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#### How to cite:

Kantzas, E. P.; Val Martin, M.; Lomas, M. R.; Eufrazio, R. M.; Renforth, P.; Lewis, A. L.; Taylor, L. L.; Mercure, J.-F.; Pollitt, H.; Vercoulen, P. V.; Vakilifard, N.; Holden, P.; Edwards, N.; Koh, L.; Pidgeon, N. F.; Banwart, S. A. and Beerling, D. J. (2022). Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. *Nature Geoscience*, 15(5) pp. 382–389.

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Version: Accepted Manuscript

Link(s) to article on publisher's website:  
<http://dx.doi.org/doi:10.1038/s41561-022-00925-2>

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# A national carbon drawdown blueprint utilizing enhanced rock weathering with agriculture

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Strategies for achieving national targets of net-zero carbon emissions (net-zero) compatible with rising agricultural production are essential for effective global climate change mitigation<sup>1,2</sup>. We address this challenge with detailed mapping of development pathways and costs to transform agricultural practices in the UK with enhanced rock weathering (ERW), an atmospheric carbon dioxide removal (CDR) technology<sup>3,4</sup>. Here we show with coupled climate-carbon-nitrogen cycle modelling that ERW deployment with croplands could deliver net CDR of 6-30 Mt CO<sub>2</sub> yr<sup>-1</sup> by 2050, representing up to 45% of the atmospheric carbon removal required nationally to meet net-zero<sup>5</sup>. Maximising CDR, lowering costs to £80-110 t<sup>-1</sup> CO<sub>2</sub>, and eliminating the energy-demanding requirement for milling rocks to fine particle sizes, requires early and sustained implementation of ERW practices. Co-benefits include mitigation of over a million tonnes of CO<sub>2(equivalent)</sub> yr<sup>-1</sup> of nitrous oxide, the third most important greenhouse gas, widespread reversal of soil acidification to boost yields on underperforming croplands, and substantial cost savings from reduced fertilizer usage. Societal acceptance is required across national-political, local community and farm scales<sup>6</sup>. Our proposed blueprint with fine-scale estimates of modelled CDR potential and cost across space and time allows targeting of priority regions and provides a guide for other nations to pursue CDR ambitions and decarbonise agriculture<sup>7,8</sup>, a major source of greenhouse gases<sup>2</sup>.

Governments worldwide are increasingly translating the UNFCCC Paris Agreement into national strategies for achieving net-zero carbon emissions by 2050. More than 120 nations have set full decarbonization goals that account for 51% of global CO<sub>2</sub> emissions, with the UK amongst several of these nations legislating for net-zero<sup>9</sup>. The UK, where the industrial revolution driven by burning fossil fuels originated, is responsible for ~ 5% of cumulative CO<sub>2</sub> emissions 1751-2018 that drive climate change<sup>10</sup>. Carbon emissions in the UK have declined by 43 percent between 1990 and 2018 due to the rise of renewables, and the transition from coal to natural gas, while growing the economy by 75%<sup>11</sup>. Continued phase out of emissions is, however, required to meet the UK's net-zero commitment together with the capture and storage of residual emissions using Carbon Dioxide Removal (CDR) technologies and a strengthening of nature-based carbon sinks<sup>5</sup>.

Enhanced rock weathering (ERW), a CDR strategy based on amending soils with crushed calcium- and magnesium-rich silicate rocks, aims to accelerate natural CO<sub>2</sub> sequestration processes<sup>3,4,7,8,12,13</sup>. Global potential for ERW deployed on croplands to draw down CO<sub>2</sub> is substantial, estimated at up to net 2 Gt CO<sub>2</sub> per year<sup>4</sup>, with co-benefits for production, soil restoration and ocean acidification. Agricultural co-benefits can create demand for ERW deployment which is unaffected by a diminishing income from carbon-tax receipts generated by other CDR technologies as the transition to clean energy advances and emissions approach net-zero<sup>14</sup>. Global action on CDR, and hence progress to net-zero, requires leadership from early-adopting countries through their development of flexible action plans to support policymakers of other nations. Assessment of the contribution of ERW to the UK's net-zero commitment is therefore required, given it is a CDR strategy for assisting with complete decarbonization whilst improving food production and rebuilding soils degraded by intensified land management<sup>8</sup>.

Here we examine in detail the technical potential of ERW implementation on arable croplands in a national net-zero context and provide a blueprint by which nations may proceed with this CDR technology as part of their legislated plans for decarbonisation. Using coupled climate-carbon-nitrogen cycle modelling of ERW (**Extended Data Fig. 1**; Methods), we constructed annual UK net 2020-2070 carbon removal budgets and CDR costs after accounting for secondary CO<sub>2</sub> emissions from the ERW supply chain (**Extended Data Fig. 2**; Methods). Coupled carbon and nitrogen cycle ERW modelling provides the fundamental advance for assessing the effects of

cropland nitrogen fertilizers on the soil alkalinity balance and mineral weathering kinetics (**Extended Data Fig. 3**; Methods), and ERW-related mitigation of nitrous oxide (N<sub>2</sub>O) emissions from agricultural soils<sup>15</sup>. Nitrous oxide is a key long-lived greenhouse gas and important stratospheric ozone depleting substance<sup>16</sup>; UK agriculture accounts for 75% of N<sub>2</sub>O emissions nationally with high external costs (~£1 billion per year)<sup>17</sup>. Our analysis, constrained by future energy policies<sup>18</sup>, utilizes basalt as an abundant natural silicate rock suitable for ERW with croplands<sup>7,8</sup>, with low- (S1), medium- (S2), and high- (S3) extraction scenarios between 2035-2050 (**Extended Data Fig. 4**; Methods).

## Temporal and spatial patterns of cropland CDR

Across low-, medium- and high-resource basalt supply scenarios (S1 to S3), ERW implementation on arable lands is simulated to remove of 6-30 Mt CO<sub>2</sub> yr<sup>-1</sup> by 2050 (**Figure 1, a-c**), i.e. up to 45% of the CO<sub>2</sub> emissions removal required for UK net-zero (balanced net-zero pathway engineered carbon removal requirement ~58 Mt CO<sub>2</sub> yr<sup>-1</sup>; range 45-112 Mt CO<sub>2</sub> yr<sup>-1</sup>)<sup>5</sup>. Modelled maximum CDR rates are predominantly governed by geographical extent of ERW application that increases as resource provision allows (**Figure 1 a-c**). Year-on-year legacy effects are also important. CDR rates per unit area increase over time with successive annual applications of rock dust, even after land area of deployment remains constant. These effects are evident in all scenarios when basalt extraction levels off and result from slower weathering silicate minerals continuing to capture CO<sub>2</sub> in years post-application, before they are fully dissolved<sup>4</sup>. By quantifying geochemical dissolution rates controlling ERW, and the chemical and kinetic processes that govern the legacy effects, our simulations provide more realistic representation of the CDR potential of ERW than previous mass balance estimates for the UK<sup>19-21</sup>.

Net-zero pathways for greenhouse gas removals in the UK<sup>5</sup>, and internationally<sup>1</sup>, have focused narrowly on Bioenergy with Carbon Capture and Storage (BECCS), and Direct Air Carbon Capture and Storage (DACCS). However, our new results indicate ERW can be an important overlooked component of national CDR technology net-zero portfolios. In S1, for example, ERW reaches a net CDR of 5 Mt CO<sub>2</sub> yr<sup>-1</sup> by 2050, equalling the DACCS estimate<sup>5</sup>, and closer to 10 Mt CO<sub>2</sub> yr<sup>-1</sup> by 2060 (**Figure 1a**). In the highest resource scenario, S3, ERW delivers approximately half of the net CDR forecast for UK BECCS facilities<sup>5</sup> by 2050 (**Figure 1c**).

