long-term carbon storage of EW carbon credits with low-reversal risk. Furthermore, EW lacks a universally agreed upon methodology for issuing carbon credits. Existing methodologies developed by private entities differ in their requirements, allowing buyers and EW suppliers to shop for the methodology that best suits their needs and undermines market integrity.

Given the scale of global carbon emissions, EW projects require an exponential increase in funding from multiple sources and sectors, both public and private, to meaningfully impact climate⁷⁴. Carbon removal via EW should be viewed as a means to foster corporate responsibility in the short-term and in the long-term compensation for hard-to-abate emissions. If EW can overcome scientific, social and financing barriers (for example, developing robust MRV framework and standards), silicate mining and processing will need to increase with EW deployment. However, given current mines and hundreds of millions to billions of tonnes of silicate material already generated⁸², this issue is unlikely to be a major barrier to scaling EW.

Policy support and public perceptions

Governments can support EW through various ways, including funding for research and development, creation of voluntary certification

Table 3 | Carbon dioxide removal policies and programmes and status in relation to enhanced weathering^a

Jurisdiction	Policy or programme	EW included	Timescale
Credit purchasing or trading			
Canada	Greening Government Strategy — Low-Carbon Fuel Procurement Program. The Canadian government commitment to purchasing \$10 million Canada dollar of carbon removal	Yes	2024–2030
USA	CDR Purchase Pilot Prize , including three phases of funding (US\$ 35 million) for CDR companies across four pathways		2023–2024
USA (California)	CA SB 643 — Carbon Dioxide Removal Purchase Program, proposing to purchase US\$ 50 million of credits between 2026 and 2035		2026–2035
UK	Incorporation of CDR into the UK Emissions Trading Scheme , designed to guide industries in the UK towards net-zero 2050 goals		2029–onwards
Practice-based subsidy			
Canada (New Brunswick)	Lime Transportation Assistance Program in New Brunswick , Newfoundland and Labrador , Nova Scotia . Financial assistance for the procurement and/or trucking of dolomitic and calcitic lime to fields for agricultural soil pH management	Lime (carbonates) eligible; silicates not eligible yet	NA
Poland	Nationwide programme for environmental regeneration of soils through liming . Payment per tonne of limestone deployed on agricultural land that has a starting pH of 5.5 or lower		2019–2023
Regulation			
Brazil	Remineralizer Law . Defines remineralizers (rock dust), classifies them as fertilizer and amends previous fertilizer laws in Brazil	Yes	NA
Research and development			
Australia	Climate-Smart Agriculture Program , including multiple categories of grants for climate-smart agriculture	Yes	2023
European Union	C-SINK , research consortium focused on reliable monitoring, reporting and verification of carbon removal		2023–2027
Germany	CDRterra . Funding for multidisciplinary research on the potential of multiple CDR pathways, including EW, to help Germany meet its 2045 greenhouse gas neutrality target		NA
UK	Greenhouse Gas Removal UKRI (CO2RE). Funding to explore multidisciplinary research across CDR pathways in the UK, including demonstration projects		2021–2025/26
UK	Leverhulme Trust . £10M. Funded the Leverhulme Centre for Climate Change Mitigation dedicated to all aspects of EW from networks of field trials to Earth system modelling, public engagement and sustainability		2016–2026
USA	Carbon Negative Shot . Funding to decrease the cost and support commercial scale-up of durable CDR to US\$ 100 tonne ⁻¹ across multiple pathways		2022–2024
Voluntary certification			
European Union	Carbon Removal and Carbon Farming Certification Framework . Voluntary certification for CDR credits using EU-developed methodologies	Likely, but no EW yet	NA
France	Label Bas-Carbone . Voluntary certification for emissions reductions and CDR in France, including a list of approved methodologies for verification of projects by sector	No	NA

CDR, carbon dioxide removal; EW, enhanced weathering; NA, not available. ^aExcept for California where the Bill will be introduced in 2025.

schemes to improve carbon market integrity, direct purchasing of carbon credits and integration into compliance markets and practice-based subsidies for EW activities (Table 3). In addition to directly supporting EW, governments can create enabling regulatory environments, alleviating barriers to deployment. Notably, policy support is contingent on public understanding of and support for EW and CDR more broadly. It is important to evaluate which policy mechanisms (or combinations of mechanisms) can be scaled responsibly in different regions, with support from communities and agricultural producers.

