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Enhanced rock weathering: Potential UK greenhouse gas removal

Overview

- Enhanced rock weathering (ERW) could be used to remove greenhouse gases from the atmosphere. It involves the spreading of rock dust on land. When rainwater mixes with the dust, the carbon dioxide (CO_2) dissolved in the rainwater is converted into minerals that are released into the soil.
- Studies suggest that ERW can also improve soil fertility and increase crop and forestry yields.
- However, there are limited long-term field trials (>5-10 years), either globally or in the UK, to provide evidence that the technique captures carbon on a large scale.
- There is also limited evidence on how different types of rock, soil, climate, and other conditions affect the efficiency of carbon dioxide removal.
- If implemented on a large scale, there are potential risks and environmental impacts. These risks are the subject of research projects.
- Barriers to scaling up rock extraction in the UK include producing large amounts of rock dust through quarrying and crushing, associated greenhouse gas emissions, and potential social and ecological impacts.
- Standardised techniques for measuring and verifying any carbon dioxide removal are yet to be agreed to maintain the integrity of carbon offsets.
- Several commercial operations of ERW occurring globally, including at least one company in the UK.

Background

CO_2 removal required for UK Net Zero 2050

The UK has committed to reaching Net Zero greenhouse gas (GHG) emissions by 2050.[1] While emissions will be mitigated where possible, the Intergovernmental Panel on Climate Change (IPCC) stated that Greenhouse Gas Removal (GGR)[2] is required to remove final emissions from hard-to-abate sectors (Box 1).[a,3] GGR involves removing GHGs, such as CO_2, directly from the atmosphere, as opposed to capture from industrial sources.[4] This removal can be nature-based, such as tree planting, or engineered with technology (PN 713).

Box 1: UK commitment to Net Zero by 2050

Under the Climate Change Act, the UK is committed to reaching Net Zero by 2050. This will be achieved by reducing emissions, and removing emissions related to hard-to-abate sectors, e.g., agriculture, aviation, and heavy industry. The IPCC has calculated that to limit global temperature rise to 1.5°C or 2°C, GGR is required.[5] Some countries are developing policies for GGR technologies.[6,7]

The UK is the first major economy to halve its GHG emissions, with a 52.7% decrease between 1990 and 2023[8] whilst also growing its economy by 79%. This is primarily due to a reduction in fossil fuels and increase in renewable energy, such as wind and solar, to 40% of UK's total electricity.[9,10] In 2023, the UK emitted 384 Mt CO_2e[b] of GHGs, a 5.4% decrease from 2022.

Several policies in the UK have sought to encourage the scaling up of GGR:

- encouraging innovation in GGR, including funding field trials[11,12]
- ensuring GGR technologies are sustainable, and the integrity of GGR approaches for inclusion in the UK Emissions Trading Scheme[13]
- requiring a robust monitoring, reporting and verification (MRV) framework to instil confidence that removals are genuine and verifiable[14,15]

The 2023 'Powering up Britain' plan categorised Enhanced Rock Weathering as an engineered GGR, but it is not yet one of the approaches quantified for Carbon budget periods that count towards the GGR sector ambition set out.[16] However, for national emissions reporting enhanced rock weathering (ERW) is likely to fall under the land use, land-use change and forestry sector (Table 1).[c,19]

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[a] Most countries do not explicitly reference GGR in their Nationally Determined Contributions (NDCs) submitted to the Paris Agreement, but many include GGR approaches such as increasing forest carbon.

[b] Mt CO_2 refers to 1,000,000 tonnes of carbon dioxide. CO_2e refers to CO_2 equivalent, considering that different gases have different greenhouse effects. For example, nitrous oxides contribute 300 times more to atmospheric warming than CO_2.

[c] Under Article 4 of the United Nations Framework Convention on Climate Change any process, activity or mechanism which removes a GHG from the atmosphere is referred to as a "sink". Human activities impact terrestrial sinks, through land use, land-use change and forestry (LULUCF), consequently, the

Academic studies suggest that ERW has the potential to contribute 6-30 Mt CO_2/year removal.[20–25] In the UK, there are several UKRI-funded ERW trials, as well as at least one private company. The 2024 State of Carbon Dioxide Removal report estimated that ERW currently removes 0.03 MtCO_2/year globally.[d,26]

Table 1 Land use, land-use change and forestry sector GGR

Technology	Storage timescale	Benefits	Risks & limitations
Enhanced rock weathering[27,28]	10,000+ years	Potential agricultural benefits, including crop yields and forestry. Could be combined with afforestation. Potential rapid scale-up from existing quarries.	Limited long-term field trials, with uncertainties around timescales and efficiency, and difficult to measure and verify CO_2 removal over the long-term. Unknown long-term impact on soil health, and environment.
Soil carbon management in agriculture[29,30]	10-100 years	Potential soil restoration.	Reversible, changes in land management lead to CO_2 release. Potential reduction in crop yields. Low CO_2 removal rate, which is difficult to measure.
Biochar,[31] organic material which is carbonised like charcoal (PN 358)	100-1000 years	Potential agricultural co-benefits when added to cropland.	Limited scalability. Possible impacts from dust and competition for biomass. Difficult to measure and verify CO_2 removal.
Nature based solutions (such as afforestation[32] and peat restoration[33])	10-100 years	Perceived as more natural, increases biodiversity.	Requires land use, competing with arable crops. Inappropriate scaling up may reduce biodiversity. Susceptible to climate change, such as wildfires and drought (PN 717).[34]

Source: PN 713.[35]

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exchange of CO_2 (carbon cycle) between the terrestrial biosphere and the atmosphere is altered. Mitigation measures in forests and other natural ecosystems provide the largest share of the LULUCF mitigation potential between 2020 and 2050 (PN 713), but accounting for ERW under the inventories of GHG emissions and removals from LULUCF could be negotiated in future.[17,18]

[d] "Novel" GGR methods refer to non-conventional and emerging techniques for carbon dioxide removal. This is the third highest of the "novel" GGR methods, behind biochar (0.79 Mt CO_2/year) and bioenergy carbon capture and storage (0.51 Mt CO_2/year). This is opposed to "conventional" GGR, which includes afforestation, reforestation, and managing forests. These make up 99.9% of current global GGR (~1860 Mt CO_2 yr^{-1}). These values are estimated from 2023 data.