Milling rocks to fine particle sizes is the most energy demanding step in the ERW supply chain<sup>19,22</sup>. We therefore assess a range of options for milled rock particle sizes, as defined by *p*80 (i.e., 80% of the particles having diameter of less than or equal to the specified value), and associated energy demands across scenarios S1 to S3 (**Figure 1 d-f**). For all scenarios, we show particle size typically has a rather small effect on net CDR for the first 10-20 years of implementation, as indicated by flat CDR isolines. In the model, ERW deployment locations are prioritised over time, starting from high and progressing to low weathering potential. Prioritization of sites with high weathering potential in the first couple of decades means basalt particles are weathered rapidly regardless of size. In S2, for example, a drawdown of 3 Mt CO<sub>2</sub> yr<sup>-1</sup> in 2035 with a *p*80 particle size of 500 µm, is achieved only 5 years earlier by milling to a *p*80 of 10 µm. Introducing the temporal dimension to ERW challenges the assumption that rocks must be ground finely to accelerate dissolution for effective CDR<sup>3,12,13,19</sup>. Coarser particles minimise health and safety risks when handling rock dust, in addition to reducing energy demand. However, as S2 and S3 encompass rock dust application on more agricultural land post-2040, with a greater proportion of sub-optimal weathering locations, the dissolution of small particles becomes relevant and the effect of *p*80 on net CDR increasingly apparent.

Energy requirements for delivering ERW are generally low. Pre-2035, the energy demand for rock grinding is minimal across all three scenarios  $\sim 1 \text{ TWh yr}^{-1}$ ; less than 0.2% of the UK's power production (**Extended Data Fig. 5**). Post-2040, the energy demand for grinding an increase rock mass to be distributed across an expanding area of arable land increases (**Extended Data Fig. 5**). However, providing rock grinding is limited to give a  $p80$  of  $100 \mu\text{m}$  or more, the energy demand is less than or equal to  $4 \text{ TWh yr}^{-1}$ , or 0.6% of UK production for all scenarios. These results mitigate prior concerns that undertaking extensive deployment of ERW in the UK may compromise energy security<sup>14</sup>.

Reducing cumulative  $\text{CO}_2$  emissions on the pathway to net-zero helps minimise the UK's contribution to the remaining future carbon budget consistent with keeping warming below a given level<sup>1</sup>. Assuming ERW practices are maintained between 2020 and 2070, the resulting cumulative net  $\text{CO}_2$  drawdown is simulated to be 200, 410, and 800  $\text{Mt CO}_2$  by 2070 (**Figure 1 g-i**). Longer-term compensatory ocean outgassing and sediment  $\text{CaCO}_3$  uptake could reduce net CDR effectiveness by 10-15% by 2070 (**Extended Data Fig. 6**). Attained over 50 years with ERW, these cumulative CDR ranges compare with an estimated  $\sim 696 \text{ Mt CO}_2$  sequestration over 100 years for afforestation of the Scottish uplands<sup>23</sup> and avoid possible soil carbon loss from tree planting<sup>24</sup> and sustained long-term management requirements. Breakdown of cumulative CDR by region reveals marked shifts in regional contributions from S1 to S3, with increasing contribution over time of croplands in Scotland, north-eastern and southwest England, and the midlands, when comparing results from S1 to S3. These regions have acidic soils where early deployment offers increasing CDR over time from legacy weathering effects. The more aggressive CDR strategy of S3 requires less optimal regions for ERW with the lowest rainfall (southeast and eastern England). Mapped UK-wide CDR rates per unit area provide fine-scale estimates of modelled carbon removal potential across space and time provide an important tool for precisely targeting ERW interventions (**Extended Data Fig. 7**). Geospatial net CDR estimates typically exceed low-carbon farming practices forming part of net zero pathways for agriculture<sup>5</sup>, including switching to less intensive tillage (typically  $\sim 1 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ )<sup>25</sup>, conversion of arable land to ley pasture ( $\sim 1$  to  $5 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ )<sup>26</sup>, and inclusion of cover crops in cropping systems ( $1.1 \pm 0.3 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ )<sup>27</sup>.

Underlying the geospatial maps of net CDR are strong cycles in alkalinity generation and soil pH, and intra-annual dissolution/precipitation of soil carbonates, driven by seasonal climate and crop production effects (**Extended Data Fig. 8**). These results show a decline in the periodic dissolution of soil (pedogenic) carbonates over decades as the cumulative effect of alkalinity systematically raises the seasonal minimum in soil pH and drives a steady increase in the net CDR per unit area each year. Rising alkalinity over time increases the soil buffer capacity, which reduces the risk of pH reversal, thereby improving  $\text{CO}_2$  storage security. These results for the UK maritime climate, consistent with soil carbonate accumulation and persistent in arid systems<sup>28</sup>, raise the monitoring, verification and reporting challenge of quantifying seasonal dynamics of soil carbonates, and soil fluid alkalinity discharge, over multiple field seasons.

## Temporal and spatial costs of cropland CDR

Costs of CDR are required to evaluate commercial feasibility, permit comparison with other CDR technologies, and for governments to understand the carbon price required to pay for it. Between 2020-2070, CDR costs fall from  $\text{£}200\text{-}250 \text{ t}^{-1} \text{ CO}_2 \text{ yr}^{-1}$  in 2020 to  $\text{£}80\text{-}110 \text{ t}^{-1} \text{ CO}_2$  by 2070 (**Figure 2 a-c**). Modelled longer-term cost trends are driven by rising CDR with successive rock dust applications (**Figure 1 a-c**) and declining renewable energy prices (**Supp Info**). Grinding rocks to smaller particle sizes carries a minor financial penalty. As geographical deployment of ERW increases in S3, the price of CDR rises transiently 2030-2050 due to higher total energy costs

associated with grinding more rock, and the requirement for more extensive logistical operations, particularly spreading of the rock dust over farms. However, it subsequently falls as CDR rates increase with repeated rock dust applications (**Figure 1**). The dominant cost elements are electricity for rock grinding and fuel for spreading the milled rock on farmland (**Figure 2d-f**). Mineral P- and K- nutrient fertilizers are expensive (£300-400 and £250-300 t<sup>-1</sup> for P and K fertilizers, respectively)<sup>29</sup>, but at application rates per unit land area typical for arable crops give savings sufficient to cover transport costs.

Modelled CDR costs for ERW practices are towards the lower-end of the range for BECCS, which varies widely across sectors<sup>5</sup> (£70-275 t<sup>-1</sup> CO<sub>2</sub>), and half that estimated for early-stage DACCS plants. DACCS CDR has an indicative price of £400 t<sup>-1</sup> CO<sub>2</sub> during the 2020s and £180 t<sup>-1</sup> CO<sub>2</sub> by 2050 as the technology develops and scales up globally<sup>1,5</sup>. ERW is thus highly competitive relative to these industrial CDR technologies that will also be required to help achieve net-zero emissions.