Policy support

EW will require sustained policy support to achieve climate-relevant scales of CDR. Initially, governments will need to fund basic and applied science and data sharing to improve understanding of physical processes associated with EW. There is also a need to develop standardization of EW methodologies using data from commercial and publicly funded field trials. The UK currently funds EW research through UKRI,

Germany through CDRterra and the USA through the Carbon Negative Shot, among other programmes and other countries actively supporting EW and carbon removal research (Table 3). The European Union is likely to create and adopt a standard for EW under its Carbon Removal and Carbon Framing certification scheme. A similar government certification scheme has been proposed in the USA, modelled after the successful Energy Star programme⁸³.

In addition to ensuring the quality of EW projects through research and oversight, governments can have a role in creating demand for EW credits. The US ([Department of Energy](#)) and Canada ([Greening Government Strategy](#)) have committed to pilot CDR purchasing programmes. The UK ([Department for Energy Security and Net Zero](#)) and Japan ([GX Emissions Trading Scheme](#)) plan to integrate carbon removal into their respective emissions trading schemes, and California has set a target of 100 Mt CO₂ captured or removed by 2045 ([California Air Resources Board](#)) in alignment with its legally binding net-zero goal. EW is likely to be an included technology in these policies over time.

Practice-based subsidies from governments can also drive EW implementation. Agricultural subsidies are ubiquitous worldwide, totalling over US\$ 400 billion annually⁸⁴. For example, in the USA, the Environmental Quality Incentives Program provides per-acre payments for activities that build soil health. Other programmes, in the USA and beyond, provide incentives for soil pH management, nutrient use efficiency, methane reduction and fertilizer use reduction, all of which are potential co-benefits of EW^{7,10,11,26}. Governments can also provide development aid, in the form of grants and low-interest loans, to other countries. Given the high potential for carbon removal via EW in low-income and middle-income countries and the potential economic benefits to smallholder farmers, development aid presents a promising opportunity to support EW globally⁸⁵.

It is important to note that different policy mechanisms require different forms of MRV – cost, precision and uncertainty of measurement, monitoring and modelling techniques must be tailored to specific policy goals. This requirement represents a challenge and opportunity to improve EW quantification at a large scale: funded through subsidies, large swaths of land could be brought into a single jurisdiction-level accounting framework, increasing the chances of meaningful estimates of carbon removal with reduced uncertainty at an acceptable cost.

Regulatory barriers

EW activities must adhere to regulations across the supply chains. Large scale deployment of EW will require clarification and, in some cases, adjustment of existing regulations to enable access to feedstocks, set safe thresholds for the application of feedstocks to working lands and manage environmental impacts across the supply chain.

EW projects could utilize alkaline feedstocks, including industrial materials with high carbon removal potential such as steel slag, fly ash and mine tailings^{82,86}. Efforts are underway to bring such EW feedstocks into alignment with existing agricultural law and practice, including Brazil's recognition of mineral feedstocks in [Remineralizer Law](#) as an agricultural input category. Additional work is needed to reconcile widely accepted practice and policy, such as liming and liming subsidies, with the growing field of EW.

EW projects must align with local laws for the transport and disposal of feedstock materials. In some instances (for example, use of commodity products such as quarry fines), requirements will be minimal. In other instances (for example, the use of some alkaline mine tailings), the feedstock material might be regulated as waste and subject to additional requirements for safe use. For example, in the USA, the Resource Conservation and Recovery Act governs the disposal of waste materials on croplands and other areas that have been considered for EW⁸⁷. Policymaker education and regulatory clarity is needed to prevent the misclassification of safe feedstock materials as wastes for the purpose of EW.

EW projects must also align with federal and local regulations regarding the safe threshold of amendments⁸⁷ (for example, fertilizers) to croplands, including accumulation of trace elements in soils. Where safety thresholds exist, EW-specific technical support for environmentally sustainable deployment of novel soil amendments is needed. Where thresholds do not exist, additional research and regulatory rulemaking is needed⁶⁷.

Public perceptions and acceptance

Scaling-up EW across different regions of the globe needs to address ethical and social issues^{88–90}. Research on perceptions of CDR and EW

can help understand when and where controversies might arise, the conditions that publics will place upon EW deployment and requirements for governance and responsible innovation^{91,92}. Public acceptance of CDR should always be viewed as provisional and conditional, building on dialogues at national-political, local community and individual farm levels. Although public concern for climate change is high in many countries, awareness and knowledge of CDR and EW is very low^{93,94}. In research, people who see EW as interfering with nature are less supportive⁹⁵, and others recognize that CDR is insufficient to address the main problem of rising GHG emissions⁹⁶.