How does enhanced weathering work?

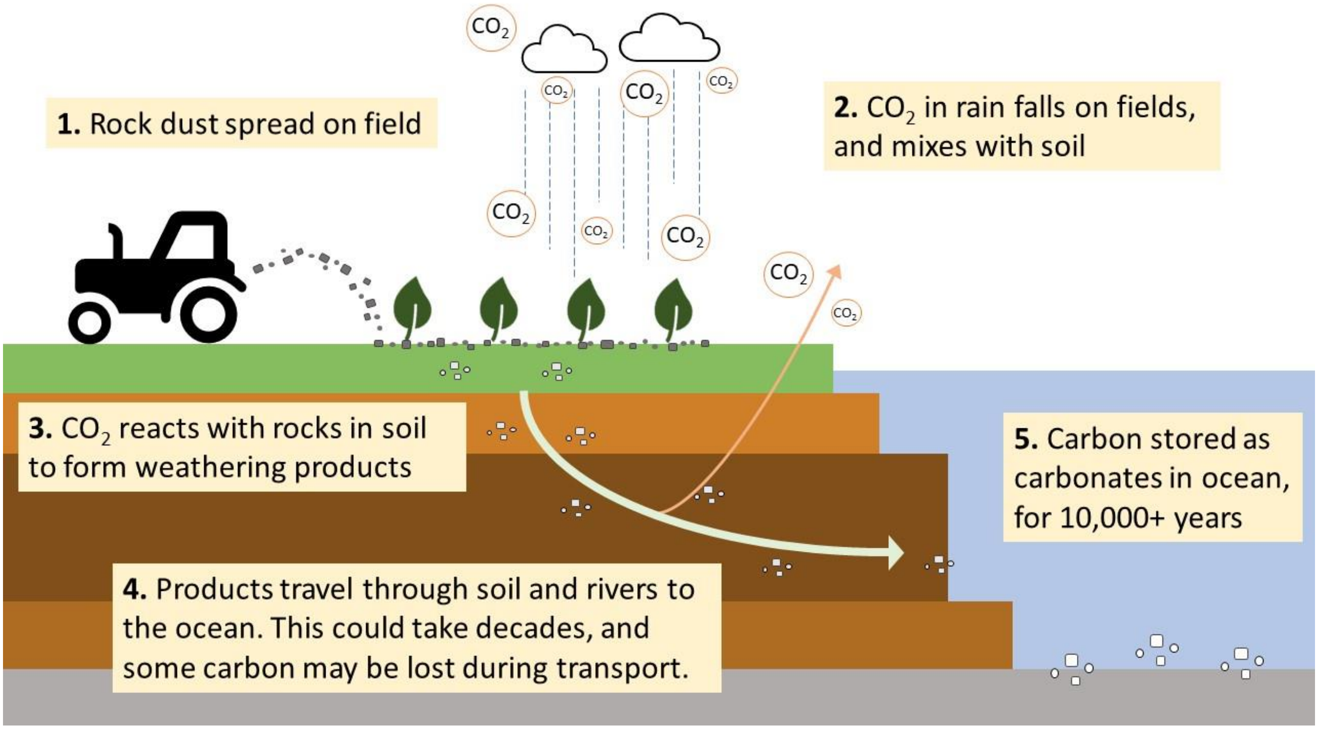
Enhancing a natural process

Rock weathering is a natural process that removes carbon dioxide from the atmosphere, at a rate of ~1100 Mt CO_2/year.[36–38] ERW aims to accelerate this process in order to help address climate change. Fine rock particles are created, increasing the reactive surface area of the rock. This is then spread over land.[39]

The process works best in climates with high annual rainfall.[24,40,41] Atmospheric carbon dioxide dissolves into rainwater, and makes it weakly acidic, meaning it reacts with rock dust (Figure 1). This reaction happens faster in more acidic soils and in warmer climates, but can also occur in mild and temperate conditions.[24,42]

When the rainwater and rock dust react, the resulting chemical products[e] are released into the soil (Figure 2). Over time, these dissolved products may be taken up by plants, remain in the soil, or be transported to a sink, such as the ocean. Here, the products react to form a solid carbonate mineral over thousands of years, which is then stable in the ocean for 10,000 years. Any CO_2 removal is only durable once these carbonate minerals have formed in the ocean.[20,21,39,43,44]

Figure 1. Simplified diagram showing how enhanced rock weathering may work. Some studies suggest there may be some re-release of carbon dioxide due to carbonate precipitation in rivers.[43]



Source: Adapted from BBC.[45]