Fine-scale spatial and temporal assessment of CDR costs, combined with analysis of regional CO<sub>2</sub> drawdown, (**Extended Data Figs. 7 and 9**), informs geographical prioritisation of near-term opportunities for rapid ERW deployment and public consultations on these activities. Results reveal a 2.5-fold geographical variation in CDR costs across the UK compared to average values throughout 2020-2070. By 2060-2070, lowest costs (£75-100 t<sup>-1</sup> CO<sub>2</sub>) occur in the north-east and southwest of England, the midlands and Scotland, where CDR rates are highest because of favourable soil weathering environments and regional climate effects on site water balance (precipitation minus evaporation). CDR costs across eastern and the south east of England are almost double those of other regions due to later, post-2040, deployment in S2 and S3 lowering CDR rates and, to a lesser extent, long transport distances between source rocks and croplands.

Nations committing to net-zero targets require carefully designed economic and policy frameworks to incentivize uptake and cover the costs of CDR technologies<sup>1,14</sup>, as well as modification of existing emissions trading schemes. Costs might be met in the near-term through farming subsidies; agriculture is heavily supported in most countries worldwide<sup>14</sup>. Actions for enhancing soil carbon storage are already subsidized in the USA, and European proposals for incentivize CDR by farmers are underway<sup>30</sup>. Redesigned agricultural policies in the UK post-Brexit aim to provide public funding to support farmers in delivering environmental public goods and contribute to net zero<sup>31</sup> by 2050. Identifying strategic options, such as ERW, with multiple co-benefits for agricultural productivity, and the environment, is key to enhancing uptake.

## **Co-benefits of ERW for agricultural production**

Arable soils are a critical resource supporting multiple ecosystem services and adoption of ERW into current agricultural practices can enhance soil functions. We quantify three major soil-based co-benefits with potential to increase the demand for early deployment of the technology: reducing excess soil acidity, increasing the primary supply of fertilizer-based mineral nutrients (phosphorus, P, and potassium, K)<sup>3,7,8</sup>, and mitigating soil N<sub>2</sub>O fluxes<sup>15</sup>.

Soil acidity (i.e., pH below 6.5)<sup>32</sup> limits yields and correction is essential for good soil management, crop growth, nutrient use efficiency and environmental protection<sup>32</sup>. Following initialization with topsoil (0-15 cm) pH values based on high resolution field datasets (Methods), implementation of ERW reduces the fraction of arable soils with pH less than 6.5 in England to 13% by 2035 (S1), and completely by 2045 and 2055 in S2 and S3, respectively (**Figure 3a**). In Scotland, where agricultural soils are more acidic than in England, the co-benefit of ERW in raising soil pH could be considerable, with reductions to 10% by 2050 in S1 and eliminating acidic soils by 2045-2050 in S2 and S3 (**Figure 3b**). Reversing soil acidification across England

and Scotland can increase nutrient uptake to boost yields on underperforming croplands<sup>32,33</sup>, lower the potential for metal toxicity<sup>7</sup> at low pH, and enhance nitrogen fixation by legumes<sup>34</sup>. Additionally, calcium released by ERW can stimulate root growth and water uptake<sup>35</sup> and multi-element basalt can fortify staple crops like cereals with important micronutrients including iron and zinc<sup>8</sup>. Raising soil pH with widespread ERW practices in the UK, and elsewhere, to improve agricultural productivity<sup>36</sup>, releases land for additional CDR opportunities, including afforestation, and bioenergy cropping<sup>1,5</sup>.

Calculated rates of inorganic P and K nutrient supply for crops via ERW of basalt are comparable to typical P and K fertilizer application rates for major tillage crops (**Extended Data Fig. 10**). ERW with basalt could therefore substantially reduce the reliance of UK agriculture on expensive and finite rock-derived sources of P and K fertilizers required to support increased agricultural production over the next 50 years in the UK, and globally, to meet the demands of a growing human population<sup>37</sup>. Reductions in P- and K- fertilizer usage lower unintended environmental impacts, supply chain CO<sub>2</sub> emissions and costs. For the UK, assuming annual fertilizer application on ERW cropland areas in S1-S3 to replenish pools of P and K being removed, avoided carbon emissions are estimated to be 0.2 to 0.8 Mt CO<sub>2</sub> yr<sup>-1</sup>, with cost savings of £100-600 million yr<sup>-1</sup> by 2070 (**Figure 3, c-f**). These savings could contribute to offsetting the cost of undertaking ERW practices, but would be reduced by precision farming techniques, including applying variable levels of fertilisers within fields, and controlled release fertilisers.

Practices that optimise the efficient use of nitrogen on croplands to reduce N<sub>2</sub>O emissions from soils are important for ambitious net-zero agriculture pathways in the UK<sup>5</sup>. Our process-based model simulations, calibrated with field data<sup>15</sup>, indicate ERW deployment on UK croplands could reduce soil N<sub>2</sub>O emissions by ~0.1 Mt CO<sub>2equivalent</sub> yr<sup>-1</sup>, ~1 Mt CO<sub>2equivalent</sub> yr<sup>-1</sup>, and ~1.5 Mt CO<sub>2equivalent</sub> yr<sup>-1</sup> by 2070, in S1 to S3, respectively (**Figure 3e**); equivalent to up to a 20% reduction relative to croplands in 2010 (**Figure 3f**). This contrasts with large-scale land-based CDR strategies for increasing soil organic carbon stocks which can increase soil N<sub>2</sub>O emissions<sup>38</sup>. ERW may therefore offer a new management option for mitigating soil N<sub>2</sub>O fluxes comparable in magnitude to other proposed abatement measures<sup>39</sup> with the additional win of CDR.

## Societal and community acceptability

Societal acceptance of ERW practices is needed from the national-political to local community and individual farm scales. ‘Acceptance’ in this context should be regarded not as an absolute mandate to proceed, but rather recognizing the need to work with stakeholders and affected publics to identify the conditions under which this technology might proceed. Additional mining operations with unintended environmental impacts raise particular sensitivities<sup>6</sup> and two of our scenarios (S2 and S3) require new mines between 2035 and 2050 to provide basalt; increases post-2035 account for delays due to complex licensing procedures (**Extended Data Fig. 4**). Concentrating resource production at larger sites (~1 Mt basalt yr<sup>-1</sup>) requires annual increases in mine number of 6% (S2) and 13% (S3); smaller mines (~250 kt yr<sup>-1</sup>) necessitate larger annual increases. However, the scale-up rate is less than the historical 10-year maximum (1960-1970) and limited to 15 years. Recycling the UK’s annually produced calcium silicate construction and demolition waste (~80 Mt yr<sup>-1</sup>)<sup>40</sup>, which has potential to substitute for basalt<sup>4</sup>, could substantially reduce mined resource demand by between 80% (S2) and 45% (S3).

Traditional mining operations provide local employment opportunities but have encountered controversy nonetheless because of concerns about sustainability, community impacts and local health and environmental risks. Mining operations to enhance national carbon sequestration may raise somewhat different risk-benefit narratives. Procedural and distributional fairness in siting

mines, alongside long-term proactive engagement with communities likely to be affected by any new mining operations, will be critical for acceptance<sup>41</sup>. Although nature-based techniques for CDR (e.g. forestry, sequestration in soils) are likely to be preferred by public groups over engineered technologies<sup>6,41</sup>, they are unlikely to be sufficient to deliver net-zero nationally or globally. Above all, broad societal support is unlikely to be forthcoming unless ERW is developed alongside an ambitious portfolio of conventional climate mitigation policies<sup>6,42</sup>.