Public engagement will be critical for gaining public acceptance of EW implementation. Affected communities will require assurances over climate and farm-scale benefits (jobs and improved yields) alongside measures to address concerns about risks to biodiversity, oceans and from mining operations. Research also highlights the importance of timescale for people, how quickly can EW work given climate urgency, and can deployment support a long-term sustainable environment^{96,97}? Hence, large reductions in emissions, alongside minimizing risks to environments (especially those seen as 'iconic')⁹⁸, are essential for gaining social acceptability. How EW is framed also matters: public is more likely to accept EW when described as a 'natural' soil enhancement approach than an 'engineered' approach^{98,99}.

An important gap in the current research of public acceptance of EW is the acceptability among directly impacted communities, such as agriculture. Local impacts will occur on farms and landscapes, along transport routes, and from mining operations. Community acceptance is often conceptualized as obtaining a local 'social license to operate'¹⁰⁰. To ensure equity, this process needs to consider fair distribution of risks and benefits, make the process of community engagement early, ongoing and comprehensive and accommodate local identities and cultural knowledge in decisions.

An under-researched question is whether agricultural communities prefer nature-based techniques for CDR (for example, forestry and conventional soil sequestration) or EW with the promise of delivering tangible economic and cultural sustainability for farms. Reliable and simple MRV, direct on-farm benefits and avoiding risks to local biodiversity are all needed to underpin a community social license. Mining operations also provide employment opportunities but have encountered community controversy because of health and environmental risks. Expanding mining operations for sequestration will raise difficult local–national risk–benefit narratives as well as questions over promises of post-extraction remediation.

Current research on public acceptance also lacks insight into the Global South. Agricultural systems in South America and Asia, experiencing high temperature and rainfall extremes, are likely to be most favourable to EW²². However, only limited information exists on perceptions and attitudes towards CDR in these regions, where governance, policies and infrastructures also differ from the Global North⁹³. In general, Global South publics have greater support for climate intervention technologies than those in the Global North, but EW receives lower support relative to other CDR because of concerns over historical mineral extraction^{92,93}. For example, EW has low support in Malaysia because of community knowledge of environmental, health and social consequences of extraction activities, alongside concerns over risks to ocean food systems⁹². Responding fully to such cultural knowledge is a prerequisite for all successful Global South CDR^{101,102}. For regions with primary tropical rainforests, incentive-induced carbon rebound¹⁰³ arising from land-use change will also need to be prevented.

Box 1 | Time lags in carbon dioxide removal

Cation exchange lags in carbon dioxide removal (CDR) occur when base cations released by weathering of crushed silicate feedstock interact with the soil exchange complex (Ca_{exch} in the case of Ca^{2+}) to replace exchangeable acidity, becoming immobilized on soil exchange sites while increasing soil base saturation^{113,114}. These exchange lags can delay carbon removal through HCO_3^- production and export. Time lags of cation exchange can vary markedly spatially³⁹, depending on background and target soil pH, fluid fluxes and soil composition (for example, cation exchange capacity and mineralogy). Developing empirical constraints on the magnitude of cation exchange lags, and validating representation of cation exchange and alkalinity breakthrough in reaction-transport models using long-term field data from solid and dissolved phases, are priorities of future research.

Cation exchange time lags introduce complications with crediting carbon removal through EW and might have impacts on project finance of selling carbon removal credits to a voluntary market registry. In situations in which CDR lag times might be quite short, scope exists for reducing them with land management practice. Developing working plans for managing cation exchange lags is important to reduce the potential impacts. For instance, tonne-for-tonne accounting on a voluntary market might be more workable in 'low-lag' regions, and pay-for-practice or jurisdiction-level accounting might make more sense for 'high-lag' regions.

It is important to emphasize that carbon removal lags are a fundamental feature of many CDR technologies, including forestry projects, biochar and ocean alkalinity enhancement, and are not by any means restricted to EW. Currently, the voluntary market does not deal effectively with removal lags in any carbon removal sector, and developing sensible strategies for effectively mitigating this issue in EW could thus have cross-sectoral importance across the CDR industry.

Summary and future perspectives

There is growing recognition of the need to avoid over-reliance on a few CDR technologies by diversifying national CDR portfolios to reduce trade-offs and policy costs and to increase sustainability^{104,105}. EW has the potential to rehabilitate degraded acidified agricultural soils, reduce the climate impacts of agriculture and bolster rural communities worldwide. However, gaps in scientific understanding and limited policy and governance frameworks must be addressed for continued effective scaling of EW. This Review highlights that scientific gaps in technical understanding of the short-term and long-term biogeochemical processes affecting carbon flows and CDR efficiency of EW from soils (cradle) to the oceans (grave), the modelling of these flows across interconnected domains of soils, groundwater, river systems and coastal oceans and the impacts of an EW deployment on yields and soils must be addressed to progress EW science and employment. Investment in large-scale EW trials offers excellent opportunities to address key scientific questions in some of these targeted priority areas.

