

1 **ARTICLE**2 **The potential for large-scale CO<sub>2</sub> removal via rock weathering on croplands**

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37 **Enhanced silicate rock weathering (ERW) deployable via croplands is a prime candidate to**  
38 **be evaluated for atmospheric Carbon Dioxide Removal (CDR), a backstop for human-**  
39 **caused climate change<sup>1</sup>. ERW has potential co-benefits for improved food and soil security**  
40 **and reduced ocean acidification<sup>2-4</sup>. We use an integrated performance modelling**  
41 **approach for an initial techno-economic assessment for 2050, quantifying how CDR**  
42 **potential and costs vary among nations in relation to business-as-usual energy policies**  
43 **and policies consistent with limiting future warming to 2 °C<sup>5</sup>. China, India, the United**  
44 **States and Brazil have large potential to help achieve average global CDR targets of 0.5 to**  
45 **2 Gt CO<sub>2</sub> yr<sup>-1</sup> with extraction costs of ~\$80-180 t<sup>-1</sup> CO<sub>2</sub>. These targets and costs are robust**  
46 **regardless of future energy policies. Deployment with existing croplands offers**  
47 **opportunities to align agriculture and climate policy. However, success will depend upon**  
48 **overcoming political and social inertia to develop regulatory and incentive frameworks.**  
49 **We discuss the challenges and opportunities of ERW deployment, including the potential**  
50 **for excess industrial silicate materials (basalt mine overburden, concrete, and iron and**  
51 **steel slag) to obviate the need for new mining, as well as uncertainties in soil weathering**  
52 **rates and land-ocean transfer of weathered products.**

53 Failure of the world to curb fossil fuel CO<sub>2</sub> emissions<sup>6</sup>, and the inadequacy of planned  
54 mitigation measures<sup>7</sup>, has been greeted with growing public consternation<sup>8</sup>, consistent with  
55 the clear intergenerational injustice of human-caused climate change<sup>9</sup>. Even the most  
56 ambitious emission phase-outs<sup>9,10</sup> fail to achieve the United Nations Framework Convention  
57 on Climate Change Paris Agreement targets for limiting global warming without the help of  
58 massive atmospheric Carbon Dioxide Removal (CDR). Extraction goals<sup>1,7,9,10</sup> later this  
59 century in most studies are on the order of at least 10 Gt CO<sub>2</sub> yr<sup>-1</sup>, although projections of  
60 rapid technological change<sup>5</sup> suggest a lower requirement of 2-2.5 Gt CO<sub>2</sub> yr<sup>-1</sup>. This  
61 formidable challenge has led to international calls for urgent research into a portfolio of CDR  
62 options to understand their feasibility, scope, costs and challenges<sup>11,12</sup>.

63 Our focus is terrestrial enhanced rock weathering (ERW), a CDR strategy based on  
64 amending soils with crushed calcium- and magnesium-rich silicate rocks to accelerate CO<sub>2</sub>  
65 sequestration<sup>2-4,13-17</sup>. Basalt, an abundant fast-weathering rock with the required mineral  
66 chemistry, is a prime target for implementing land-based ERW because of its potential co-  
67 benefits for crop production<sup>18</sup> and soil health<sup>2-4</sup>. ERW liberates base cations, generating  
68 alkalinity such that atmospheric CO<sub>2</sub> is converted into dissolved inorganic carbon (principally  
69 hydrogen carbonate ions; HCO<sub>3</sub><sup>-</sup>) that is removed via soil drainage waters. These weathering  
70 products are transported via land surface runoff to the oceans with a storage lifetime  
71 exceeding 100,000 years<sup>19</sup>. Depending on soil type, atmospheric CO<sub>2</sub>-derived dissolved  
72 inorganic carbon may also be sequestered through the formation of soil carbonate minerals,  
73 which reduces the efficiency of carbon sequestration by ~50%<sup>19</sup>. Logistical infrastructure to  
74 apply basaltic rock dust to managed croplands already exists due to the common need to  
75 apply crushed limestone to reverse soil acidification from intensive cropping<sup>2-4</sup>. Thus, rapid  
76 deployment at large scale appears feasible within decades, with important ancillary benefits  
77 including mitigation of ocean acidification<sup>15-18</sup>. Carbon sequestration by ERW on croplands,  
78 a biogeochemical CDR option supporting multiple United Nations sustainable development  
79 goals and ecosystem services<sup>4,20</sup>, and a pragmatic land-use choice to maximise scalability and  
80 co-benefits, thus warrants detailed examination.

81 We constructed a performance model with sub-national level of detail to assess  
82 quantitatively the CDR capacity and costs for land-based ERW implementation in major  
83 economies, constrained by available agricultural land area and energy production (including

84 USA, India, China, Brazil, and Europe) (**Extended Data Fig. 1**). For rock weathering within  
85 the soil profile, we developed a 1-D vertical reactive transport model with steady-state flow,  
86 and a source term representing rock grain dissolution (Methods; SI figs. S1-S12; SI tables S1-  
87 S5). Our work builds on advances made in prior ERW research largely on tropical forested  
88 ecosystems<sup>15-17,21,22</sup>, with the practical aims of understanding the capacity of agriculture to  
89 capture carbon via soil amendment with milled basalt. For this initial nation-by-nation  
90 assessment, we examine the sensitivity of net CDR with current croplands to projected  
91 national energy production for 2050 under a business-as-usual energy (BAU) scenario based  
92 on ongoing energy transitions<sup>5</sup>. This is compared with a 2°C scenario, which includes a wide  
93 range of policy measures designed to respect the 2°C target with 75% probability<sup>5</sup> (SI tables  
94 S6-S12).

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## 96 **Carbon removal potential via ERW**

97 Our geospatial analyses define a new technical potential CDR range for those nations with  
98 high capacity for ERW deployment on cropland (**Figure 1**; SI figs. S13-S15). For each  
99 nation, we generate CO<sub>2</sub> capture curves by ranking CDR potential from the highest to the  
100 lowest grid cells with increasing ERW deployment. National median CO<sub>2</sub> removal curves  
101 typically show CDR capacity rising with increasing cropland area, with carbon removal by  
102 silicate soil amendment reaching a plateau or declining in the case of Canada (**Figure 1**).  
103 These patterns reflect expansion of ERW into climatically unfavourable agricultural land,  
104 causing CDR potential to slow relative to the carbon penalty of logistical operations, and the  
105 3% limit in national energy available for grinding (**Extended Data Fig. 2**). Overall trends in  
106 national CDR curves are relatively insensitive to the choice of energy scenario. China is the  
107 exception because its large increase in low carbon energy usage projected under the 2°C  
108 scenario<sup>5</sup> allows net CDR to rise by substantially reducing secondary CO<sub>2</sub> emissions from  
109 logistical operations (**Figure 1**). This contrasts with results for India, whose total energy  
110 production falls by ~40% with a transition to low carbon energy production in the 2°C  
111 scenario, lowering energy available for grinding basalt, and thus the potential for increased  
112 CDR by ERW. Reductions in energy production for other nations in the 2°C scenario  
113 compared with the BAU scenario similarly lower their potential for increased CDR with the  
114 transition to low carbon energy.