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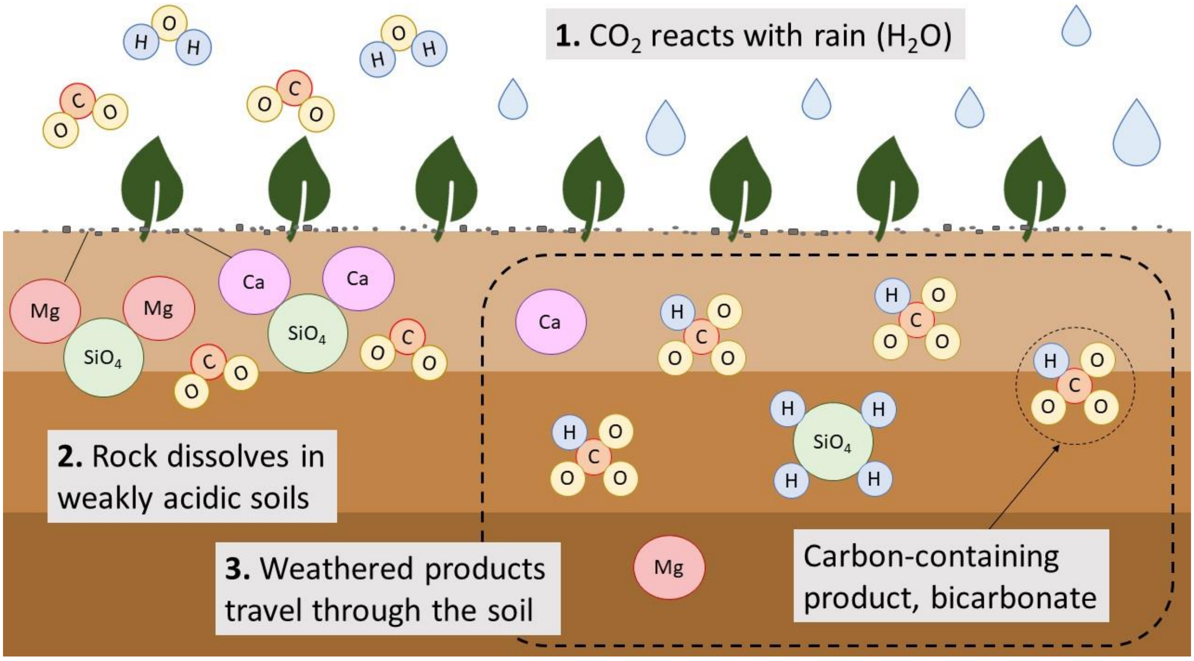
[e] These dissolved products include metal elements, primarily magnesium (Mg^{2+}) and calcium (Ca^{2+}), and the carbon-containing product, called bicarbonate (HCO_3^-).

Figure 2. Diagram showing the chemical reactions that occur when silicate rock undergoes enhanced weathering.[46]



Uncertainties with CO_2 removal efficiency

Some studies suggest the amount of CO_2 removal depends on types and amounts of rock applied, rainfall, temperature, and soil types.[41] For example, modelling studies suggest grain size of rock dust would ideally be 10-100 µm[f] in diameter for CO_2 removal to be effective[g] and to liberate enough nutrients to influence soil health.[36,47–50] However, other researchers dispute the importance of grain size for repeated treatments over decadal timescales.[51]

Several uncertainties remain with ERW, including the rate of CO_2 removal, timescales involved,[52–54] and the efficiency of transport to the ocean, with the potential for some carbon to be re-released. Timescales and permanence are discussed later.[43,55,56]

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[f] µm is a unit referred to as a micrometre, a length of measurement equal to one millionth of a metre (1,000 µm is equal to 1 mm, an average human hair has a diameter of about 100 µm).

[g] This study[47] suggests the amount of powder dissolved within a timeframe of 10 years is approximately 16% (<100 µm), 55% (<10 µm) and 99.9% (<1 µm). This corresponds to an annual CO_2 removal of 0.045 t CO_2 t^{-1} of rock (<100 µm) and 0.153 t CO_2 t^{-1} of rock (<10 µm).

Potential contribution of Enhanced Weathering to Net Zero

The Climate Change Committee suggest that GGR technologies could provide up to ~60% of GGR by 2050.[h,57] The remaining 40% of GGR are expected through Land Use, Land-Use Change and Forestry (LULUCF) nature-based solutions (Table 1), which potentially includes ERW.[58]

Studies suggest that ERW may be a rapidly scalable technology, and several rocks or other secondary sources have been suggested for this process (Table 2).[20]

However, these studies assume:

- readily available renewable energy from a net zero energy sector by 2035
- increased scaling of quarrying processes
- rapid uptake of the technology by famers

Studies suggest ERW is best suited to locations that are humid.[24,36,42] However, there is potential in the US, Canada & Europe due to silicate rock resources,[i] and a mild rainy climate.

There are several UK field trials and international published studies (Table 3). In addition, commercial operations have begun in several locations, including the company UNDO, which has spread 179,000 tonnes of rock dust in the UK.[59]

Potential benefits for agriculture

The Climate Change Committee state agriculture is a hard-to-abate sector.[60–62] There is interest within the sector to work toward reducing emissions, including through nature-based carbon offsetting approaches.[63,64] ERW removes CO_2, and can also improve crop yields.[39]

Improve depleted soils to increase crop yields

Silicate rocks contain nutrients that plants require for healthy growth, such as magnesium, calcium, silica, phosphorus and potassium.[j] Some studies demonstrate an increased nutrient boost and crop yield of ~5-20% after rock dust application, suggesting that nutrients from the rock dust are released in a form available to plants.[66–72] Silicate rock dust is added to soils in Brazil (Box 2).

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[h] Bioenergy Carbon Capture & Storage & Direct Air Carbon Capture & Storage (PN 690 and PN 713).

[i] Silicate rock is the primary rock type considered for enhanced rock weathering (Table 2).

[j] Plants take nutrients from the soil to grow. After the crops are harvested, these nutrients are removed from the soil system. Usually, fertilisers are applied to replace these nutrients. The main macronutrients are nitrogen, phosphorus, and potassium. Micronutrients are only required in small amounts, and include elements like iron, copper, manganese, zinc, molybdenum and chlorine (PN 710).[65]