Advancing scientific understanding of the performance of EW needs continuous, long-term, large-scale instrumented EW field

trials lasting for 10–15 years. Long-term trials allow rigorous evaluation of mechanistic EW hypotheses concerning the biological, geochemical and physical processes and their dynamic interactions that control weathering rates and CDR time lags (Box 1) and improve understanding of secondary mineral formation. The slow development of these EW by-products, with feedback on EW processes, means that work conducted on field trials to date cannot be extrapolated into the future with confidence. Hence, field trials spanning a decade or more are needed. Long-term field trials can also be used to assess any impacts of EW on stabilization (or otherwise) of SOC via organo-mineral complexation¹⁰⁶. There is also an urgent need for more systematic documentation of yield benefits associated with EW implementation.

The potential for stacking EW with other proposed CDR strategies^{7,107,108} is largely unexplored. EW can effectively combine with afforestation and/or reforestation schemes to stimulate tree growth and organic carbon sequestration while simultaneously delivering inorganic carbon removal. Combining EW with afforestation in China could strengthen the carbon sink¹⁰⁹. Co-deployment of EW and biochar on croplands can also lead to additive carbon sequestration¹¹⁰.

Rapidly growing commercial investment in EW with agriculture is accelerating deployment at a rate that is arguably ahead of scientific and social understanding. This situation creates notable risks. First, venture-backed EW companies supplying carbon removal credits to voluntary market registries that are not transparent and robust could undermine public trust in EW. Second, if governance and incentive frameworks are not developed at pace with technical understanding, there is considerable risk that EW will not be accepted by key stakeholders regardless of technical rigour. Realizing the potential of EW requires the long-term, coordinated development of robust technical understanding and responsible frameworks for policy and governance. Continued investment in fundamental EW research and policy is needed to address knowledge gaps and to promote sustainable, responsible long-term growth.

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References

1. Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways* (World Meteorological Organization, 2018).
2. van Dijk, M., Morley, T., Rau, M. & Saghai, Y. A meta-analysis of projected global food demand and population risk of hunger for the period 2010–2050. *Nat. Food* **2**, 494–501 (2021).
3. Mbaw, C. et al. In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (eds Shukla, P. R. et al.) (World Meteorological Organization, 2019).
4. Hartmann, J. et al. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* **51**, 113–149 (2013).
5. Beerling, D. J. et al. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. *Nature* **583**, 242–248 (2020).
6. Goll, D. S. et al. Potential CO_2 removal from enhanced weathering by ecosystem responses to powdered rock. *Nat. Geosci.* **14**, 545–549 (2021).
7. Beerling, D. J. et al. Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* **4**, 138–147 (2018).
8. Taylor, L. L. et al. (2016). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Change* **6**, 402–406 (2016).
9. Kanzaki, Y., Planavsky, N. J. & Reinhard, C. T. New estimates of the storage permanence and ocean co-benefits of enhanced rock weathering. *PNAS Nexus* **2**, pgad059 (2023).
10. Beerling, D. J. et al. Transforming US agriculture for carbon removal with enhanced weathering. *Nature* **638**, 425–434 (2025).