115 Recognising the urgent need to assess large-scale options for meeting near-term CO<sub>2</sub>  
116 removal goals<sup>10</sup>, we determine the potential contribution of nations to achieve CDR targets  
117 across the 0.5-2 Gt CO<sub>2</sub> yr<sup>-1</sup> range (**Table 1**; **Extended Data Fig. 3**). Overall, we find the  
118 three top ranked countries with the highest CDR potential are coincidentally the highest fossil  
119 fuel CO<sub>2</sub> emitters (China, USA and India)<sup>6</sup> (**Figure 1**). Indonesia and Brazil, with CO<sub>2</sub>  
120 emissions 10-20 times lower than the USA and China, have relatively high CDR potential  
121 due to extensive agricultural lands and climates suitable for high silicate rock weathering  
122 efficiency. European countries have an order-of-magnitude lower CDR potential than China,  
123 USA, and India, mainly because of lower agricultural land area. The top five European  
124 nations with the highest net CDR potential could offset 30% of the EU27's current emissions  
125 and the top three European countries with highest CDR potential are also the largest  
126 European emitters of CO<sub>2</sub> from fossil fuels (Germany, Spain and Poland)<sup>6</sup>. Our ERW  
127 scenarios (**Table 1**) correspond to an aggregate CDR of 25-100 Gt CO<sub>2</sub> if sustained over 5  
128 decades. This would save up to 10% of the remaining cumulative carbon emission budget

129 (~900 Gt CO<sub>2</sub>) that gives a likely chance of limiting global warming to less than 2°C above  
130 the pre-industrial average surface temperature<sup>10</sup>.

131 In the context of our CDR targets, ERW has a similar potential to that of other CDR  
132 strategies<sup>23</sup> estimated for 2050, including bio-energy with carbon capture and storage  
133 (BECCS), widely adopted in IPCC future scenarios (0.5-5 Gt CO<sub>2</sub> yr<sup>-1</sup>), direct air carbon  
134 capture and storage (DAC) (0.5-5 Gt CO<sub>2</sub> yr<sup>-1</sup>), biochar (0.5 to 2 Gt CO<sub>2</sub> yr<sup>-1</sup>), soil organic  
135 carbon (SOC) sequestration (0.5-5 Gt CO<sub>2</sub> yr<sup>-1</sup>), and afforestation/reforestation (0.5-3.6 Gt  
136 CO<sub>2</sub> yr<sup>-1</sup>). One benefit of country level analysis for CDR is the scope for comparative  
137 assessments with other technologies and opportunities for co-deployment. For example, our  
138 ERW CDR range is comparable with large-scale implementation of BECCS in USA by 2040  
139 (0.3-0.6 Gt CO<sub>2</sub> yr<sup>-1</sup>), as constrained by biomass productivity, location and capacity of CO<sub>2</sub>  
140 storage sites<sup>24</sup>. ERW avoids competition for land used in food production, and related  
141 increased demands of BECCS for freshwater and polluting fertilizers<sup>25</sup>, with CO<sub>2</sub> being  
142 treated as a resource for mineral weathering. Co-deployment of ERW with feedstock crops  
143 for BECCS and biochar could enhance the feasibility and carbon sequestration potential of  
144 these strategies<sup>4,26</sup>.

145 Inorganic carbon sequestration by ERW appears comparable to SOC sequestration,  
146 another proposed CDR strategy (~2.5 Gt CO<sub>2</sub> yr<sup>-1</sup> by 2100)<sup>27</sup> using agricultural land, but with  
147 potentially greater long-term security of C-storage. Co-deployment of ERW and SOC  
148 sequestration at large-scale might, therefore, contribute substantially to the 5 Gt CO<sub>2</sub> yr<sup>-1</sup>  
149 carbon removal target suggested in decarbonization scenarios<sup>10</sup> for 2050. Compatibility of  
150 ERW and SOC sequestration may be realistic given that amendment of acidic organic-rich  
151 soils with silicate minerals, and resultant pH increase, had no effect on respiratory CO<sub>2</sub>  
152 fluxes<sup>28,29</sup>, contrary to concerns that increased soil pH may accelerate organic matter  
153 decomposition<sup>30</sup>. However, efficacy of CO<sub>2</sub> removal, sink saturation, and permanency of  
154 storage with these approaches, separately and interactively, are uncertain<sup>11,23</sup>. Abatement of  
155 soil N<sub>2</sub>O emissions by basalt application to conventionally managed arable and perennial  
156 crops<sup>31</sup>, and of N<sub>2</sub>O and CH<sub>4</sub> emissions by application of artificial silicates to rice  
157 agriculture<sup>32</sup>, is possible. Such effects would further lower adverse impacts of agriculture on  
158 climate per unit yield, amplifying the climate mitigation potential of ERW.

159 Greenhouse gas emissions reductions aimed at limiting future warming are defined  
160 under the Paris Agreement by Nationally Determined Contributions (NDCs)<sup>33</sup>. As yet, most  
161 of the top 10 fossil carbon emitting nations are failing to meet their 2030 NDC pledges  
162 which, even if met, imply a median warming (2.6–3.1 °C) exceeding the Paris agreement<sup>33</sup>.  
163 Warming of this magnitude could allow the Earth system to cross thresholds for irreversible  
164 planetary heating and long-term multi-metre sea-level rise, with potentially disastrous  
165 consequences for coastal cities<sup>34</sup>. NDC pledged carbon emission reductions undergo periodic  
166 revision in response to trends in greenhouse gas emissions, uptake of low-carbon energy  
167 technology, and climate<sup>33</sup> and hence are not set for 2050. We therefore illustrate the potential  
168 for undertaking ERW with agricultural lands to strengthen near-term national 2030 NDCs  
169 (**Figure 2**).

170 Results show that China may be able to augment its pledged 2030 NDCs by ~5-10%,  
171 with similar gains for the USA, which has opted-out of the Paris agreement. For India, the  
172 gain rises to 40% of its current pledged emissions, and Brazil may be able to offset 100% of  
173 its pledged 2030 CO<sub>2</sub> emissions plus some fraction of those from other countries (**Figure 2**).  
174 Other countries outside Europe considered in our analysis (Indonesia, Canada, Mexico) may  
175 be able to augment their NDCs by up to 30% (**Figure 2**). In Europe, ERW could aid

176 significant decarbonisation of France and Spain (up to approximately 40%), and to a lesser  
177 extent Poland, Italy and Germany (all ~10%) (**Figure 2**). ERW, therefore, has a role to play  
178 in compensating for residual carbon emissions from sectors recognized as being difficult to  
179 decarbonize, e.g., transportation by aviation, shipping, and agriculture<sup>1,11</sup>.

## 180 **Costs of carbon removal via ERW**

181 Cost assessment is needed to evaluate commercial feasibility of ERW and to put a price on  
182 climate mitigation actions (**Extended Data Fig. 4**). Our cost estimates based on current  
183 prices fall within the range of prior ERW assessments ( $\$75\text{-}250 \text{ tCO}_2^{-1}$ )<sup>21-23</sup> while resolving  
184 differences among nations (**Figure 3; Table 1; SI figs. S16-S25; SI tables S13-S14**).  
185 Average costs in USA ( $\$160\text{-}180 \text{ t}^{-1} \text{ CO}_2$ ), Canada and European nations ( $\$160\text{-}190 \text{ t}^{-1} \text{ CO}_2$ )  
186 are almost 50% higher than those in China, India, Mexico, Indonesia, and Brazil ( $\$55\text{-}120 \text{ t}^{-1}$   
187  $\text{CO}_2$ ). The difference largely reflects labour, diesel and electricity costs.

188 Defined as the cost of  $\text{CO}_2$  removal and storage, the price of carbon is a proposed  
189 economic enabler for bringing CDR strategies to market<sup>11</sup>. Carbon price is forecast by the  
190 World Bank<sup>11</sup> to reach  $\$100\text{-}150 \text{ t}^{-1} \text{ CO}_2$  by 2050. Costs per t  $\text{CO}_2$  removed are generally  
191 within this projected carbon price range in all nations, but unit costs increase when cropland  
192 area exceeds the optimal fraction, because the efficiency of weathering and CDR falls  
193 (**Figure 3; Table 1**). A carbon price of  $\$100\text{-}150 \text{ t}^{-1} \text{ CO}_2$  would cover most of the ERW  
194 costs for the key nations reported here. It would make ERW an economically attractive  
195 option for fast-growing nations, such as India, China, Indonesia, Brazil and Mexico given  
196 their estimated  $\text{CO}_2$  extraction costs of  $\sim \$75\text{-}100 \text{ t}^{-1} \text{ CO}_2$  (**Figure 3**).