Table 2 Potential source materials for ERW

Rock type/ Material	Product type	R_{CO2}:[k] CO_2 capture potential	Benefits	Risks & limitations[l]
Basalt[22,50,66] (dolerite)	Primary	Medium, 0.11-0.33	Existing byproduct fines[m] stock in UK from the aggregate industry. Large resource in the UK (~630,000 Mt). Low concentration of toxic elements.	Requires large scale quarrying in the UK if implemented at scale. Potential resource not ideally located for farmland but is for forestry.
Olivine[50,73,74] (dunite)	Primary	High, 0.70-0.82	High weathering rate and CO_2 removal rate.	Contains heavy metals, such as nickel and chromium, that can be toxic to crops. Limited resource in UK.
Wollastonite[73,75,76]	Primary	High	High weathering rate and CO_2 removal rate.	Rare, and requires specific quarrying for CO_2 removal.
Serpentinite[77–79]	Primary	Low	High weathering rate, in some mine wastes.	May contain asbestos, which is hazardous if inhaled.[80,81]
Greenlandic glacial rock flour[82,83]	Primary	Medium, 0.25	High supply of material, small grain size, proven agricultural benefits.	Potential GHG emissions & environmental impact due to transport to farmland.
Other silicate rocks[84]	Primary	Low	Significant resource in the UK.	Unknown potential for ERW.
Concrete, construction & demolition waste[85,86]	Secondary	Medium, 0.08-0.19	Cement is similar in composition to primary silicate rocks. Crushing is common onsite with demolition. Small grain size.	There may have been carbonation of the material during the building's lifespan. Probable low concentration of toxic elements, but contamination may be present.
Legacy mine deposits[87]	Secondary	Low	Location could be well known.	Potential contaminants.
Industrial waste[88–90]	Secondary	Low	Abundant resource, encourages recycling.	Potential contaminants.

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[k] R_{CO2} refers to the total CO_2 capture potential of different materials and is the ratio of the amount of carbon dioxide removed per tonne of rock. For example, R_{CO2} of 0.2 refers to 200 kg of CO_2 which may be removed per 1000 kg of rock which is fully weathered. These values are specific for UK resources.[50]

[l] There are currently no regulations for applying potentially hazardous or toxic rock dust to crops.

[m] Byproduct fines refer to fine-grained material, which is generated during quarrying and crushing, which isn't commercially productive.

Table 3: Ongoing UK field trials in ERW & published ERW field trials

Location (organisation)	Timeline of trial	Application t ha^{-1}yr^{-1} [n]	Setting, field sizes & results	
			Reported removal[o]	Reported co-benefits[p]
Lowland arable land, Norfolk[91,92]	4 years (2019-2022)	40 x 4 years (basalt)	n/a	n/a
Lowland grassland, North Wyke, Devon[93]	4 years (2021-2025)	40 x 3 years (basalt)	n/a	n/a
Lowland arable land, Harpenden, Hertfordshire[94]	3 years (2021-2024)	40 x 3 years (basalt)	n/a	n/a
Glandwr Forest, Wales[95,96] (The Carbon Community)	May 2021 onwards	40 x 2 years (basalt)	n/a	n/a
Upland grassland, Plynlimon (Pumlumon), mid-Wales[97,98]	4 years (2021-2025)	20 x 2 years (basalt)	n/a	n/a
USA Corn Belt[67]	4 years (2016-2020)	50 x 4 years (basalt)	10.5 ± 3.8	Maize and soybean yields improved 12-16%
Newcastle, UK (UNDO)[66]	1 year (2022-2023)	18.86 x 1 yr (basalt)	n/a	20.5% & 9.3% yield increase, +0.20 soil pH.
Vojens, Denmark[82,83]	3 years (2019-2021)	10, 50 x 1 yr (Greenland rock flour)	0.728	Yield increase in first year only, maize by 59 kg ha^{-1} and potato by 90 kg ha^{-1}
Ontario, Canada[99]	3 years, 2016-2018	2.1 x 3 years (wollastonite)	6.05	Higher inorganic content, ~0.20 soil pH increase.
Forest, New Hampshire, USA[100]	15 years, 1999-2014	3.44 x 1 year (wollastonite)	0.025-0.13[q]	Increase in biomass and reduced soil respiration.
Oil palm plantation, Malaysia[84]	3 years, 2018-2021	50 x 1 year (andesite)	~0.4 per year	n/a
Central China[68]	3 years, 2019-2021	100 x 3 years (silicate rock dust)	4.31 ± 0.82	7 ± 4.3 % yield increase, 11 ± 4.6 % biomass increase, soil restoration
Uppsala, Sweden[71]	3 years, 2007-2009	5, 50 x 1 yr (1 mm SEER volcanic dust)	n/a	No effect on yield, plant nutrient content, or soil chemistry.

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[n] t ha^{-1} yr^{-1} refers to the amount in tonnes of rock dust added to each hectare every year.

[o] Unit: t CO_2 ha^{-1} is tonnes of CO_2 removed from the atmosphere through ERW per hectare of land.

[p] These are likely to depend on soil type and crop grown, which aren't always mentioned in studies.

[q] The total removal was 8.5-11.5 t CO_2 ha^{-1}, and this value refers to how much more removal there was compared to the baseline, which are adjacent plots of forest where nothing was added.

Potential improved soil chemistry

Soil acidity (a pH lower than 6.5) can be natural but can also be caused by application of inorganic fertilisers and limits yields.[101,102] Rock dust addition has a "liming effect", where increasing the soil pH of acidified soils causes crop yield increases due to improved nutrient use.[103]

Some stakeholders suggest that the yields measured by short-term (~1-3 year) field trials show this initial increase to a maximum crop yield, and that there may not be a longer-term yield increase.[104] This process may help establish trees in forestry.[105]

Increasing soil pH may lead to lower fluxes[r] of the GHGs, methane and nitrous oxides (N_2O) from the soil (PN 710).[20,44,110] UK agriculture currently accounts for 75% of N_2O emissions nationally. One study suggests up to 1 Mt CO_2 equivalent (CO_2e) N_2O emissions could be reduced through the 2050 ERW deployment scenario.[103,111] However, there is currently limited evidence to support this from field trials.