11. Swoboda, P., Döring, T. F. & Hamer, M. Remineralizing soils? The agricultural usage of silicate rock powders: a review. *Sci. Total Environ.* **807**, 150976 (2021).
12. Hopkins, B. M., Lal, R., Lyons, W. B. & Welch, S. A carbon capture potential and environmental impact of concrete weathering. *Sci. Total Environ.* **957**, 177692 (2024).
13. McDermott, F., Bryson, M., Magee, R. & van Aken, D. Enhanced weathering for CO₂ removal using carbonate-rich crushed concrete: a pilot study from SE Ireland. *App. Geochem.* **169**, 106056 (2024).
14. Berner, E. K. & Berner, R. A. *Global Environment: Water, Air, and Geochemical Cycles* 2nd edn (Princeton Univ. Press, 2012).
15. Drever, J. I. *The Geochemistry of Natural Waters: Surface and Groundwater Environments* (Prentice Hall, 1997).
16. Kelland, M. E. et al. Increased yield and CO₂ sequestration potential with the C₄ cereal crop *Sorghum bicolor* cultivated in basaltic rock dust amended agricultural soil. *Glob. Change Biol.* **26**, 3658–3676 (2020).
17. Manning, D. A. C. Biological enhancement of soil carbonate precipitation: passive removal of atmospheric CO₂. *Min. Mag.* **72**, 639–649 (2008).
18. Zamanian, K., Pustovoytov, K. & Kuzaykov, Y. Pedogenic carbonates: forms and formation processes. *Earth Sci. Rev.* **157**, 1–17 (2016).
19. Bullock, L. A., James, R. H., Matter, J., Renforth, P. & Teagle, D. A. H. Global carbon dioxide removal potential of waste materials from metal and diamond mining. *Front. Clim.* **3**, 694175 (2021).
20. Bandstra, J. Z. et al. in *Kinetics of Water–Rock Interaction* (eds Brantley, S. L., Kubicki, J. D. & White, A. F.) 737–823 (Springer, 2008).
21. Kemp, S. J., Lewis, A. L. & Roshon, J. C. Detection and quantification of low levels of carbonate mineral species using thermogravimetric-mass spectrometry to validate CO₂ drawdown via enhanced rock weathering. *App. Geochem.* **146**, 105465 (2022).
22. Edwards, D. P. et al. Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. *Biol. Lett.* **13**, 20160715 (2017).
23. Brantley, S. L. et al. How temperature-dependent silicate weathering acts as Earth's geological thermostat. *Science* **379**, 382–389 (2023).
24. Moosdorf, N., Renforth, P. & Hartmann, J. Carbon dioxide efficiency of terrestrial enhanced weathering. *Environ. Sci. Technol.* **48**, 4809–4816 (2014).
25. Li, Z., Planavsky, N. J. & Reinhard, C. T. Geospatial assessment of the cost and energy demand of feedstock grinding for enhanced rock weathering in the coterminous United States. *Front. Clim.* **6**, 1380651 (2024).
26. Kantzas, E. P. et al. Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. *Nat. Geosci.* **15**, 382–389 (2022).
27. Amann, T. et al. Enhanced weathering and related element fluxes — a cropland mesocosm approach. *Biogeosciences* **17**, 103–119 (2020).
28. Bufer, A. et al. Co-variation of silicate, carbonate and sulfide weathering drives CO₂ release with erosion. *Nat. Geo.* **14**, 211–216 (2021).
29. Larkin, C. S. et al. Quantification of CO₂ removal in a large-scale enhanced weathering field trial on an oil palm plantation in Sabah, Malaysia. *Front. Clim.* **4**, 959229 (2022).
30. Beerling, D. J. et al. Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits. *Proc. Natl Acad. Sci. USA* **121**, e2319436121 (2024).
31. Gaillardet, J., Dupré, B., Louvat, P. & Allègre, C. J. Global silicate weathering and CO₂ consumption rates deduced from the chemistry of large rivers. *Chem. Geol.* **159**, 3–30 (1999).
32. Jacobson, A. D. & Blum, J. D. Relationship between mechanical erosion and atmospheric CO₂ consumption in the New Zealand Southern Alps. *Geology* **31**, 865–868 (2003).