197 Our estimated ERW costs of carbon removal for nations are comparable to estimates  
198 summarized for BECCS ( $\$100$  to  $200 \text{ t}^{-1} \text{ CO}_2$ ), DAC ( $\$100\text{-}300 \text{ t}^{-1} \text{ CO}_2$ ), and biochar ( $\$30\text{-}$   
199  $\$120 \text{ t}^{-1} \text{ CO}_2$ ), but higher than estimates for SOC sequestration ( $\$0\text{-}10 \text{ t}^{-1} \text{ CO}_2$ )<sup>23</sup>.  
200 Afforestation/reforestation and practices that increase soil carbon in natural ecosystems,  
201 including wetland restoration, have lower estimated costs ( $<\$100 \text{ t}^{-1} \text{ CO}_2$ )<sup>23</sup>. These options,  
202 like ERW, require assessment of possible indirect unintended positive climate feedbacks.

203 Per capita metrics help conceptualize the matter of costs in terms relevant to citizens.  
204 Current fossil fuel emissions per person per year<sup>6</sup> are 16.5 t  $\text{CO}_2$  (USA), 15.1 t  $\text{CO}_2$  (Canada),  
205 7.5 t  $\text{CO}_2$  (China), 7.3 t  $\text{CO}_2$  (EU28), 2.6 t  $\text{CO}_2$  (Brazil), 1.8 t  $\text{CO}_2$  (Indonesia) and 1.7 t  $\text{CO}_2$   
206 (India). ERW cannot offset all fossil fuel emissions, but using its cost as a guide, the per  
207 capita annual cost of achieving zero net emissions, a goal for decarbonisation, would be  
208 highest for Canada ( $\$3004$ ), the USA ( $\$2780$ ), China ( $\$832$ ) and EU28 nations ( $\$1288$ ).  
209 Costs fall substantially for citizens in Brazil ( $\$300$ ), Indonesia ( $\$103$ ) and India ( $\$135$ )  
210 (**Table 1**).

211 At this early stage of research and development, costs are uncertain and in need of  
212 demonstration projects<sup>7,11,12</sup>. Costs will likely decline as the market expands and  
213 technologies develop. This includes emergence of more energy-efficient, low-carbon  
214 technologies for rock grinding. Costs may also decline via co-deployment with  
215 afforestation/reforestation projects or agroforestry as part of worldwide carbon-offset trading  
216 schemes<sup>7</sup>. Net cost of ERW may be lower if rock dust is used as a fertilizer in organic  
217 agriculture, which currently occupies 57.8 million hectares, because it adds economic value  
218 by improving soil health, fertility and ecosystem services<sup>35</sup>.

219

## 220 **Implementation challenges and opportunities**

221 Our analysis of the techno-economic potential for CDR via ERW strengthens the case for  
222 evaluating all aspects of practical deployment in developed and developing economies. This  
223 includes meeting rock demand through alternative sources that avoid mining expansion,  
224 widening to more complete economic valuation, through to public perception and social  
225 acceptance.

226 National demand for crushed silicate rock is contingent on extent of ERW deployment  
227 (**Extended Data Fig. 5**). Within our scenarios, the demand for basalt required for ERW rises  
228 with an increasing CDR target and scales with agricultural land area (**Table 1**). Safeguarding  
229 against substantial increased mining and possible adverse impacts on livelihoods<sup>36</sup>, requires  
230 exploiting underutilized stockpiles of crushed basalt produced as a by-product of the  
231 aggregate industry. Mining generates a continuous but usually discarded finely powered  
232 silicate by-product utilizable for ERW without embodied CO<sub>2</sub> emissions that reduce CDR  
233 efficiency (**Extended Data Fig. 6**)<sup>21-23</sup>, and which has been accumulating worldwide for  
234 decades. However, national inventories of the location, availability and extent of this  
235 resource are required to assess the potential contribution of this resource to carbon removal.

236 Requirement for mining may be further reduced by utilizing artificial silicate by-  
237 products from industrial processes<sup>37,38</sup>, including calcium-rich silicates produced by iron and  
238 steel manufacturing (slags) with a long history of agricultural usage<sup>4,39</sup>. This material is  
239 recycled as low value aggregate (~\$5 t<sup>-1</sup>), and often stockpiled at production sites or  
240 disposed of in landfills, whereas it could become a valuable commodity for CDR. The  
241 largest amounts of by-products from the construction and demolition industry are cement,  
242 sand, and masonry. Following separation from other materials (e.g., metals and plastics), the  
243 cement comprises relatively ‘clean’ calcium-rich silicates and may be suitable for application  
244 to soils, but this suggestion requires field trials to assess suitability. Cement contributes ~6%  
245 to global CO<sub>2</sub> emissions<sup>6</sup> and ERW may represent a land management option for valorising  
246 by-products to capture carbon and improve the sustainability of this worldwide industry.

247 We forecast production of artificial calcium-rich cements for construction and by-  
248 product slag from steel manufacturing for Brazil, China, India, and the USA, to understand  
249 their potential role in meeting silicate demand for ERW (**Figure 4**). Differences between  
250 national production estimates are driven by forecast population increases over the coming  
251 century, and per capita consumption trends for the material under the middle-of-the-road  
252 Shared Socioeconomic Pathway (Methods). Bulk silicate production, linked to the  
253 construction and demolition sector, is modelled to increase substantially in all four nations,  
254 with China and India having combined production by 2060 of ~13 Gt yr<sup>-1</sup> (**Figure 4**). China  
255 and India dominate with above-average per capita cement consumption compared to the  
256 global average, and substantially larger populations than the USA and Brazil<sup>38</sup>. Thus, bulk  
257 silicate production of these two nations could meet the demand for ERW with large CDR  
258 potential (**Table 1**). Although chemically similar to basalt, these artificial calcium-rich  
259 silicates contain minerals that dissolve several orders of magnitude faster, react rapidly with  
260 CO<sub>2</sub> in soils under ambient conditions<sup>40</sup>, and are produced in fine particle sizes that facilitate  
261 accelerated weathering<sup>41</sup>.

262 Agricultural production can benefit substantially from increased resource use  
263 efficiency, reducing consumption of raw materials and recovering mineral nutrients from  
264 silicate by-products<sup>32,42,43</sup>, and overburden legacy reserves<sup>44</sup>. However, application of any  
265 silicate material to agricultural soils requires careful assessment of the risks including  
266 potential release of metals and persistent organic compounds (SI table S15). Undertaking

267 ERW practices with these materials addresses a critical need to fertilise soils with silica and  
268 other nutrients lost by harvesting that gradually depletes plant-available pools<sup>39</sup>.  
269 Intensification of food production across 24 million hectares of productive agricultural land  
270 in South Asia and China, for example, is creating acidified, desilicated soils exhausted in  
271 plant nutrients (potassium, zinc and available phosphorus) that limit yields<sup>45</sup>. Yet these  
272 negative effects may be reversible with ERW treatments given fertilization of irrigated rice  
273 using either natural and/or artificial silicates (e.g., recycled steel slags) replenishing plant  
274 available silica pools, increasing yields and soil pH, and decreasing the mobility of  
275 potentially toxic trace elements (e.g., arsenic)<sup>46</sup>. ERW may therefore also have a role in  
276 remediation of toxic metal contaminated soils and sediments across 20 million hectares of  
277 cultivated land in southern China and elsewhere<sup>47</sup>.