Using a byproduct or waste

Most commercial operations and all UK-based trials have used basalt dust that is a byproduct of hard rock production,[s] which is otherwise considered unprofitable. It provides a use for a material that quarry companies may otherwise need to store. However, basalt or other rock sources may have a value and cannot be considered waste. For example, aggregate companies may use this dust to "backfill" quarries and there are several other industrial uses.[113]

There have also been several studies and recommendations to use secondary products, such as demolition or industrial waste (Table 2). These products would need to be tested for potentially harmful elements or chemicals, and may not be ideal for application in agriculture, but some could be applied in urban green infrastructure areas or in forestry.[85,114]

Box 2: Brazil Law of Remineralisation 2013

Rock dust application is a common practice in Brazil, where agricultural soils are depleted in valuable nutrients due to high weathering and erosion rates caused by a hot and humid climate and intensive agricultural production.[115]

The practice was formally mandated by the 2013 Law of Remineralisation,[116] with the aim of adding nutrients to depleted soils as part of Brazil's national strategy for food security. Rock dust is a widely available cheap natural fertiliser for rural communities, in comparison to expensive standard artificial fertilisers (PN 710).[117,118] 30 certified mines produce the dust, and the national plan of fertilisers included a goal to certify up to 1000 mines by 2050.[119]

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[r] Bacteria in the soil control the amount of methane and nitrous oxide gas which is released. Some studies suggest that these bacteria release less of these gases in higher soil pH conditions created by ERW, decreasing the flux of these out of the soil.[44,106,107–109]

[s] Roughly 20%[112] by weight of all hard rock extracted becomes the byproduct rock dust, which is too small for most aggregate markets and currently has limited profitability in the aggregates industry.

Logistics of potential deployment in UK

Location of rock resources and farmland

There are significant UK magnesium and calcium-rich silicate rock resources (Figure 3),[50] but ~60% of these are protected under environmental designations.[t] In the UK, 353 Mt of reserve is associated with active quarries. In addition, there is ~630,000 Mt that is not under designation, which is ~4,200 km^2, quarried to a depth of 50 m at a density of ~3 $t\ m^{-3}$.[u,22]

Basalt rock reserves are primarily located in Scotland, and northern England (Figure 3). There are resources in Northern Ireland and the Inner Hebrides, but shipping would be required to move these resources to farmlands in England.[22,120] It may be optimal to add rock dust to acidic soils within a certain distance from quarries, so ideally ERW would be deployed in northwest England, Wales, and Scotland.

There would be logistical challenges for delivering rock dust to farms elsewhere in England, with careful planning needed to minimise emissions (Figure 4).[121] It may be easier to deploy ERW in urban areas with good transport links, such as gardens, brownfield sites, or highways.[85] However, it is easier to apply at scale in forestry or agricultural areas, where there is existing infrastructure and machinery.[24,42,67,104]

Short-term resource: aggregate byproduct fines

There is adequate availability of rock resources in the form of byproduct fines in the UK for deployment of ERW over the next few decades. The current production of silicate rock is estimated at 15 Mt/year, of which fines are estimated at ~3.7 Mt/year.[22,50,103,120,121]

Current reserves of this byproduct are estimated at ~490 Mt. This could meet demand for 10 years at ~50 Mt/year of rock supply if added to all UK farmland.[22] In practice, a smaller amount of farmland will be used, with the resource lasting longer.

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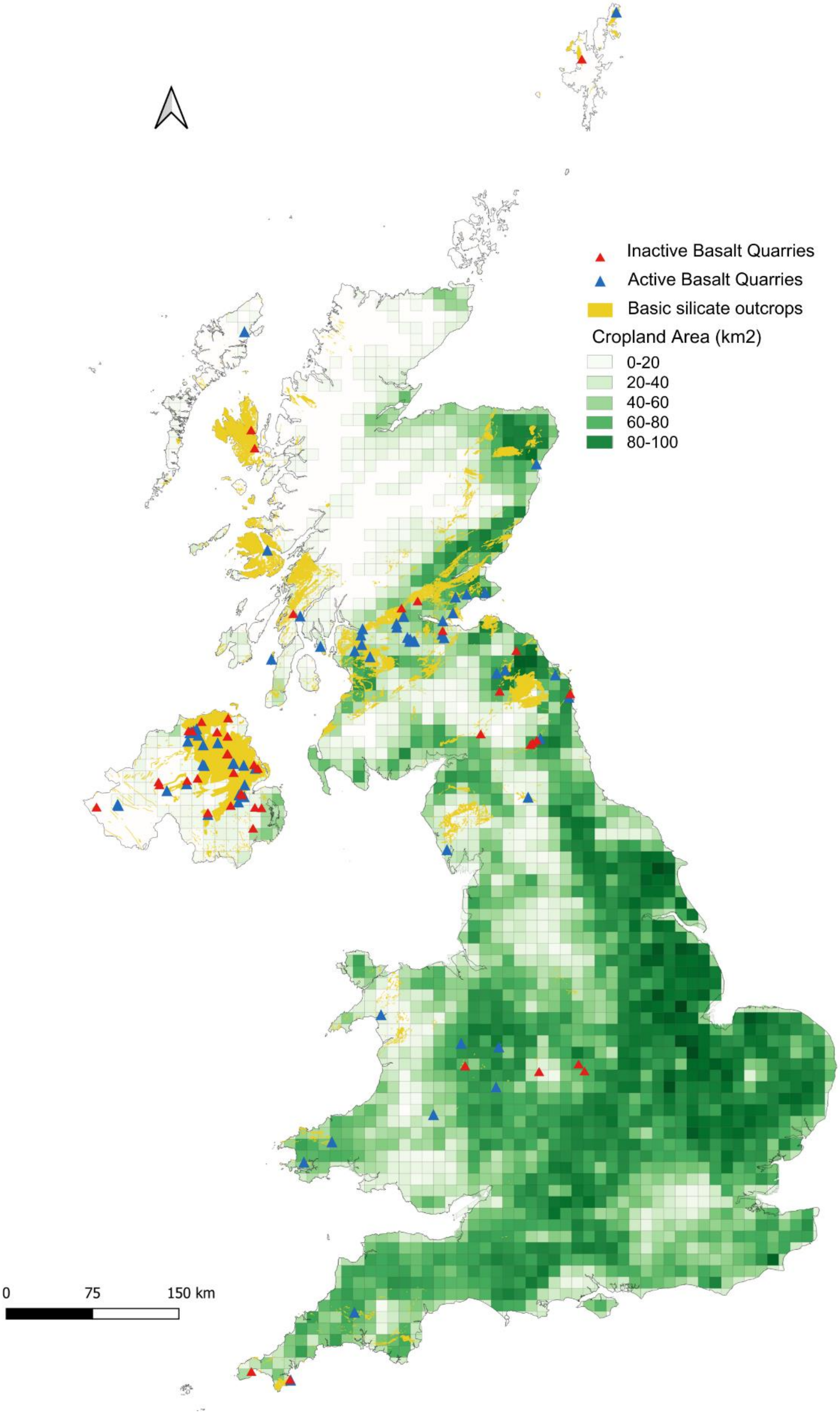
[t] Most of this land is protected under designations such as Area of Natural Beauty (AONB) or Site of Special Scientific Interest (SSSI) therefore cannot be destroyed for quarrying.