## Conclusions

Our analysis indicates that ERW, a technically straightforward CDR technology to implement, could prove transformative for utilizing agriculture to mitigate climate change<sup>4,7,8</sup> and play a critical role in national CDR portfolio programmes. Unlike industrial CDR processes including BECCS or DACCS, ERW may be rolled out without major new industrial infrastructure, and incentivised through amended agricultural subsidy frameworks. Maximising CDR, lowering costs to £80-110 t<sup>-1</sup> CO<sub>2</sub> yr<sup>-1</sup> by 2070, and eliminating the energy-demanding requirement for milling rocks to fine particle sizes, requires early and sustained implementation of ERW practices, subject to public acceptance. Our findings underscore the urgent need for long-term field trials across a range of agricultural systems to evaluate this technology with empirical evidence. High-resolution geospatial ERW assessments provide a detailed basis for mapping out routes to technological development and afford opportunities to minimize social and economic barriers by identifying priority regions for public engagement. Scaling up ERW in the UK and other G20 nations will require funding, public support, regulation and governance to ensure sustainability, and a stable policy framework<sup>1,5,11,21</sup> to accelerate global CDR goals with agriculture<sup>7,8</sup> as the world transitions to net-zero.

## Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at ...

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## Methods

**Resource Extraction Scenarios.** Scenario 1 (S1, low supply): per capita production of aggregate continues to fall from 1.9 to 1.5 t yr<sup>-1</sup> by 2032 and remains constant thereafter, with the spare capacity used and ramped up for ERW. Scenario 2 (S2, medium supply): rock extraction is scaled by 7% (half the historical maximum rate of increase) until total additional capacity is equal to the maximum historical value in 1990 (100 Mt yr<sup>-1</sup>), and Scenario 3 (S3, high supply): rock extraction is scaled by 15% (i.e., historical annual 10-year rolling average) until the additional capacity is 160 Mt yr<sup>-1</sup>; i.e., equivalent to the total increase in UK crushed rock supply post-1945 (Supplementary Information, Detailed Methods, Table S1). Our extraction of resources scales at rates compatible with historical patterns (**Extended Data Fig. 4**) and those envisioned for delivering CDR by BECCS, and its supply chains, and DACCS<sup>5</sup>.

**Coupled climate-C-N cycle ERW simulations.** Our model simulation framework (**Extended Data Fig 1**) starts with future UK climates (2020-2070) from the medium-mitigation future pathway climate (SSP3-7.0) ensemble of CMIP6 runs with the Community Earth System Model v.2. Future climates were used to drive the Community Land Model v.5 (CLM5) to simulate at high spatial resolution (23 km × 31 km) and temporal (30 min) resolution terrestrial carbon and nitrogen cycling with prognostic crop growth and other ecosystem processes, including heterotrophic respiration<sup>43</sup>. CLM5 simulates monthly crop productivity, soil hydrology (precipitation minus evapotranspiration), soil respiration and nitrogen cycling. CLM5 has representation of eight crop functional types, each with specific ecophysiological, phenological and biogeochemical parameters<sup>44</sup>. We initialized CLM5 simulations for 2010 using fully spun-up conditions from global runs at ~100 km × 100 km resolution, adding an extra 60-year spin-up in the regional set-up to stabilize the CN pools to the higher resolution setting.

CLM5 includes an interactive nitrogen fertilization scheme that simulates fertilization by adding nitrogen directly to the soil mineral nitrogen pool to meet crop nitrogen demands using both synthetic fertilizer and manure application<sup>43</sup>. Synthetic fertilizer application is prescribed by crop type and varies spatially for each year based on the Land Use Model Intercomparison Project and land cover change time series (LUH2 for historical and SSP3 for future)<sup>45</sup>. N-fertilizer rates increase by 18% per decade from 2020 to 2050 in agreement with forecasts of future N-fertilizer usage<sup>46</sup>, and then stabilise from 2050 to 2070. Average UK CLM5 fertilizer application rates (148 kg N ha<sup>-1</sup>yr<sup>-1</sup>) are consistent with current practices<sup>47</sup>. Organic fertilizer is applied at a fixed rate (20 kg N ha<sup>-1</sup>yr<sup>-1</sup>) throughout the simulations.

CLM5 tracks nitrogen content in soil, plant, and organic matter as an array of separate nitrogen pools and biogeochemical transformations, with exchange fluxes of nitrogen between these pools<sup>43,48</sup>. The model represents inorganic N transformations based on the DayCent model, which includes separate dissolved NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> pools, as well as environmentally controlled nitrification, denitrification and volatilization rates. To model the effect of basalt addition on fluxes of N<sub>2</sub>O from soil, we included the updated denitrification DayCent module<sup>15</sup>, modified to capture the soil pH ranges in UK croplands. CLM5 predicted soil nitrogen emissions within the range of estimates in UK croplands based on bottom-up inventories and field observations (Supplementary Table S2).

**Nitrogen cycling and soil profile ERW modelling.** Our analysis uses a 1-D vertical reactive transport model for rock weathering with steady-state flow, and a source term representing rock grain dissolution within the soil profile<sup>4</sup> with significant advancements to incorporate the effects of the biogeochemical transformations of nitrogen fertilizers ((Supplementary Information, Detailed Methods; Figures S1-S4). The core model accounts for changing dissolution rates with soil depth and time as grains dissolve, and chemical inhibition of dissolution as pore fluids

approach equilibrium with respect to the reacting basaltic mineral phases, and the formation and dissolution of pedogenic calcium carbonate mineral in equilibrium with pore fluids. Simulations consider UK basalts with measured mineralogy from a suite of three locations (Supplementary Tables S3, S4). We model ERW of a defined particle size distribution (psd) with the theory developed previously<sup>4</sup>. We account for repeated basalt applications by combining the psd of the existing basalt with the psd of the new application. As the existing psds at each soil level are at different stages of weathering, the combined psd at each level and for each mineral is calculated and tracked over time<sup>4</sup>. Simulated mineral dissolution fluxes from the model output were used to calculate the release of P and K over time. Mass transfer of P within the relatively more rapidly dissolving<sup>49</sup> accessory mineral apatite is calculated based on the P content of the rock and the volume of bulk minerals dissolved during each time step.

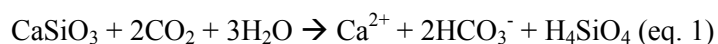
A significant theoretical advance over previous modelling is the inclusion of mechanistic simulation of nitrogen cycling processes coupled to ERW via sixteen nitrogen transformations that influence the soil weathering environment (Supplementary Tables S5, S6). The modelling accounts for 20 depths (20 soil layers) in the soil profile at each location with a monthly time-step; variables passed from CLM5 by time and depth, to the 1-D ERW model are given in Supplementary Table S3. At each depth, we compute nitrogen transformation effects on soil water alkalinity with reaction stoichiometries that add or remove alkalinity. Together with soil CO<sub>2</sub> levels, this affects pore water pH and the aqueous speciation that determines mineral weathering rates. This modelling advance allows us to mechanistically account for the impact of N fertilisation, recognised to potentially lead to nitric acid dominated weathering<sup>50,51</sup> at low pH with no carbon capture, of cropland on basalt weathering rates. Dynamic modelling at monthly time-steps resolves seasonal cycles of CDR via alkalinity fluxes and soil carbonate formation/dissolution in response to future changes in atmospheric CO<sub>2</sub>, climate, land surface hydrology, and crop and soil processes.