278 More broadly, innovative ERW practices via soil amendments with targeted silicate  
279 minerals could help rebuild rapidly deteriorating agricultural soils on which over six billion  
280 people depend directly for food<sup>48</sup>. Such practices may complement other approaches to soil  
281 improvement, including conservation tillage and nitrogen-fixing cover crops. The current  
282 substantial rate of agricultural top-soil depletion requires urgent remedial action, with  
283 significant economic costs apparent already in China where degradation of soils supporting  
284 wheat, maize and rice production costs an estimated \$12 billion annually<sup>48</sup>. Targeted  
285 amendment of agricultural soils for CO<sub>2</sub> removal may have a role in slowing rates of soil loss  
286 by up to 45%, with the accelerated weathering of added minerals replacing inorganic  
287 nutrients and resultant formation of clays and mineral organic aggregates increasing the  
288 cation exchange capacity and water storage capacity of rebuilt soils<sup>4,20</sup>. Addition of trace  
289 amounts of zinc and iron could also improve public health by reversing the effect of rising  
290 CO<sub>2</sub> levels on the declining nutritional value of food crops<sup>49</sup>.

291 Feasibility of mobilizing millions of smallholder communities to adopt ERW practices  
292 in China and India will depend on demonstrating soil improvements can reverse yield  
293 declines, and on government subsidies. Farming practices adopted for increasing sustainable  
294 productivity, for example, have transformed agriculture across 37 million hectares in China,  
295 increasing profits by \$12.2 billion over a decade<sup>50</sup>. With 2.5 billion smallholders farming  
296 60% of the world's arable land, a similar outreach programme could be used throughout Asia,  
297 with farmers earning more profits from higher yields while sequestering CO<sub>2</sub>. Involving  
298 local scientists in conducting research into its effectiveness and safety to build trust and  
299 engagement with smallholder farmers is key, alongside involvement with policymakers and  
300 stakeholders. This increases the potential to bring smallholders out of extreme poverty and,  
301 in the regions with climates suitable for non-irrigated agriculture, restore highly degraded  
302 soils not suitable currently for food production.

303 Realizing the potential of ERW as a biogeochemical approach to sequester CO<sub>2</sub> by  
304 altering land management practices will depend on the commitment of farmers and  
305 governments, implementation of the right policy frameworks, and wider public acceptance.  
306 Understanding the balance between positive and negative outcomes in terms of public  
307 acceptance of the inevitable trade-offs between local mining activities versus global  
308 sequestered carbon, requires empirical testing with stakeholders and the wider public.  
309 Crucially, such testing needs to understand the conditions that society might place upon the  
310 development and large-scale deployment of ERW technologies, as part of a wider responsible  
311 research and innovation programme<sup>51</sup>.

312

313 **Uncertainties**

314 Our analysis of the techno-economic potential of CDR by ERW is subject to several  
315 uncertainties, particularly variation in our baseline application rate and basalt mineralogy. It  
316 also identifies priority areas benefitting from more research of ERW under field conditions.

317 Extrapolation of laboratory weathering rates to the field scale is a recognized potential  
318 source of uncertainty in calculated CDR rates by ERW<sup>2-4,22-24</sup>. We addressed this by Monte  
319 Carlo analysis of the fractal dimension accounting for uncertainty in the apparent reacting  
320 surface area of grains for ERW conducted at large geographical scales. Together with the  
321 chemical affinity effects accounted for in our model, we constrain some of the systematic  
322 errors embedded in prior ERW assessments<sup>15-17,21,22</sup>.

323 Surface passivation, a component of chemical inhibition, occurs as weathering proceeds,  
324 creating leached layers and relatively stable secondary minerals, which potentially inhibit the  
325 mass transfer kinetics of elements from the dissolving surfaces of primary minerals. Current  
326 state-of-knowledge<sup>52</sup> precludes a detailed treatment of the role of surface passivation by  
327 formation of amorphous silica-rich surfaces for basalt grains added to agricultural soils. ERW  
328 analysis will benefit from future research to improve mechanistic insight and formulation of  
329 kinetic equations.

330 It remains to be determined if our theoretical analyses of the techno-economic potential  
331 for this CDR approach are consistent with findings from long-term field-scale ERW trials.  
332 Such trials are urgently required to assess weathering and CO<sub>2</sub> removal efficiency of freshly  
333 crushed rock grains with highly reactive surfaces added to agricultural soils subject to  
334 periodic wet-dry cycles during the growing season<sup>3</sup>. The potential for trapping of weathered  
335 cations on ion exchange surfaces or within secondary minerals other than carbonates  
336 delaying, or even preventing, land-ocean transfer will depend on soil type, climate,  
337 hydrological conditions, application rate and management practices. Duration of carbon  
338 sequestration rate, and possibility for CO<sub>2</sub> sink saturation with ERW on croplands, are both  
339 poorly constrained by data, in common with other land-based CDR strategies<sup>11,23</sup>, and affect  
340 cumulative CDR potential in coming decades. Other areas for further research include  
341 quantification of biogeochemical transformations of carbon and nitrogen associated with  
342 organic and inorganic fertilization practices, atmospheric deposition, and the role of  
343 rhizosphere biology.

344

## 345 **Conclusions**

346 Techno-economic assessment of ERW's potential to contribute large-scale CDR requires  
347 further integration of nation-by-nation quantitative analysis together with large-scale pilot  
348 demonstrators supported by fundamental process studies and public engagement. Our  
349 analysis identifies engineering challenges if ERW were to be scaled-up to help meet  
350 ambitious CDR targets as part of a wider portfolio of options<sup>1,7,11,12</sup>. ERW estimated costs  
351 are comparable to current estimates for the intensive carbon removal technologies, BECCS  
352 and DAC, and with potential for ancillary benefits by limiting coastal zone acidification and  
353 improving food and soil security. Nations that may have large ERW potential, including  
354 China, the United States and India, are all vulnerable to climate change and resultant sea-  
355 level rise<sup>34</sup>. Their high risks of economic damage<sup>53</sup> and social disruption provide impetus for  
356 creative co-design of agricultural and climate policies. Success requires incentives and  
357 regulatory frameworks that overcome social and political inertia. Silicate demand of nations  
358 must also be met in a way that facilitates social acceptance<sup>51,54</sup> and preservation of  
359 biodiversity<sup>4,20</sup>.



360 Deployment of any CDR strategy is inhibited by concern that it may erode society's  
361 perception of the climate threat and the urgency of mitigation measures<sup>54</sup>. The ancillary  
362 benefits of ERW may aid its early use and relieve such concern. Innovative 'climate-smart'  
363 farming practices can be designed with ERW to draw down CO<sub>2</sub> and other greenhouse gases  
364 while recycling nutrients, aiding soil water storage, and supporting crop production<sup>4,18,20</sup>.  
365 Such practices can help restore deteriorating top-soils that underpin food security for billions  
366 of people while maximizing societal co-benefits needed to incentivise deployment<sup>20</sup>.  
367 Financial, industrial and policy road-mapping that links short-term and long-term goals is  
368 needed, including a broader analysis of risks<sup>23</sup> and co-benefits<sup>2-4,18,20</sup>, to determine the role  
369 that ERW might play in climate risk mitigation.