[u] $t\ m^{-3}$ is a unit for density of the rock, in tonnes per cubic metre.

Figure 3. Locations of farmlands and silicate rock resources in the UK. Most of the rock resources are in north-east England, Northern Ireland, and Scotland. "Cropland" here refers to cultivated farmland.



Source: Mohammad Madankan.[22]

Highest scale-up scenario

In the UK, reserves of basalt are currently being depleted faster than new quarries can open, with a 52% replacement rate average from 2012-2021.[121] Permits could be applied for to extract the remaining ~630,000 Mt of basalt rock in the UK.[22]

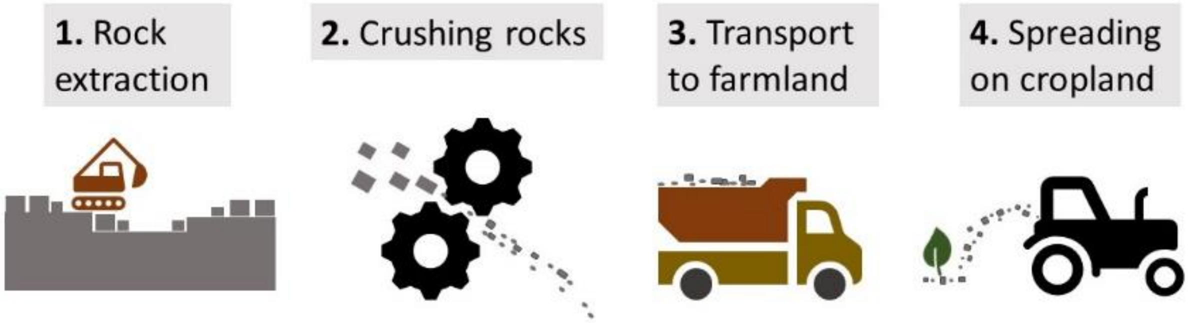
Some studies suggest that the UK could achieve 20-30 Mt CO_2/year through ERW.[20] This is the highest scale-up scenario,[v] but it is unlikely that all farmland will be suitable for ERW.[20] Alternatively, research suggest that a lower scenario of 6 Mt CO_2/year is more reasonable because required rock dust could be sourced by increasing output from current quarries.[20,103]

Transport

Stakeholders suggest that with coarse material, lorries can transport up to 20 tonnes of rock, and trains could transport up to 1,500 tonnes.[121] However, it may be more difficult to transport fine material as dust can jam up machinery, leading to higher costs for transport.[122] Carbon neutral transport infrastructure including electric heavy goods vehicles would minimise GHG emissions, but stakeholders suggest that there may be a lack of railway infrastructure to support potentially dispersed quarry locations.[122] Currently rail transport moves ~17 Mt of aggregates annually.

There are a range of estimates of the quarry to farmland distance that is still carbon efficient. In Brazil, a study suggested an average road distance of 65 km was reasonable.[123] However, this estimate appeared to only account for the one-way transport of lorries, and did not consider trains.

Figure 4. The four main steps of logistics for ERW, which may lead to subsequent GHG emissions.[121,124,125] Further discussion in Table 4.



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[v] For this scenario, 40 t of crushed rock are added annually to the UK's ~10.5 million hectares of farmland, and this would require 180 Mt/year rock supply (the Great Pyramid of Giza is 6 Mt). In 2019, 21 Mt of igneous rock was extracted in the UK, so this is an nine-fold increase in extraction rate.[120]

Potential barriers to implementation

Potential greenhouse gas emissions in the supply chain

Scaling up rock supply and extraction rate

Due to planning regulations, the time from initial selection of a new quarry site to extraction is currently 15-20 years. Scaling up rock extraction rates is likely to initially come from extensions of existing operations, or reopening closed quarries.[121]

Competition with aggregate industries may control economic value of rock dust. The market for primary aggregates is mainly construction use. Basalt is a valuable material for road building because it has a higher Polished Stone Value[w] than some other rock types, and there is a lack of an artificial equivalent. This basalt is placed on tarmac roads to increase the skid resistance and help cars to brake safely.[127]

Rock extraction involves drilling and blasting, which emit GHGs (Table 4).[128] In Brazil, Vale, a metals & mining company, has achieved 100%[x] of their mining extraction and transport operations[y] running on energy from renewable sources.[129] However, there is currently limited capability and infrastructure in the UK for large scale renewable energy extraction, or electric vehicle transport to remote farms.[z,131]

Energy required for crushing rock

At present, basalt rock is crushed for other industrial uses, and as the dust used in ERW is a byproduct the GHG emissions are not included in life cycle analyses. However, if dust is produced specifically to scale up the ERW process, crushing hard rock would be an energy intensive step. Stakeholders suggest that the majority[aa] of energy required to scale up ERW would be for crushing and transport (Figure 4).[50]

There is a trade-off between the energy used and GHGs released during crushing, and rate of ERW. Smaller particle sizes may lead to an increased rate of weathering, with some studies estimating 10-100 μm is ideal for CO_2 removal to occur over a decade.[20,48]

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[w] Polished Stone Value refers to the ability of aggregates resist to polishing by constant passing of tyres. The road surface layer needs to retain its rough texture to provide skid resistance for traffic.[126]

[x] Vale is supplied by renewable energy of 2.6 GW, equivalent to consumption of ~3 million people.[129,130]

[y] These operations do not include crushing aggregate rocks.