The initial alkalinity profile in each grid cell is determined from the starting soil pH and the PCO<sub>2</sub> profile at steady-state based on spin-up of the model with average long-term biomass production and soil organic matter decomposition that reflects the long-term land use history of a particular location. Alkalinity mass and flux balance for an adaptive time-step accounts for alkalinity and acidity inputs from 1) mineral dissolution rates and secondary mineral precipitation (pedogenic carbonate), 2) biomass production and decomposition<sup>52</sup> and 3) biogeochemical N transformations. The soil pH profile is determined from an empirical soil pH buffering capacity<sup>53</sup> relating soil pH to the alkalinity at each depth. The soil PCO<sub>2</sub> depth profile of a grid cell is generated with the standard gas diffusion equation<sup>54</sup>, scaled by monthly soil respiration from CLM5. At any particular location, the soil solution is in dynamic equilibrium with dissolved inorganic carbon species and the values of gas phase soil and atmospheric PCO<sub>2</sub>. The relative change induced by weathering will be the consumption of H<sup>+</sup> and the production of HCO<sub>3</sub><sup>-</sup>.

Using this modelling framework (**Extended Data Fig. 1**), we analysed a baseline application rate of 40 t ha<sup>-1</sup> yr<sup>-1</sup> (equivalent to a <2 mm layer of rock powder distributed on croplands) to UK croplands. Similar road transport of mass occurs in reverse during grain transport from field to market during UK harvest<sup>55</sup>, indicating appropriate capacity of rural transport networks to move basalt to the fields for ERW.

**Gross CDR calculations.** Gross CDR by ERW of crushed basalt applied to soils is calculated as the sum of two pathways: 1) the transfer of weathered base cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup>) from soil drainage waters to surface waters that are charge balanced by the formation of HCO<sub>3</sub><sup>-</sup> ions and transported to the ocean (eq. 1), and 2) formation of pedogenic carbonates (eq. 2).

Pathway 1 for calcium ions:



Pathway 2 for calcium carbonate formation:



CDR, via pathway 1, potentially sequesters two moles of CO<sub>2</sub> from the atmosphere per mole of divalent cation. However, ocean carbonate chemistry reduces the efficiency of CO<sub>2</sub> removal to an extent depending on ocean temperature, salinity and the surface ocean dissolved CO<sub>2</sub> concentration. We used annual ERW alkalinity flux time series (2020-2070) calculated with our 1-D ERW model for scenarios 1 to 3 as inputs to GENIE (version 2.7.7)<sup>56,57</sup>. GENIE is an intermediate complexity Earth System Model with ocean biogeochemistry and allows computation of oceanic CDR via pathway 1. Uncertainty for each scenario was determined by ensemble GENIE simulations with 86 different parameter sets that vary 28 parameters, each calibrated to simulate a reasonable preindustrial and historical transient climate and carbon cycle<sup>56-58</sup>. CDR via pathway 2 occurs if dissolved inorganic carbon derived from atmospheric CO<sub>2</sub> precipitates as pedogenic carbonate, and sequesters 1 mol of CO<sub>2</sub> per mole of Ca<sup>2+</sup>.

**Costs and carbon emissions of logistical operations. Mining.** Breakdown of mining costs in £/t of rock for the year 2010 and a representative granite mine of 1.5k daily/375k annual output were obtained from a comprehensive analysis of UK aggregate mining<sup>59</sup>. Capital expenditure costs (CAPEX) amounted to £24,395,636 over a 50-year life cycle (£1.30/t rock) while operating expenses (OPEX) amounted to £1,150,072 per year (£3.07/t rock) for a total £4.37/t rock for the year 2010. To obtain cost projections over 2020-2070, the contribution of wages, diesel fuel and electricity consumption in OPEX (35.9%, 2.5% and 20.0% respectively) were normalized and projected for 2020-2070 using E3ME outputs of median wage, diesel prices and industrial electricity tariff respectively (Supplementary Figure S5). CAPEX and the remaining OPEX (plant, buildings, equipment, tyres) costs in £/t rock remained constant over the period. Emissions of CO<sub>2</sub> eq./t rock extracted using diesel fuel and explosives were set at 4.29 kg CO<sub>2</sub> eq./t rock<sup>59</sup>. Emissions of CO<sub>2</sub> eq. per unit of electricity consumed were obtained by combining electricity requirements per tonne of rock (1.48 kWh/t rock) and projected Life Cycle Emissions (LCE) in kg CO<sub>2</sub> eq./kWh from 2020-2070.

**Grinding.** Grinding breakdown costs were obtained from Renforth (2012). CAPEX costs were set at £1.59/t rock while OPEX for plant, buildings and equipment at £0.97/t rock. Diesel fuel and personnel costs (£0.08/t rock and £0.85/t rock for 2010) were projected to 2020-2070 using the methodology described above. We expressed electricity consumption per tonne of rock grinded as a function of particle size, defined as *p*80, where 80% of the particles are equal to or less than a specified diameter<sup>4</sup>. To obtain electricity costs we multiplied electricity consumption (kWh/t rock milled) by E3ME projections of the unit cost of electricity (£/kWh) and grinding emissions by multiplying electricity consumption by E3ME projections of electricity production LCE (g CO<sub>2</sub>eq/kWh).

**Spreading.** Spreading costs were set to £8.3/t rock for the year 2020 by averaging costs in the UK and USA<sup>4</sup>. Spreading costs were assigned equally to equipment, fuel/electricity and wages with E3ME data used to provide cost projections to 2070 for the last two. A sigmoid function showing transition to electric cars was obtained from E3ME, to which a 10-year lag was added to signify a delayed uptake by heavy agriculture vehicles (Supplementary Figure S5). Spreading emissions were set to 0.003 kg CO<sub>2</sub>/t rock<sup>19</sup>. Our cost assessments assume ERW practices are undertaken on farms as part of business-as-usual land management practices. Pricing of external contracting of land management for rock dust application to soils is uncertain but could increase CDR prices per t CO<sub>2</sub> on the order of 10-15%.

**Fertilizers.** Projections of phosphorus (P) fertilizer prices (2020-2070) for a global medium resource scenario were obtained from ref 60, showing an increase in global prices due to depletion of phosphate reserves<sup>61,62</sup>. Even though potassium (K) resources are also depleting, we kept K prices constant as alternative technologies and opening of new mines in the Global South might alleviate the problem<sup>63</sup>. UK fertilizer prices for the year 2020 were used<sup>64</sup> as a baseline for our projections. Fertilizer savings were obtained as the product of release (kg) of P and K by their unit price (£/kg) over the time period 2020-2070. Life cycle assessment CO<sub>2</sub> emissions for P and K fertiliser were calculated as average values for different time horizons from the methodologies included in the Ecoinvent database<sup>65</sup> (Supplementary Table S7). Global Markets for these products were selected for this analysis to include all that those fertilisers coming to the UK from any region of the world.

**Energy requirements.** Electricity supply characteristics for the UK were obtained from E3ME simulations (see next section). Annual electricity supply increases from 320 GWh yr<sup>-1</sup> in 2020 to 637 GWh yr<sup>-1</sup> in 2070, with Life Cycle Emissions dropping from 177.4 gCO<sub>2</sub>/kWh to -64.5 gCO<sub>2</sub>/kWh. The electricity mix profile shows an initial transition to onshore wind energy, followed by a significant uptake of solar and various carbon capture and storage technologies.