370

### 371 **Online content**

372 Any methods, additional references, Nature Research reporting summaries, source data,  
373 extended data, Supplementary Information, acknowledgements, peer review information;  
374 details of author contributions and competing interests; and statements of data and code  
375 availability are available [at ...](#)

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494

495 **Methods Summary**

496 **Carbon removal simulation framework**

497 Our analysis is based on a 1-D vertical reactive transport model for rock weathering with  
498 steady-state flow<sup>55,56</sup>, and a source term representing rock grain dissolution within the soil  
499 profile (SI Methods). The model accounts for changing dissolution rates with soil depth and  
500 time as grains dissolve, and chemical inhibition of dissolution as pore fluids approach  
501 equilibrium with respect to the reacting basaltic mineral phases, and the formation of  
502 pedogenic calcium carbonate mineral in equilibrium with pore fluids. Simulations consider  
503 basalts exhibiting relatively slow- versus fast-dissolution rates due to differing mineralogy  
504 (SI tables S1-S3). Basaltic minerals undergo dissolution at different rates, with some  
505 minerals continuing to undergo dissolution and capture CO<sub>2</sub> after the first year of application.  
506 Thus calculating representative annual CO<sub>2</sub> removal rates requires computing average rates  
507 derived from repeated basaltic rock dust applications (**Extended Data Fig. 7**).

508

509 **Transport equation.** The calculated state variable in the transport equation is the dissolved  
510 molar equivalents of elements released by stoichiometric dissolution of mineral  $i$ , in units of  
511 mole L<sup>-1</sup>.  $\phi$  is volumetric water content,  $C_i$  is dissolved concentration (mole L<sup>-1</sup>) of mineral  $i$   
512 transferred to solution,  $t$  is time (y),  $q$  is vertical water flux (m y<sup>-1</sup>),  $z$  is distance along vertical  
513 flow path (m),  $R_i$  is the weathering rate of basalt mineral  $i$  (mole per litre of bulk soil per  
514 year) and  $C_{eq_i}$  is the solution concentration of weathering product at equilibrium with the  
515 mineral phase  $i$  (Equation 1).

$$\phi \frac{\partial C_i}{\partial t} = -q \frac{\partial C_i}{\partial z} + R_i \left( 1 - \frac{C_i}{C_{eq_i}} \right) \quad (1)$$

516

517

518

519 **Mineral mass balance.** The change in mass of basalt mineral  $i$ ,  $B_i$ , is defined by the rate of  
520 stoichiometric mass transfer of mineral  $i$  elements to solution. Equation 2 is required because  
521 we are considering a finite mass of weathering rock, which over time can react to completion,  
522 as opposed to *in situ* weathering of the lithosphere, e.g. when considering weathering and  
523 geomorphology<sup>56</sup>.

$$\frac{\partial B_i}{\partial t} = -R_i \left( 1 - \frac{C_i}{C_{eq_i}} \right) \quad (2)$$

524

525

526

527 **Removal of weathering products.** The total mass balance over time for basalt mineral  
528 weathering allows calculation of the products transported from the soil profile. The total mass  
529 of weathering basalt is defined as follows where  $m$  is the total number of weathering minerals  
530 in the rock,  $t_f$  is the duration of weathering (year) and  $L$  is the total depth of the soil profile  
531 (m).

$$\text{Total weathered Basalt} = \sum_{i=1}^m \phi \int_{z=0}^L C_i(t, z) dz + q \int_{t=0}^{t_f} C_i(t, L) dt \quad (3)$$

532

533

534 We define  $q$  as the net annual sum of water gained through precipitation<sup>57</sup> and irrigation<sup>58</sup>,  
535 minus crop evapotranspiration<sup>59</sup>, as calculated with high spatial resolution gridded datasets  
536 (**Extended Data Figs. 8 and 9**; SI Table S14).

537

538 **Rate law.** We modelled application of a crushed fast- or slow-weathering basalt, with  
539 specified mineral weight fractions and physical-chemical characteristics (SI Tables S1-S3).  
540 Rates of basalt grain weathering define the source term for weathering products and are  
541 calculated as a function of soil pH, soil temperature, soil hydrology and crop net primary  
542 productivity (NPP) using the linear transition state theory rate law<sup>60-62</sup>. Plant-enhanced basalt  
543 weathering is modelled empirically for annual and woody crops with power functions fitted  
544 to data (SI fig. S4; SI Table S4). These functions represent the effects of a range of  
545 rhizosphere processes that accelerate the physical breakdown and chemical dissolution of  
546 minerals, including the activities of nutrient scavenging mycorrhizal fungi that physically  
547 disrupt and chemically etch mineral surfaces, and bio-production of low molecular weight  
548 organic compounds and chelating agents<sup>63,64</sup>.

549 Soil pH of each grid cell is dynamically calculated from the alkalinity mass and flux  
550 balance for an adaptive time-step, controlled by mineral dissolution rates on mineral  
551 dissolution, following initialization with a top soil (0-15 cm) pH value based on field data  
552 from global soil databases (SI Table S14); soil pH buffering capacity is accounted for with an  
553 empirical soil pH buffer function<sup>65</sup>. The soil  $p\text{CO}_2$  depth profile of a grid cell is generated  
554 with the standard gas diffusion equation<sup>66</sup> scaled by crop NPP  $\times 1.5$  to account for combined  
555 autotrophic and heterotrophic respiration<sup>67</sup>. The alkalinity balance considers net acidity input  
556 during crop growth for biomass-cations removed from the field<sup>68</sup>, and secondary mineral  
557 precipitation of calcite<sup>18</sup>.

558

### 559 **Model advances**

560 We incorporate three further significant advances into the above 1-D vertical steady-state  
561 flow model. First, we provide a numerical basis for calculating weathering rates using log-  
562 normal particle size distributions of basalt grains produced by mechanical crushing and  
563 grinding for soil amendment<sup>22,69,70</sup>. This conceptualisation improves on the simplified case of  
564 a single mean particle diameter, previously used in ERW calculations<sup>16-18,22,23</sup>. Second, we  
565 apply the fractal dimension for surface roughness to relate reacting surface area to basalt  
566 mass across physical scales of weathering from the laboratory at which weathering kinetic  
567 parameter values are empirically determined to the field at which model results reflect CDR  
568 operations<sup>71</sup>. The fractal dimension effectively provides a means of consolidating  
569 measurements taken at different scales and accounts for uncertainties in grain topography and  
570 porosity<sup>72</sup>, and mass transfer rates from rock grains to flowing soil water. Finally, we  
571 calculate mean rates of rock dust weathering and  $\text{CO}_2$  removal following annual applications  
572 by tracking cohorts of particles applied over a 10-year time horizon and their mineral  
573 composition (**Extended Data Fig. 7**).

574

### 575 **Base-line simulations**

576 Using this modelling framework, we analysed a baseline application rate of  $40 \text{ t ha}^{-1} \text{ yr}^{-1}$   
577 (equivalent to a  $<2 \text{ mm}$  layer of rock powder distributed on croplands), which falls within the  
578 range of basalt amendments shown to improve crop production in field trials<sup>4</sup>. Net CDR is  
579 defined as the difference between  $\text{CO}_2$  capture by ERW as dissolved inorganic carbon and  
580 soil (pedogenic) carbonate and the sum of  $\text{CO}_2$  emissions for logistical operations. Carbon  
581 emissions per unit mass of ground rock depend on particle size (**Extended Data Fig. 10**), the

582 CO<sub>2</sub> emissions per kilowatt-hour of electricity generated from component energy sources  
583 (fossil fuels, nuclear and renewables), as well as the carbon costs of sourcing and transporting  
584 the silicate materials. Rock grinding to reduce particle size and maximise CDR is the  
585 primary energy consuming operation in ERW<sup>22,23,73</sup>.

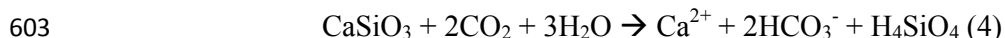
586 Assessment of basalt transport from source regions to croplands is based on road and  
587 rail network analyses to calculate distances, costs, and carbon emissions for each scenario (SI  
588 Methods Section 2.3). Our approach improves on prior analyses, which assumed a fixed  
589 radius between rock dust source and site of application<sup>73</sup>. We go beyond global cost  
590 estimates<sup>23</sup> by using national fuel (diesel), labour and infrastructure costs to undertake  
591 logistical operations, and the price of energy inputs to grind rocks. Our analysis thus  
592 represents the first techno-economic assessment in which detailed ERW carbon and  
593 economic costs vary within and between nations and account for socio-technical uncertainties  
594 in energy production.