[z] The study that suggests a range of 6-30 Mt CO_2/year removal by in the UK by 2050 assumes that the crushing and transport can be completed with renewable energy, in order to minimise GHG emissions.[20] In addition, they assume the diesel ban policy and availability of electric heavy goods vehicles for basalt transportation after 2030.

[aa] 77-94% is due to crushing and transport, with a total energy cost of 656-3501 kWh per tonne of CO_2 removed, depending on the transport distance and rock type.[50]

There may be a significant investment cost for scaling up crushing machinery.[120] In 2021, the UK production of crushed rock was ~150 Mt/year.[132] For ~8 Mt CO_2/year removal through ERW in the UK by 2070, 20-30 Mt/year of crushed basalt is required.[20] This would require a 20%[bb] increase in the UK's capacity for crushing.

Table 4: Estimates for potential GHG emissions during ERW, primarily based on Brazil case study

Process	Current Fuel	CO_2e emissions t^{-1} rock (% of CO_2 removal potential[cc])	
		Using byproducts	Actively quarrying
Mining: Drilling, Blasting, Loading	Diesel & Water, Explosives	Burden free	~7 kg[dd] (3.5 %)
Crushing to 5mm	Diesel, Electricity, Water	Burden free	~2 kg[ee] (1 %)
Crushing to <100µm	Diesel, Electricity, Water	Burden free	~15 kg[ff] (7.5 %)
Loading & transport (average 65 km, one way)	Diesel for lorries	~17 kg (8.5 %)[123]	
Spreading	Diesel	~2 kg (1%)[125]	
Total:		**~19 kg (9.5 %)**	**~43 kg[gg] (21.5 %)**

Scientific uncertainties

Stakeholders suggest that there are several potential risks and unknowns with ERW:

- rate of CO_2 removal, and the effects of grain size, amount of rock, rock type and climate conditions[40,49,50,52,135,136,137]
- timescales for transport to ocean, and any potential re-release of CO_2[53,55]
- timescale of storage in the ocean, and any potential re-release of CO_2[55]
- standardised measuring, reporting, and verifying of carbon dioxide removal[138]
- potential negative impacts on environment from rock extraction and spreading[139]

[bb] Similarly, to achieve ~25 Mt CO_2 removal per year, 100 Mt/year of crushed basalt rock is required,[20] which is an increase in crushing capacity of ~67%.

[cc] Assumes CO_2 removal potential (R_{CO2}) of 0.2; 200 kg CO_2 removed per ton of basalt, before emissions.

[dd] Based on 5.22 kWh t^{-1} rock,[123] CO_2 emissions per kWh is ~1340g CO_2 kWh^{-1}.[50,133]

[ee] Crushing to 5 mm requires 5.42 kWh t^{-1} basalt, assuming 400g CO_2 kWh^{-1}.[50,123]

[ff] Based on 19 kWh t^{-1} rock, from ~1.6 mm to 50-150 µm.[134]

[gg] The net sequestration rate is ~167 kg CO_{2eq} per tonne of rock, when actively quarrying for material.

Measurement, Reporting & Verification (MRV)

Stakeholders suggest that a key aspect to maintain integrity of carbon credits in the voluntary carbon market, or for inclusion in the UK Emissions Trading Scheme,[hh,142] is to accurately and transparently measure, report and verify carbon dioxide removal from the atmosphere (PN 713). [ii,35,143,144]

However, there is currently no commonly agreed standardised Measurement, Reporting & Verification (MRV) process for enhanced weathering.[145] Stakeholders suggest that an open access method to verify any CO_2 removal would be optimal.[146]

There are several methods proposed to measure the CO_2 removal, including analysing soils, pore waters, drone pictures, and gases in the air.[jj,67,82,87,88,138] However, these methods are in an early stage of development and rely on technical equipment and clean rooms.[148]

Some researchers say that ideally there should be a model-based process to estimate the rate of carbon dioxide removal, which could be verified by in-field measurements.[67,84,149] These models would need to take into account weather changes, initial soil, and other local conditions. Alternatively, one study suggests tracking a proxy for CO_2 removal would be cheaper and easier.[88]

Timescales and permanence of carbon dioxide removal

The timescales and permanence of CO_2 removal is poorly quantified for ERW, due to a lack of evidence from long-term field trials, and relatively small changes in chemistry from smaller trials (Table 3).[66–68,70,71]

The amount of CO_2 removal and the timescales involved likely depends on local conditions, as well as the rock type, and is not well quantified in these varying conditions (Table 3).[135,150,151] In addition, the rate of weathering depends on rainfall,[kk] and the process may not work well in long-term drought conditions, which may become more common in some areas with climate change.[136,152]

One commonly used method to estimate CO_2 removal measures the loss of magnesium and calcium from the soil, which infers the total CO_2 that will be eventually removed over time (Figure 2).[20,21,24] However, this method does not

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[hh] In the responses to the DESNZ consultation on GGR business model, responders highlighted the need for government-approved monitoring, reporting and verification (MRV) standards and guidelines on storage permanence to build confidence in the integrity of GGR projects. DESNZ also highlighted that GHG removal is more difficult to monitor, report and verify for ERW compared to contained processes where the amount of mineralized CO2 can be measured.[140,141]

[ii] Only credits from the regulated compliance market (e.g., EU or UK Emissions Trading Schemes) can be claimed by businesses, regions or countries as ‘offsets’ and count towards Nationally Determined Contributions (NDCs) and national net zero targets for sectors such as agriculture. Voluntary carbon market credits for ERW would not count towards sector targets.