33. Kantola, I. B. et al. Improved net carbon budgets in the US Midwest through direct measured impacts of enhanced weathering. *Glob. Change Biol.* **29**, 7012–7028 (2023).
34. April, R., Newton, R. & Coles, L. T. Chemical weathering in two Adirondack watersheds: past and present-day rates. *GSA Bull.* **97**, 1232–1238 (1986).
35. Reershemius, T. et al. Initial validation of a soil-based mass-balance approach for empirical monitoring of enhanced rock weathering rates. *Environ. Sci. Technol.* **57**, 19497–19507 (2023).
36. Bradford, M. A. et al. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. *Geoderma* **440**, 116719 (2023).
37. Suhrhoff, T. J. et al. A tool for assessing the sensitivity of soil-based approaches for quantifying enhanced weathering: a US case study. *Front. Clim.* **6**, 1346117 (2024).
38. Malik, A. A. et al. Land use driven change in soil pH affects microbial carbon cycling processes. *Nat. Commun.* **9**, 3591 (2018).
39. Kanzaki, Y. et al. Soil cation storage as a key control on the carbon removal dynamics of enhanced weathering. *Environ. Res. Lett.* **20**, 074055 (2025).
40. Dietzen, C. & Rosing, M. T. Quantification of CO₂ uptake by enhanced weathering of silicate minerals applied to acidic soils. *Int. J. Greenh. Gas Control* **125**, 103872 (2023).
41. Galla, J. K. et al. The evolution of lithium isotope signatures in fluids draining actively weathering hillslopes. *Earth Planet. Sci. Lett.* **567**, 116988 (2021).
42. Wolters, T. et al. The derivation of denitrification conditions in groundwater: combined method approach and application for Germany. *Ecol. Indic.* **144**, 109564 (2022).
43. Tivig, M., Keller, D. P. & Oschlies, A. Riverine nitrogen supply to the global ocean and its limited impact on global marine primary production: a feedback study using an Earth system model. *Biogeosciences* **18**, 5327–5350 (2021).
44. Sarmiento, J. L. & Gruber, N. *Ocean Biogeochemical Dynamics* 528 (Princeton Univ. Press, 20206).
45. Zhang, S. et al. A framework for modeling carbon loss from rivers following enhanced terrestrial weathering. *Environ. Res. Lett.* **20**, 024014 (2025).
46. Harrington, K. J., Hilton, R. G. & Henderson, G. M. Implications of riverine response to enhanced weathering for CO₂ removal in the UK. *App. Geochem.* **152**, 105643 (2023).
47. Bertagni, M. B. & Porporato, A. The carbon capture efficiency of natural water alkalization: implications for enhanced weathering. *Sci. Total Environ.* **838**, 156524 (2022).
48. Mackenzie, F. T. & Kump, L. R. Reverse weathering, clay mineral formation, and oceanic element cycles. *Science* **270**, 586–587 (1995).
49. Michalopoulos, P. & Aller, R. Rapid clay mineral formation in Amazon delta cycles: reverse weathering and oceanic elemental cycles. *Science* **270**, 614–617 (1995).
50. Michalopoulos, P. & Aller, R. Early diagenesis of biogenic silica in the Amazon delta: alteration, authigenic clay formation, and storage. *Geochim. Cosmochim. Acta* **68**, 1061–1085 (2004).
51. Suplis, O. et al. Calcium carbonate dissolution patterns in the ocean. *Nat. Geosci.* **14**, 423–428 (2021).
52. Motlaghzadeh, K. et al. Applying equity principles leads to higher carbon removal obligations in Canada. *Commun. Earth Environ.* **6**, 88 (2025).
53. Steefel, C. I. et al. Reactive transport codes for subsurface environmental simulations. *Comp. Geosci.* **19**, 445–478 (2015).
54. Kanzaki, Y. et al. Soil cycles of elements simulator for predicting terrestrial regulation of greenhouse gases: SCEPTER v0.9. *Geosci. Model Dev.* **15**, 4959–4990 (2022).
55. Kanzaki, Y. et al. In silico calculation of soil pH by SCEPTER v1.0. *Geosci. Model Dev.* **17**, 4515–4532 (2024).
56. Zhang, S. et al. River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering. *Limnol. Oceanogr.* **67**, S148–S157 (2022).