595

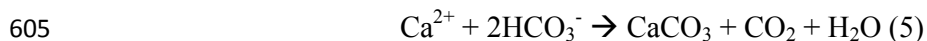
### 596 **Carbon dioxide removal**

597 We calculate carbon dioxide removal (CDR) by ERW of crushed basalt applied to soils via  
598 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  
599 drainage waters to surface waters that are charge balanced by the formation of HCO<sub>3</sub><sup>-</sup> ions  
600 and transported to the ocean (Equation 4), and 2) formation of pedogenic carbonates  
601 (Equation 5).

602 Pathway 1 for calcium ions:



604 Pathway 2 for calcium carbonate formation:



606 Monovalent and divalent base cations are released from basaltic minerals by dissolution  
607 based on stoichiometry (SI Table S2). CDR, via pathway 1, potentially sequesters two moles  
608 of CO<sub>2</sub> from the atmosphere per mole of divalent cation. However, ocean carbonate  
609 chemistry reduces the efficiency of CO<sub>2</sub> removal ( $\eta$ ) to an extent depending on ocean  
610 temperature, salinity and the surface ocean dissolved CO<sub>2</sub> concentration. We calculate  $\eta$  for  
611 average ocean temperature (17 °C), salinity (35‰) and an RCP8.5 2050 dissolved  $p\text{CO}_2$  of  
612 600  $\mu\text{atm}$ , giving  $\eta = 0.86$ , i.e., 0.86 mole of CO<sub>2</sub> removal per mole of monovalent cation and  
613 1.72 mol of CO<sub>2</sub> removed per mol of divalent cation added to the oceans<sup>20</sup>. For Pathway 1,  
614 the efficiency of CDR =  $\eta \times \sum(\text{mol monovalent cations}) + 2\eta \times \sum(\text{mol divalent cations})$ .

615 CDR via pathway 2 can occur if dissolved inorganic carbon derived from atmospheric  
616 CO<sub>2</sub> precipitates as pedogenic carbonate, and sequesters 1 mol of CO<sub>2</sub> per mole of Ca<sup>2+</sup>  
617 instead of 1.72 mol of CO<sub>2</sub> via pathway 2 and is therefore less efficient. Thus for any given  
618 grid cell, we compute CO<sub>2</sub> removal by ERW as the alkalinity flux in soil drainage and  
619 pedogenic calcite precipitation. Possible CO<sub>2</sub> degassing due to changes in surface water  
620 chemistry during transport in large river systems<sup>74</sup> is not considered.

621

### 622 **Cost assessment modelling**

623 An overview of the environmental costs model and its linkages with the performance model  
624 is presented in **Extended Data Fig. 4**. We include contributions to total cost of 1) mining, 2)  
625 processing<sup>75,76</sup>, 3) distribution and transport and 4) spreading on agricultural land. We  
626 considered how the cost of energy and the carbon emissions varied with grinding to different

627 particle size distributions (**Extended Data Fig. 10**). Grinding to finer particles requires  
 628 greater energy and results in higher carbon emissions. We defined the particle size  
 629 distribution by the  $p80$  value; i.e. 80% of the particle mass with less than or equal to a  
 630 specified particle size. We calculated the optimized  $p80$  that results in maximum net CDR  
 631 for each grid cell and this was conducted for different fractions of a country's crop area (0.1  
 632 to 1.0 at 0.1 increments), ordered according to weathering potential. For a given  $p80$  value,  
 633 we calculate the weathering rate for each grid cell, sort them in descending order and find the  
 634 grid cells that comprise the cumulative area fraction for each increment.

635 Optimization is conducted for each combination of the two types of basalt and the two  
 636 quasi-log-normal particle size distributions for each country (SI Tables S1-S3). Country-  
 637 specific electricity production and the forecast fractional contributions to electricity  
 638 production by different energy sources (coal, natural gas, oil, solar PV, concentrated solar  
 639 power, hydropower, wind, marine) for 2050 are based on business-as-usual (BAU), i.e.,  
 640 currently implemented energy policies, and energy projections consistent with a 2°C (2°C)  
 641 warming scenario (**Extended Data Fig. 9**)<sup>5</sup>. National CO<sub>2</sub> emissions for electricity  
 642 generation consistent with both scenarios were based on results reported in Ref<sup>5</sup> (SI Tables  
 643 S6-S9). Industrialized nations (e.g., Canada) consume up to ~2% of their total energy  
 644 production on rock comminution (crushing and grinding) processes<sup>77</sup>. We assume a future  
 645 maximum upper limit of 3% energy consumption for all nations, based on the rationale that  
 646 current rates for developed nations grow from around 2% today in-line with national  
 647 projected energy production<sup>5</sup> in 2050 (**Extended Data Fig. 2**).

648 Distribution costs and emissions were calculated by performing spatial analysis with  
 649 ArcGIS software. Basalt rock sources were identified from the GLiM rock database<sup>78</sup>,  
 650 excluding those in protected areas<sup>79</sup>. We then performed a global transport (rail and road)  
 651 network analysis by modelling a logistic ERW supply by creating an Origin-Destination Cost  
 652 Matrix using GIS<sup>80,81</sup>. For larger datasets, the Origin-Destination cost matrix searches and  
 653 measures the least-cost paths along the network from multiple origins to multiple destinations  
 654 to identify the most cost-effective or shortest route between a source and destination.  
 655 Transport analyses used the lowest emission option between rail and road network to  
 656 calculate distribution costs and CO<sub>2</sub> emissions (SI Tables S10-S12). Freight-rail emissions  
 657 were obtained from 2050 projections of reduced carbon emissions following improvements in  
 658 energy efficiency<sup>82</sup>. Rail CO<sub>2</sub> emissions were the same for both the business-as-usual (BAU)  
 659 and 2°C scenarios. For road transport, we considered estimated energy consumption of  
 660 currently/shortly available heavy electric trucks 1.38 (kWh/km)<sup>83</sup> and projected carbon  
 661 emissions in the electricity sector of each country for BAU or the 2°C scenario<sup>5</sup>.

662

### 663 **Forecasting bulk silicate waste production**

664 We developed a model that relates global per capita material production (for cement) or  
 665 consumption (steel)  $P$  to per capita gross world product ( $GWP$ )<sup>84,85</sup> through historical global  
 666 data using nonlinear least squares (Equation 6).

$$667 \quad P = ae^{-b/GWP} \quad (6)$$

668 where  $a$  and  $b$  are regression constants. The derived saturation value,  $a$ , was used in a further  
 669 regression through national data normalised to 2014 production and GDP (Equation 7).

$$670 \quad P = P_{REF} \times (1 + ((m + r) \times \Delta GDP)) \times e^{(a \times (1 - e^{-(m \times \Delta GDP)})) - (m \times \Delta GDP)} \quad (7)$$

671 where  $P_{REF}$  is the global per capita consumption in a given reference year (2014),  $\Delta GDP$  is  
 672 the deviation of the per capita gross domestic product from the reference year, and  $m$  and  $r$

673 are regression constants. These results were used together with averaged projections of  
674 future GDP (SI Table S14) from the ‘middle-of-the-road’ Shared Socioeconomic Pathway  
675 (SSP2) to derive nationally resolved projections of future per capita  
676 consumption/production<sup>85</sup>. SSP2 potentially represents the largest material production  
677 pathway, as other SSPs forecast lower consumption or economic growth producing 30-50%  
678 less material globally. We have not considered the penetration of recycling into steel  
679 production beyond its current rate. Cement and cement kiln dust have no capacity to be  
680 recycled as cement. The total production/consumption at a given time,  $T(t)$ , was calculated by  
681 multiplying the population,  $Pop(t)$ , by production or consumption ( $P$ ). We assume 115 kg of  
682 cement kiln dust is produced as a by-product in kilns for every tonne of clinker, and have  
683 modelled the production of demolition waste following an average 50-year service life  
684 (normally distributed with a standard deviation of 10 years)<sup>86</sup>. The ratio of pig iron to steel  
685 production (0.72) was obtained using linear regression of 1960-2014 data, negating the need  
686 to explicitly model pig iron displacement from scrap recycling, and assuming the scrap ratio  
687 remains unchanged. All steel and blast furnace slag was considered available for reaction  
688 with CO<sub>2</sub>. Between 2006–2014, 185 kg of blast furnace slag and 117 kg of steel slag was  
689 produced for every tonne of crude steel<sup>87</sup>.