Cost of enhanced rock weathering in £/t CO<sub>2</sub> CDR was obtained for annual from eq. 3 by summing up the logistical costs for all locations (£) that rock is applied according to each scenario for the particular year and dividing by their total net CDR (t CO<sub>2</sub>) (eq. 3). Mining and spreading costs are functions of year as the application rate is the same for all locations. Grinding costs are a function of year and *p80*. Transport costs are function of year and location and consider distance from the rock source. P and K release is a function of year, *p80* and location, as both particle size and location (climate) affect weathering rates and subsequently elemental release. All processes costs are functions of year due to time-varying wage, fuel, electricity and fertilizer costs.

$$\begin{aligned} & Costs(y, p80) \\ &= \sum_{Locations} \frac{Min(y) + Grind(y, p80) + Transp(y, loc) + Spread(y) - P(y, p80, loc) - K(y, p80, loc)}{CO_2 \text{ Gross Seq}(y, p80, loc) - CO_2 \text{ Secondary Emissions}(y, p80, loc)} \end{aligned}$$

(eq 3)

Secondary emissions (t CO<sub>2</sub>) for each location were obtained by summing the emissions of each process (t CO<sub>2</sub>/ t rock) in that year and multiplying by rock application (t rock) (eq. 4)

$$CO_2 \text{ Secondary Emissions}(y, p80, loc) = [Min(y) + Grind(y, p80) + Transp(y, loc) + Spread(y) - P(y, p80, loc) - K(y, p80, loc)] \times Rock(y, loc)$$

(eq. 4)

An initial run was performed to order the grid cells based on their weathering potential. Rock was then applied prioritizing grid cells with the highest potential while the addition of rock in new areas each year was constrained by the annual rock availability of each scenario.

**Transportation.** Detailed transport analyses (based on UK road and rail networks) were undertaken to calculate distances costs and CO<sub>2</sub> emissions for the distribution of rock dust from source areas to croplands. We used the GLiM database for the UK distribution of basalt deposits<sup>66</sup> and the 2019 land cover map (see Drivers, below), to calculate transportation distances, cost (pound per tonne of rock dust per kilometre), and emissions (CO<sub>2</sub> g<sup>-1</sup> tonne-kilometre) from potential local rock sources to cropland areas, together with UK road and rail transport networks<sup>67</sup>. Spatial analysis was undertaken with least-cost path algorithms from ArcGIS software<sup>68</sup>.

Wages and electricity/fuel prices and CO<sub>2</sub> emission factors were derived from E3ME's 1.5 °C energy scenario<sup>18</sup>, raw data were normalized based on the 2010 index for predicting the 2020-2070

time-series for transport costs and CO<sub>2</sub> emissions. We started using typical fuel/electricity consumption for both freight road, 2.82 km/litre and 3.07 kwh/km (ref 69) and rail, 98 km/litre (ref. 70), to estimate projected transport efficiency expressed in cost/emissions of a tonne of rock dust per kilometre (t km<sup>-1</sup>)<sup>71</sup>. Transport cost distribution per tonne-kilometre was derived using generic road and rail cost models that include wages, fuel, maintenance and depreciation<sup>72,73</sup>. UK rail freight diesel-to-electricity decarbonization transition is already ongoing<sup>74</sup>, and we used the continued projection for this transport mode<sup>75</sup>. For road freight, the transport technology transition from the E3ME for electric vehicles was adopted, modified under the assumption that diesel ban policies and the availability of electric Heavy Goods Vehicles for basalt transportation take place after 2030<sup>76</sup>.

**Energy and economic forecasts.** UK energy-economic modelling (2020-2070)<sup>77-79</sup> was based on an updated version of the scenario described in ref. 18 that includes carbon pricing and has responses for the power sector (output and efficiency) consistent with government policy<sup>80</sup> (Supplementary Information, Detailed Methods). Total renewable energy sources over time are similar but with solar instead of 40GW of offshore wind. The simulations consider the phase-out of conventional vehicles by 2030, in line with government policy, and a consistent move of aviation and freight towards biofuels, and electrified rail, as well as increased efficiency in buildings and use of heat pumps. These simulations provide outputs for the UK for 2020 to 2070 of CO<sub>2</sub> emissions per unit energy, total energy mix and output, labour costs, electricity costs, fuel costs, and road and rail transport costs that are inputs for calculating the costs of ERW CDR and secondary emissions during the grinding of rocks (**Extended Data Fig. 2**).

**Drivers.** Top-soil pH was obtained by spatially averaging two high resolution gridded datasets (1 × 1 km, 0.05° × 0.05°, respectively)<sup>81,82</sup> with resulting pH distribution over croplands similar to measurements of over 200,000 agricultural soil samples<sup>32</sup>. High resolution monthly soil temperature and precipitation data (0.1°x0.1°) from a global, multi-model data assimilation system<sup>83</sup> provide a baseline UK current climate (2001-2015) on which monthly anomalies of soil temperature and precipitation (2020-2070) from CLM5 were superimposed.

We used a high-resolution vector crop cover map (scale:1:2500, minimum unit: 2 ha) for the UK<sup>84</sup> with 8 crop classes: spring/winter wheat, spring/winter barley, field beans, maize, oilseed rape, and potatoes. This assumes stationarity in the current geographies of arable cropping across the scenarios. CLM5 includes parametrizations for spring wheat and maize, and we obtained monthly fields of net primary production (NPP), evapotranspiration, soil respiration, soil field capacity and irrigation for 2020-2070. These outputs were spatially interpolated to match the resolution of the crop cover map and overlaid to get monthly fields of spring wheat and maize on the appropriate locations. To compute NPP for the other crop types represented by the crop cover map, we obtained annual UK yields for each crop<sup>84</sup> for the period 2000-2019 and converted them to NPP after ref.<sup>85</sup>. Using this data, we build linear regression models to obtain a relationship between annual NPP of spring wheat and each of the remaining crops ( $p < 0.05$  for all crops except field beans), thus obtaining annual NPP for each crop type in each grid-cell by using CLM5 simulated values of spring NPP as a predictor variable. The monthly distribution of NPP for each crop was obtained by normalizing the monthly time series of spring wheat NPP from CLM5 in each grid-cell, to sum to the desired annual NPP for each crop as obtained from its regression model and then shifting the signal according to UK-specific crop calendars, using a delay signal function.

Using CLM5 spring wheat monthly data, we employed regression trees<sup>86</sup> to build a predictive model with monthly transpiration as a target variable and monthly air temperature and NPP as predictor variables ( $R^2 = 0.92$ , 5-fold cross-validation). We then drove this model with the NPP of the remaining crops to calculate corresponding transpiration for their respective grid cells. A

similar approach was used for evaporation ( $R^2 = 0.69$ ). For soil respiration, the predictor variables were NPP, soil temperature and soil field capacity ( $R^2 = 0.72$ ). All datasets were re-gridded to  $1/24^\circ$  resolution by spatial interpolation.

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**Acknowledgements.** We thank Corrine Le Quéré, Adrian Collins, Rob Freckleton, Jonathan Leake and Jonathan Scurlock for comments on an earlier draft, and gratefully acknowledge funding of this research with a Leverhulme Research Centre Award (RC-2015-029) from the Leverhulme Trust. M.V.M. acknowledges funding from the UKRI Future Leaders Fellowship Programme (MR/T019867/1) and P.R. UKRI funding under the UK Greenhouse Gas Removal Programme (NE/P019943/1, NE/P019730/1). We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling responsible for CMIP and thank the climate modelling groups for producing and making available their model output. For CMIP the US

Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

**Author contributions.** D.J.B., E.P.K., M.V.M., M.R.L., P.R. and S.A.B. designed the study, E.P.K., M.V.M and M.R.L. undertook model development, simulations and coding, with input from L.L.T., S.A.B. and D.J.B. E.P.K. undertook data analysis and synthesis, R.M.E. and L.K. undertook the UK transport analyses, P.R. developed the silicate supply scenarios, A.L. undertook the X-ray diffraction analyses of UK basalts, and N.P. wrote sections on public perception. N.V. and P.B.H. undertook the GENIE analyses, J.-F.M., H.P., N.R.E. and P.B.H. provided analyses and data on UK national economics, energy production, and CO<sub>2</sub> emissions. L.L.T. led drafting the Supplementary Information section. D.J.B. and S.A.B. wrote the manuscript with input from co-authors.