57. Streffer, J. et al. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **13**, 034010 (2018).
58. Chen, A. et al. Experimentally-calibrated estimation of CO₂ removal potentials of enhanced weathering. *Sci. Total Environ.* **900**, 165766 (2023).
59. Rockstrom, J. et al. A roadmap for rapid decarbonisation. *Science* **355**, 1269–1271 (2017).
60. Guo, F. et al. Improving food security and farmland carbon sequestration in China through enhanced rock weathering: field evidence and potential assessment in different humid regions. *Sci. Total Environ.* **903**, 166118 (2023).
61. Van Straaten, P. Farming with rocks and minerals: challenges and opportunities. *Ann. Braz. Acad. Sci.* **78**, 731–747 (2006).
62. Alewell, C. et al. Global phosphorus shortage will be aggravated by soil erosions. *Nat. Commun.* **11**, 4546 (2020).
63. Brownlie, W. J. et al. Global food security threatened by potassium neglect. *Nat. Food* **5**, 111–115 (2024).
64. Blanco-Betes, E. et al. In silico assessment of the potential of basalt amendments to reduce N₂O emissions from bioenergy crops. *Glob. Change Biol. Bioenergy* **13**, 224–241 (2020).
65. Chiaravallotti, I. et al. Mitigation of soil nitrous oxide emissions during maize production with basalt amendments. *Front. Clim.* **5**, 1203043 (2023).
66. Weber, J. C. et al. Global agricultural N₂O emission reduction strategies deliver climate benefits with minimum impact on stratospheric O₃ recovery. *npj Clim. Atmos. Sci.* **7**, 121 (2024).
67. Levy, C. R. et al. Enhanced rock weathering for carbon removal — monitoring and mitigating potential environmental impacts on agricultural land. *Environ. Sci. Technol.* **58**, 17215–17226 (2024).
68. Dupla, X., Moller, B., Baveye, P. C. & Grand, S. Potential accumulation of toxic trace elements in soils during enhanced rock weathering. *Eur. J. Soil Sci.* **74**, e13343 (2023).
69. Richardson, J. B. Basalt rock dust amendment on soil health properties and inorganic nutrients — laboratory and field study at two organic farm soils in New England, USA. *Agriculture* **15**, 52 (2025).
70. Uchibayashi, H. et al. Impact of basalt application on soil chemical properties and elemental uptake by paddy rice through enhanced rock weathering. *Soil Sci. Plant Nutr.* <https://doi.org/10.1080/00380768.2024.2448457> (2025).
71. Wang, F. et al. Wollastonite power application increases rice yield and CO₂ sequestration in Northeast China. *Plant Soil* **502**, 589–603 (2024).
72. Skov, K. et al. Initial agronomic benefits of enhanced weathering using basalt: a study of spring oat in a temperate climate. *PLoS ONE* **19**, e0295031 (2024).
73. Delina, R. E. et al. Chromium occurrence in a nickel laterite profile and its implications to surrounding surface waters. *Chem. Geol.* **558**, 119863 (2020).
74. Mannion, P. et al. Carbon removals: how to scale a new gigaton industry. <https://www.mckinsey.com/capabilities/sustainability/our-insights/carbon-removals-how-to-scale-a-new-gigaton-industry/> (2023).
75. Net Zero Stocktake. Technical Report, Energy and Climate Intelligence Unit, Data-Driven EnviroLab, New Climate Institute, Oxford Net Zero (2023).
76. Probst, B. S. et al. Systematic assessment of the achieved emissions reduction of carbon crediting projects. *Nat. Commun.* **15**, 9562 (2024).
77. Popkin, G. Shaky ground. *Science* **381**, 369–373 (2023).
78. Dupla, X. et al. Are soil carbon credits empty promises? Shortcomings of current soil carbon quantification methodologies and improvement avenues. *Soil Use Manag.* **40**, e13092 (2024).
79. Barbato, C. T. & Strong, A. L. Farmer perspectives on the carbon markets incentivizing agricultural soil carbon sequestration. *npj Clim. Action* **2**, 26 (2023).