690

#### 691 **Data availability**

692 Datasets on global crop production and yield are available at: <http://www.earthstat.org/>, accessed on  
693 18/12/2019

694 Datasets on global crop evapotranspiration are available at: [https://www.uni-  
695 frankfurt.de/45217988/Global\\_Crop\\_Water\\_Model\\_GCWM](https://www.uni-frankfurt.de/45217988/Global_Crop_Water_Model_GCWM), accessed on 18/12/2019

696 Datasets on global crop irrigation are available at: <https://zenodo.org/record/1209296>, accessed on  
697 accessed 18/12/2019

698 Datasets on global precipitation are available at: <http://www.climatologylab.org/terraclimate.html>,  
699 accessed on 18/12/2019

700 Datasets on global soil surface pH are available at: <https://daac.ornl.gov/SOILS/guides/HWSD.html>,  
701 accessed on 18/12/2019

702 Datasets on global soil temperature are available at: <https://esgf-node.llnl.gov/search/cmip5/>, accessed  
703 on 18/12/2019

704 Datasets on diesel prices are available at <https://data.worldbank.org/indicator/EP.PMP.DESL.CD>

705 Datasets on mining costs are available at <http://www.infomine.com/>

706 Datasets on gross national income per capita are available at  
707 <https://data.worldbank.org/indicator/ny.gnp.pcap.pp.cd>

708 Datasets for projections of future GDP linked to Shared Socioeconomic Pathways are available at:  
709 <https://tntcat.iiasa.ac.at/SspDb>

710

#### 711 **Source data**

712 Source Data for figures 1 to 4 are available from nature.com [please insert web location of the  
713 uploaded datasets].

#### 714 **Code availability**

715 The Matlab codes developed for this study belong to the Leverhulme Centre for Climate Change  
716 Mitigation. We will make them available upon reasonable request.

717



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809 M.R.L. undertook model development and coding, with input from P.W., S.A.B., S.Q. and D.J.B.  
810 E.P.K. undertook data analysis and synthesis, R.M.E. and L.K. undertook the GIS transport analyses,  
811 P.R. the silicate production modelling, and N.P. wrote sections on public perception. J.-F.M., H.P.,  
812 N.R.E. and P.B.H. provided data on national energy production and sources, and CO<sub>2</sub> emissions for  
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815 manuscript, with input from J.H.

816

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

818

#### 819 **Supplementary Information.**

820 This file contains Methods, Figures S1 to S25, Tables S1 to S15, and References.

821

822 **Correspondence and requests for materials** should be addressed to D.J.B.

823

#### 824 **Peer review information.**

825

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828

## Figure legends

829

830

831 **Fig. 1 | Carbon removal via enhanced rock weathering with croplands.** Net carbon  
832 dioxide removal (CDR) curves for nations with the highest CDR potential worldwide (**a-g**)  
833 and in Europe (**h-l**) as a function of increasing enhanced rock weathering deployment across  
834 existing croplands. Note y-axis scale changes. Results are shown for the business-as-usual  
835 (BAU) and the 2°C energy policy scenarios. Grey shaded area for each nation represents the  
836 90% confidence interval calculated for basalts with relatively slow- versus fast-weathering  
837 rates for the BAU scenario; short green dashed lines indicate the 90% confidence limits of the  
838 corresponding 2°C scenario simulations. Uncertainty in net CDR increases as ERW deploys  
839 onto croplands occupying a wider range of environmental conditions.

840

841 **Fig. 2 | Augmentation of pledged CO<sub>2</sub> emissions reduction by enhanced rock**  
842 **weathering.** Fraction of 2030 national determined carbon (NDC) emissions reductions by  
843 enhanced weathering for nations with the highest CDR potential worldwide (**a-g**) and in  
844 Europe (**h-l**), as a function of increasing enhanced rock weathering deployment across  
845 croplands. Note y-axis scale changes. Results are shown for the business-as-usual (BAU)  
846 energy policy and the 2°C energy policy scenarios. Grey shaded area for each nation  
847 represents the 90% confidence interval calculated for basalts with relatively slow- versus fast-  
848 weathering rates for the BAU scenario; short green dashed lines indicate the 90% confidence  
849 limits of the corresponding 2°C scenario simulations.

850

851 **Fig. 3 | Costs of carbon extraction via enhanced rock weathering with croplands.** Costs  
852 of CO<sub>2</sub> extraction from air by ERW for nations with the highest CDR potential worldwide (**a-**  
853 **g**) and in Europe (**h-l**), as a function of increasing enhanced rock weathering deployment  
854 across croplands. Results are shown for the business-as-usual (BAU) and the 2°C energy  
855 policy scenarios. Grey shaded area for each nation represents the 90% confidence interval  
856 calculated for basalts with relatively slow- versus fast-weathering rates for the BAU scenario;  
857 short green dashed lines indicate the 90% confidence limits of the corresponding 2°C  
858 scenario simulations.

859

860 **Fig. 4 | Forecast increases in national bulk silicate production over the next century.**  
861 Simulated future increases in bulk artificial silicate by products (slag, cement, kiln dust, and  
862 cementitious demolition waste) production during the 21<sup>st</sup> Century are given for **(a)** China,  
863 **(b)** India, **(c)** USA and **(d)** Brazil. Based on the middle-of-the-road Shared Socioeconomic  
864 Pathway (Methods).

865

866

## Extended Data Figure legends

867

868

869 **Extended Data Fig. 1 | Performance model schematic.** Detailed methods are provided in  
870 SI Methods, Sections 1-2. Spatially resolved key drivers are mapped in Extended Data Fig.  
871 8; sources given in SI Table S14.

872

873 **Extended Data Fig. 2 | Cumulative energy demand for rock grinding by nation.** Results  
874 are shown for the top seven nations of the world **(a)** to **(g)**, and the top five European nations  
875 **(h)** to **(i)**, as ranked by net CO<sub>2</sub> removal capacity, with increasing fractional cropland area of  
876 enhanced rock weathering deployment. Curves depict simulations for the business as usual  
877 (BAU) and 2°C energy policy scenarios. Grey shaded area for each nation represents the  
878 90% confidence interval calculated for basalts with relatively slow- versus fast-weathering  
879 rates for the BAU scenario; short green dashed lines indicate the 90% confidence limits of the  
880 corresponding 2°C scenario simulations.

881

882 **Extended Data Fig. 3 | Simulated net CO<sub>2</sub> removal with croplands via enhanced rock**  
883 **weathering.** Net rates of CO<sub>2</sub> sequestration on croplands (annual and perennial combined)  
884 for the four target global CO<sub>2</sub> removal rates, 0.5, 1.0, 1.5 and 2.0 Gt CO<sub>2</sub> yr<sup>-1</sup> (Table 1) for the  
885 business-as-usual (BAU) **(a)** to **(d)** and the 2°C **(e)** to **(h)** energy policy scenarios.