**Competing Interests.** The authors declare no competing interests.

**Supplementary Information.**

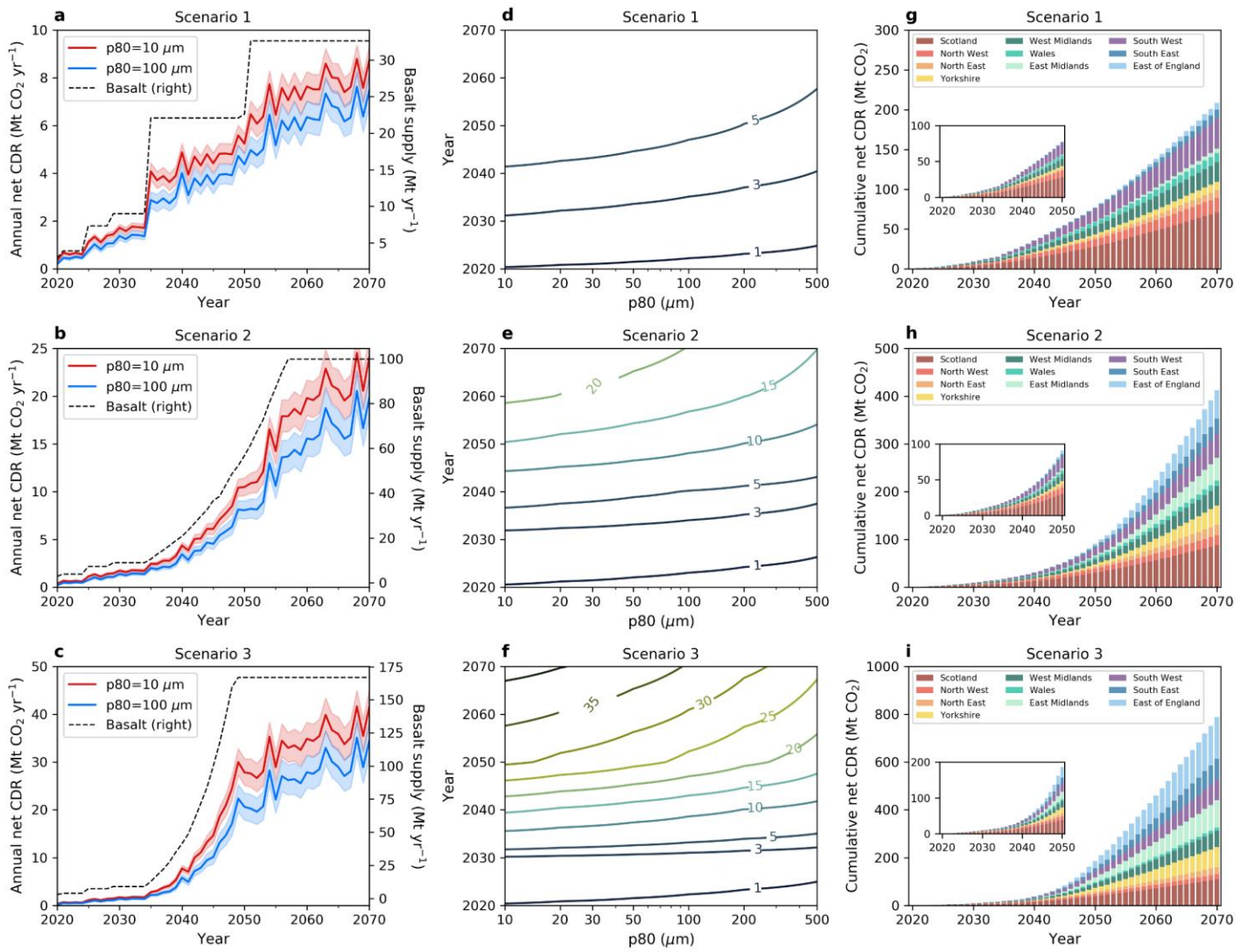
This file contains Detailed Methods, Figures S1 to S5, Tables S1 to S7, and References.

## Figure legends

**Figure 1 | Net carbon dioxide removal by enhanced rock weathering deployed with UK arable croplands.** Panels (a), (b) and (c) display simulated net carbon dioxide removal (CDR) and for low- (S1), medium- (S2), and high- (S3) resource extraction scenarios, respectively, and annual basalt extracted (dashed line). Results are shown for two particle size distributions ( $p_{80} = 10 \mu\text{m}$  diameter and  $p_{80} = 100 \mu\text{m}$  diameter;  $p_{80} = 80\%$  of particles  $\leq$  specified value). Shaded area denotes 95% confidence limits. Panels (d), (e) and (f) display iso-lines of equal UK net CDR (in units of  $\text{Mt CO}_2 \text{ yr}^{-1}$ ) for the three resource extraction scenarios over time (2020-2070). Panels (a) to (f) are mean results for three UK-specific basalts. Panels (g), (h) and (i) display cumulative net CDR over time for low-, medium- and high-resource extraction scenarios by UK region, respectively; mean of simulations with two  $p_{80}$ s (10 and 100  $\mu\text{m}$ ) and three UK-specific basalts.