80. Oldfield, E. E. et al. Crediting agricultural soil carbon sequestration. *Science* **375**, 1222–1225 (2022).
81. Hong, A. et al. *State of the Voluntary Carbon Market 2023* (Carbon Direct, 2023).
82. Renforth, P. The negative emissions potential of alkaline materials. *Nat. Commun.* **10**, 1401 (2019).
83. Broberg, D. et al. *Government Intervention in Support of Quality Carbon Credits* (Bipartisan Policy Centre, Carbon Direct, 2023).
84. Amaglobeli, D., Benson, T. & Mogues, T. *Agricultural Producer Subsidies: Navigating Challenges and Policy Considerations* (IMF Notes, 2024).
85. Boudinot, F. G. et al. *Enhanced Rock Weathering in the Global South: Exploring Potential for Enhanced Agricultural Productivity and Carbon Dioxide Drawdown* (Precision Development & Institute for Governance & Sustainable Development, Cornell Univ., 2023).
86. Xu, P. & Reinhard, C. T. Evaluating the carbon capture potential of industrial waste as a feedstock for enhancing weathering. *Environ. Res. Lett.* **20**, 044013 (2025).
87. Webb, R. M. *The Law of Enhanced Weathering for Carbon Dioxide Removal* (Columbia Law School, 2020).
88. Fritz, L., Baum, C. M., Brutschin, E., Low, S. & Sovacool, B. K. Climate beliefs, climate technologies and transformation pathways: contextualizing public perceptions in 22 countries. *Glob. Environ. Change* **87**, 102880 (2024).
89. Buck, H. J. Rapid scale-up of negative emissions technologies: social barriers and social implications. *Clim. Change* **139**, 155–167 (2016).
90. Cox, E., Pidgeon, N., Spence, E. & Thomas, G. Blurred lines: the ethics and policy of greenhouse gas removal at scale. *Front. Environ. Sci.* **6**, 38 (2018).
91. Rayner, S. et al. The Oxford principles. *Clim. Change* **121**, 499–512 (2013).
92. Cox, E. et al. Question-led innovation: public priorities for enhanced weathering research in Malaysia. *Environ. Sci. Policy* **163**, 103977 (2025).
93. Baum, C., Fritz, L., Low, S. & Sovacool, B. K. Public perception and support of climate intervention technologies across the Global North and the Global South. *Nat. Commun.* **15**, 2060 (2024).
94. Spence, E., Cox, E. & Pidgeon, N. F. Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. *Clim. Change* **165**, 23 (2021).
95. Wolske, K. S., Raimi, K. T., Campbell-Arva, V. & Hart, P. S. Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions. *Clim. Change* **152**, 345–361 (2019).
96. Butler, C., Demski, C. C., Parkhill, K. A., Pidgeon, N. F. & Spence, A. Public values for energy futures: framing, indeterminacy and policy making. *Energy Policy* **87**, 665–672 (2015).
97. Cox, E., Spence, E. & Pidgeon, N. Public perceptions of carbon dioxide removal in the US and UK. *Nat. Clim. Change* **10**, 744–749 (2020).
98. Cox, E., Spence, E. & Pidgeon, N. F. Deliberating enhanced weathering: public frames, iconic ecosystems, and the governance of carbon removal at scale. *Public Underst. Sci.* **31**, 960–977 (2022).
99. Low, S., Fritz, L., Baum, C. M. & Sovacool, B. K. Public perceptions on carbon removal from focus groups in 22 countries. *Nat. Commun.* **15**, 3453 (2024).
100. Gough, C. & Mander, S. Beyond social acceptability: applying lessons from CCS social science to support deployment of BECCS. *Curr. Sust. Renew. Energy Rep.* **6**, 116–123 (2019).
101. Bennett, N. J. & Satterfield, T. Environmental governance: a practical framework to guide design, evaluation, and analysis. *Conserv. Lett.* **11**, e12600 (2018).
102. Buck, H. J. Mining the air: political ecologies of the circular carbon economy. *Environ. Plan. E Nat. Space* **5**, 1086–1105 (2021).
103. McLaren, D. Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Clim. Change* **162**, 2411–2428 (2020).
104. Fuhrman, J. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Change* **13**, 341–350 (2023).
105. Chiquier, S. et al. Integrated assessment of carbon dioxide removal portfolios: land, energy, and economic trade-offs for climate policy. *Environ. Res. Lett.* **20**, 024002 (2025).
106. Xu, T. et al. Enhanced silicate weathering accelerates forest carbon sequestration by stimulating the soil mineral carbon pump. *Glob. Change Biol.* **30**, e17464 (2024).
107. Amann, T. & Hartmann, J. Ideas and perspectives: synergies from co-deployment of negative emission technologies. *Biogeosciences* **16**, 2949–2960 (2019).
108. Buss, W. et al. Applying minerals to soil to draw down atmospheric carbon dioxide through synergistic organic and inorganic pathways. *Commun. Earth Environ.* **5**, 602 (2024).
109. Wu, W. et al. Prospects for the potential carbon sink effects of afforestation to enhance weathering in China. *J. Asian Earth Sci.* **276**, 106370 (2024).
110. Honvault, N. et al. Additive effects of basalt enhanced weathering and biochar co-application on carbon sequestration, soil nutrient status and plant performance in a mesocosm experiment. *Appl. Geochem.* **169**, 106054 (2024).
111. Baek, S. H. et al. Impact of climate on the global capacity for enhanced rock weathering on croplands. *Earth's Fut.* **11**, e2023EF003698 (2023).
112. Lauvaset, S. K. et al. GLODAPv2.022: the latest version of the global interior ocean biogeochemical data product. *Earth Syst. Sci. Data* **14**, 5543–5572 (2022).
113. Kopittke, P. M. & Menzies, N. W. A review of the use of basic cation exchange ratio and the 'ideal' soil. *Soil. Sci. Am. J.* **71**, 259–265 (2007).
114. McLean, E. O., Hartwig, R. C., Eckert, D. J. & Triplett, G. B. Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops. II. Field studies. *Agron. J.* **75**, 635–639 (1983).

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Author contributions

D.J.B. led the writing with contributions from other authors. All authors contributed to discussion, review and editing of the article.

Competing interests

D.J.B. has a minority equity stake in companies (Future Forest and Undo) and is an advisory board member of The Carbon Community, a UK carbon removal charity. N.J.P. and C.T.R. were co-founders of the CDR company Lithos Carbon but have no remaining financial ties to the company. The remaining authors declare no competing interests.

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