886

887 **Extended Data Fig. 4 | Schematic overview of the environmental economics model.**  
888 Interactions are shown between the performance model, calculating net CO<sub>2</sub> removal, and the  
889 major components of the environmental economic model. Spatially resolved key drivers are  
890 mapped in Extended Data Fig. 9; sources given in SI Table S14.

891

892 **Extended Data Fig. 5 | Cumulative silicate demand by nation.** Results are shown for the  
893 top seven nations of the world **(a)** to **(g)**, and the top five European nations **(h)** to **(i)**, as  
894 ranked by net CO<sub>2</sub> removal capacity, with increasing fractional cropland area deployment of  
895 enhanced rock weathering. Note y-axis scale changes for European countries. Curves are the  
896 same irrespective of energy policy scenario.

897

898 **Extended Data Fig. 6 | Secondary CO<sub>2</sub> emissions from logistical enhanced rock**  
899 **weathering operations in 2050.** Results are shown for **(a)** the top seven nations of the world  
900 and **(b)** the top five European nations for the business-as-usual (BAU) and for the same  
901 groupings in **(c)** and **(d)** for the 2 °C energy policy scenarios. For each country, bars from  
902 left to right, are for a 0.25, 0.5, 0.75 and 1.0 fraction of ERW deployment on croplands.  
903 Under the BAU scenario, CO<sub>2</sub> emissions from grinding dominate secondary emissions  
904 associated with ERW, except for France where low carbon nuclear power dominates. Under  
905 the 2°C energy policy scenario, **(c)** and **(d)**, secondary CO<sub>2</sub> emissions generally drop for most  
906 nations as they transition to low carbon energy sources in 2050 and implement negative  
907 emissions.

908

909

910

911

912 **Extended Data Fig. 7 | Multi-year performance model simulations of weathering.**  
913 Illustrative multi-year simulations of annual basalt application with the performance model  
914 showing the effects on soil pH, average efficiency of CO<sub>2</sub> removal (RCO<sub>2</sub>), and soil mineral  
915 masses over a 10-year time horizon. **(a)** - **(c)** denote pH, RCO<sub>2</sub> and mineral mass results for  
916 the tholeiitic basalt, respectively and **(d)** to **(f)** results of the same quantities for the alkali  
917 basalt (SI Tables S1-S3). All simulations used the same *p*80 particle size (100 μm) and were  
918 undertaken at 20 °C. Multi-year simulations capture the effect of basaltic minerals  
919 undergoing dissolution at different rates, with some minerals continuing to undergo  
920 dissolution and capture CO<sub>2</sub> after the first year of application. It allows computing average  
921 rates of weathering and CO<sub>2</sub> removal from repeated basaltic rock dust applications. Our  
922 extended theory underpinning our simulation framework tracks cohorts of particles applied  
923 each year and their mineral composition over time to account for cumulative effects (SI  
924 Methods).

925

926 **Extended Data Fig. 8 | Spatially resolved drivers of the performance model.** **(a)** soil  
927 temperature from the HadGEM RCP8.5 simulation for 2050, **(b)** HYDE harmonized soil pH  
928 database, **(c)** annual cropland soil water infiltration (irrigation water + precipitation minus  
929 evapotranspiration), **(d)** and **(e)** net primary production index for annual and perennial crops  
930 as derived from FAO datasets, respectively. Data sources and spatial resolution are specified  
931 in SI Table S14.

932

933 **Extended Data Fig. 9 | Spatially resolved drivers for environmental economics**  
934 **modelling.** **(a)** Industrial diesel prices (US dollar, USD), CO<sub>2</sub> emissions intensity for **(b)** the  
935 business-as-usual scenario (BAU), and **(c)** the 2 °C scenario, **(d)** gross national income per  
936 capita and **(e)** industrial electricity prices (US dollar, USD). Data sources and spatial  
937 resolution are specified in SI Table S14.

938

939 **Extended Data Fig. 10 | Relationship between particle size, surface area and grinding**  
940 **energy.** **(a)** Relationship between particle size and surface area, **(b)** surface area and grinding  
941 energy and **(c)** particle size and grinding energy, where *p*80 is defined as 80% of the particles  
942 having a diameter less than or equal to the specified size. Derived from data in Ref<sup>73</sup>.

943

944

**Table 1. Carbon dioxide removal (CDR) targets for enhanced weathering with croplands in 2050.** Relative contribution of each nation is determined by their peak CDR capacity\*. Values are means of both energy scenarios; see main text for details.

Target		Cropland area	National CDR	Silicate demand	Cost
905	Gt CO <sub>2</sub> yr <sup>-1</sup>	(%)	(Gt CO <sub>2</sub> yr <sup>-1</sup> )	(Gt yr <sup>-1</sup> )	(US\$ t CO <sub>2</sub> <sup>-1</sup> yr <sup>-1</sup> )
950	World				
951	China	10	0.13	0.77	102.1
952	USA	11	0.11	0.63	160.3
953	India	11	0.15	0.84	78.4
954	Brazil	10	0.041	0.22	123.8
955	Indonesia	10	0.017	0.091	54.3
956	Canada	10	0.022	0.13	177.6
957	Mexico	10	0.013	0.073	97.5
958	Europe				
959	France	10	0.017	0.085	158.1
960	Germany	11	0.012	0.066	167.8
961	Italy	11	0.0070	0.039	181.9
962	Spain	10	0.012	0.066	192.8
962	Poland	10	0.0085	0.050	171.6
963	World				
964	China	23	0.26	1.59	109.3
965	USA	24	0.21	1.26	168.5
966	India	23	0.24	1.50	79.9
967	Brazil	23	0.083	0.45	116.4
968	Indonesia	25	0.033	0.18	57.5
969	Canada	16	0.030	0.20	191.7
970	Mexico	23	0.025	0.15	103.1
971	Europe				
972	France	24	0.034	0.17	160.4
972	Germany	25	0.025	0.14	171.7
973	Italy	23	0.014	0.083	191.0
974	Spain	17	0.018	0.10	190.9
975	Poland	17	0.012	0.081	170.9
976	World				
977	China	38	0.40	2.48	114.5
978	USA	39	0.32	1.99	173.1
979	India	36	0.37	2.35	80.2
980	Brazil	36	0.13	0.71	110.5
981	Indonesia	41	0.050	0.28	58.6
982	Canada	25	0.045	0.35	207.3
983	Mexico	37	0.038	0.23	105.6
984	Europe				
985	France	38	0.050	0.26	159.5
985	Germany	39	0.037	0.20	173.6
986	Italy	37	0.021	0.13	194.1
987	Spain	28	0.026	0.17	189.3
988	Poland	27	0.019	0.13	171.3
989	World				
990	China	55	0.53	3.46	120.7
991	USA	55	0.42	2.72	176.7
992	India	51	0.49	3.30	80.9
993	Brazil	51	0.17	0.98	106.2
994	Indonesia	59	0.067	0.38	59.4
995	Canada	35	0.060	0.51	220.3
996	Mexico	52	0.050	0.33	106.8
997	Europe				
998	France	54	0.067	0.36	157.1
998	Germany	57	0.050	0.28	175.9
999	Italy	55	0.029	0.18	193.3
1000	Spain	41	0.035	0.25	190.7
1001	Poland	38	0.025	0.19	175.4

\*For each country  $i$ , we assigned its contribution to a CDR target as below;  $CDR_{MAX}$  is the maximum CDR value attainable by a country:  $CDR_{Contr}(i) = CDR_{Target} \frac{CDR_{MAX}(i)}{\sum_{j=1}^{Countries} CDR_{MAX}(j)}$