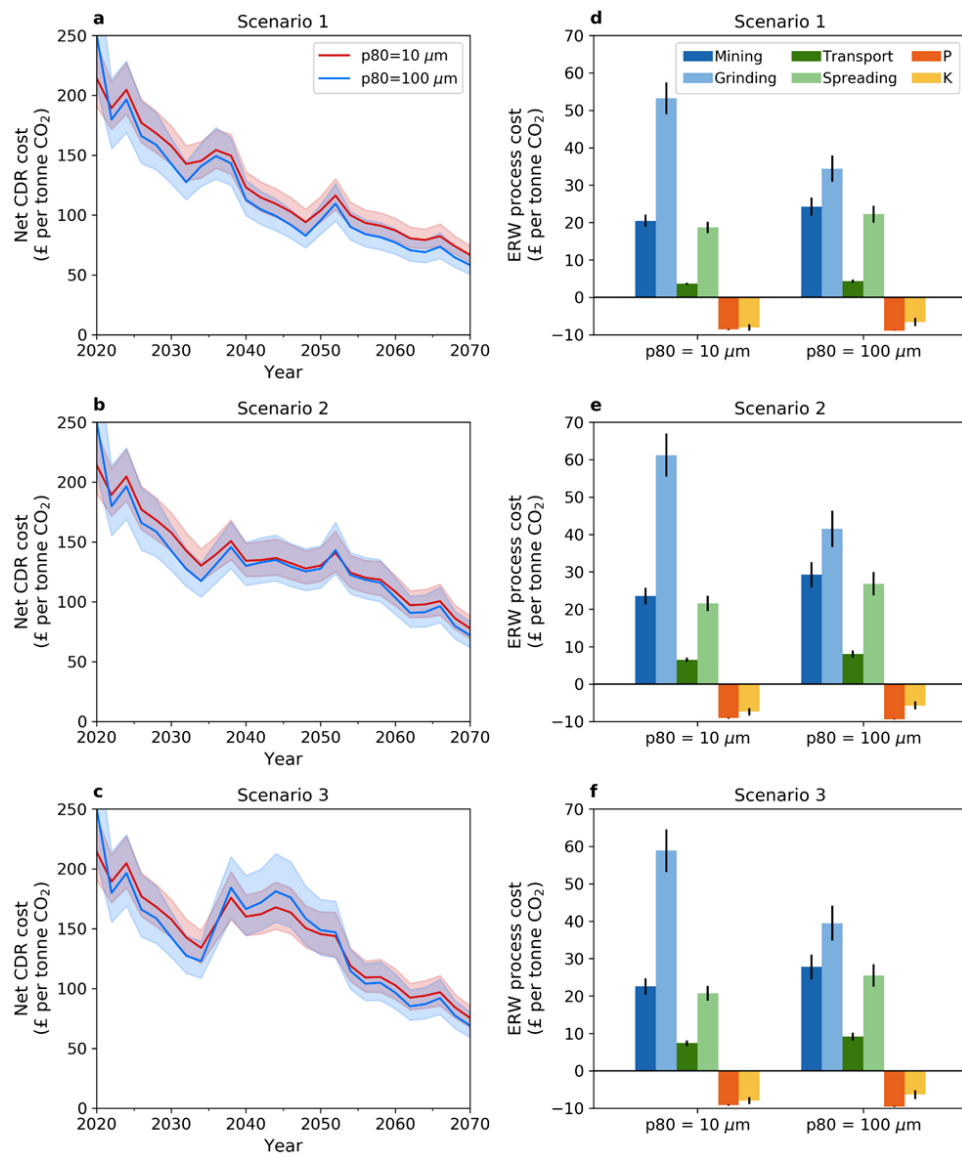
**Figure 2 | Costs of carbon dioxide removal by enhanced rock weathering deployed with UK arable croplands.** Panels (a), (b) and (c) display costs of net carbon dioxide removal for low- (S1) medium- (S2) and high- (S3) resource extraction scenarios, respectively, over time (2020-2070). Results are shown for two particle size distributions ( $p_{80} = 10 \mu\text{m}$  diameter and  $p_{80} = 100 \mu\text{m}$  diameter). Shaded area denotes 95% confidence limits. Panels (d), (e) and (f) show the breakdown between ERW processes contributing to CDR costs, including savings resulting from basalt substituting for phosphorus (P) and potassium (K) fertilizers averaged for 2060-2070. Errors indicate 95% confidence limits. All panels display average results for three UK-specific basalts.

**Figure 3 | Agricultural ecosystem co-benefits of enhanced rock weathering.** Reduction in the fraction of acidic land in (a) England and (b) Scotland following deployment of ERW,  $\text{CO}_2$  emissions avoided (c) and cost savings (d) resulting from using basalt to substitute for phosphorous (P) and potassium (K) fertilizers. Panel (e) and (f) display soil  $\text{N}_2\text{O}$  emission reductions from croplands (as  $\text{CO}_2$  equivalents), and percentage change from 2010, following ERW deployment.  $\text{N}_2\text{O}$  results are shown as 10-yr annual running averages with 95% confidence limits (shaded areas). Results are shown for low- (S1), medium- (S2) and high- (S3) resource extraction scenarios in all panels. All results are the mean of three UK-specific basalt simulations and two particle size distributions ( $p_{80} = 10 \mu\text{m}$  diameter and  $p_{80} = 100 \mu\text{m}$  diameter).



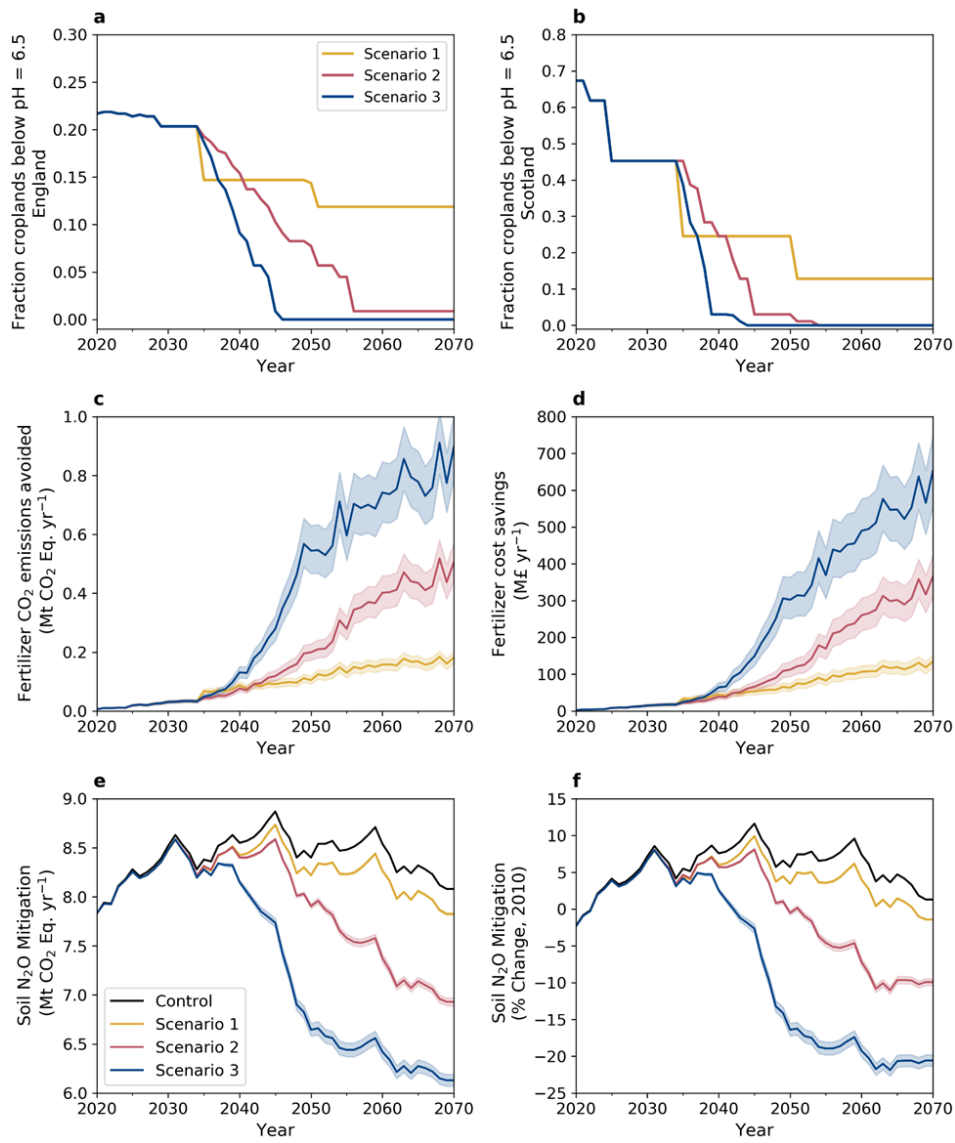
**Figure 1 | Net carbon dioxide removal by enhanced rock weathering deployed with UK arable lands.**

(Kantzas *et al.*)



**Figure 2 | Costs of carbon dioxide removal by enhanced rock weathering deployed with UK arable lands.**

(Kantzas *et al.*)



**Figure 3 | Agricultural ecosystem co-benefits of enhanced rock weathering.**  
(Kantzas *et al.*)