[jj] A common method to estimate the time-integrated carbon dioxide removal involves measuring the loss of weathered products in the soil. Alternatively, some researchers focus on measuring soil pore water chemistry. One lab-based method involves centrifugation, which is low cost.[147]

[kk] Conversely, extreme rainfall events and flooding may hamper ERW by affecting efficient bicarbonate transport to the ocean.

account for uncertainty[ll] in the weathering process, and potential delays in transport of bicarbonate to the ocean.

In addition, there may be CO_2 leakage, particularly in acidic conditions, which could react with the bicarbonate and lead to the carbon dioxide being re-released.[43,55,56] It may be the case that only specific alkaline conditions in soils and watercourses will allow for efficient bicarbonate transport to the ocean.[155]

Overall, there is a lack of evidence to demonstrate the long term rate of CO_2 removal and that the storage of carbon in the ocean is durable at large scales, and to quantify exactly how long the carbon will be stored for.[43,56,156–158]

Potential environmental impacts

Regulation of additives & rock source composition

Currently, rock dust being used in UK operations is classed as a natural byproduct, with no regulations on its application. If material used is a waste from other industries or processes, it may be subject to waste regulations.[159,160] The rock dust for ERW is not in the current list of exemptions from waste regulations for benefits when spread on agricultural land.[161]

Particular rock types such as Olivine (Table 2) can contain trace metals and other potentially toxic chemicals, and are unsuitable for agricultural ERW purposes.[73,162,163] Some stakeholders have suggested introducing regulations on rock composition that is spread on land, to protect food security.[164]

Potential impact on nature and soil conditions

The lack of long-term field trials means that there is uncertainty in estimating the potential impact of adding tonnes of rock on soil health, and nearby environments. Current trials show no increase in soil trace metal accumulation in the soil or crops after 4 years of adding basalt.[67]

Soil health is defined as the capacity of a soil to function as a living ecosystem and to support and sustain plants, animals and humans, and maintain environmental quality, with the 'soil microbiome'[mm] playing a key role in this (PN 601). The impacts of ERW on the biological aspects of soil quality, such as the soil microbiome, are unknown.

On a large scale, ERW may significantly change the chemistry and potentially water quality of local waterways, including streams and larger rivers, and oceans, and there may be an impact on aquatic life, such as microbes, fish and smaller animals.[139]

[ll] Stakeholders suggest that temporary retention of magnesium and calcium on "soil cation exchange sites" may cause a delay in transport of the weathered products.

[mm] The 'soil microbiome' refers to communities of microbes within the soil, which include bacteria and fungi, but also archaea (single-celled organisms initially identified in extreme habitats), protists (organisms that have a nucleus and aren't land plants, fungi, or animals, unlike bacteria, contain a nucleus) and viruses.

In the Plynlimon (Pumlumon) upland grassland trial (Table 3), there are small peat flushes adjacent to the trial area. Peatland in the UK is being restored and maintained[nn] to reduce carbon emissions (PN 668).[33] One result of ERW is slightly increased soil pH, which could affect adjacent peatland and its acidic conditions that provide long term carbon storage.

Sites of Special Scientific Interest (SSSIs)[oo] are sensitive habitats that are protected by law.[166] It is uncertain whether runoff from rock dust could impact plant species in nearby habitats (PN 710).[167–170]

There would likely be adverse environmental impacts due to quarrying at scale, such as destruction of habitats, noise, water and air pollution, including GHG emissions.[171–174]

Air quality in spreading locations

If inhaled over many years, some types of silicate rock dust may lead to silicosis, which is a long-term lung disease.[81,175–178]

Farmers who are spreading rock dust will need to wear respiratory masks to ensure compliance with health and safety standards. Airborne dust transport depends on particle size and wind speed. Stakeholders suggest education is required to minimise local concerns and ensure that adequate safety measures are implemented.[179]

There may need to be controls on when rock dust is applied, depending on weather conditions – ideally, it should be on low wind days, with damp conditions to minimise airborne dust. Some stakeholders suggest applying wet rock dust to fields to minimise these concerns. Additionally, it may be necessary to implement air quality monitoring.

Social impact

Public perceptions

One study[pp] analysed public perceptions of enhanced weathering in the UK,[180] and found that awareness of ERW was low. They carefully explained ERW to try not to impact judgement, and after this, most participants supported small-scale trials. However, whilst trials into effectiveness and risk were acceptable, this was only under the condition that the research was well-controlled.[qq]

In addition, participants were sceptical that some emissions are produced during the extraction process, before CO_2 is removed. Participants were also concerned about

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[nn] The Woodland and Peatland Carbon Codes verify carbon dioxide removal in natural environments.[165]

[oo] Sites of Special Scientific Interest (SSSI) are designated to conserve wildlife, geology, or landform features. SSSI designation is a devolved matter.

[pp] Sample size, n = 935

[qq] Participants mentioned the need for scientific independence, strict monitoring, risk minimisation, and transparency of results.

risks such as traffic, pollution, environmental and social impacts, the efficiency of the CO_2 removal process, and any potential unknowns.

A study in Australia and New Zealand[rr] found slightly more than half of participants were positive about ERW. Participants were positive about the idea that the ERW process is not artificial and relatively sustainable over the short-term using quarry byproduct, and it was viewed as having some controllable risk.[181]

These studies demonstrate that there is generally more acceptance for nature-based solutions over technology-based CO_2 removal. A "semi-natural" classification of ERW may help to improve its perception.[182,183]

When scaling up, public awareness of ERW will increase as people see new quarries opening, and rock dust being spread on land. This may lead to concern about hazards such as air quality. Studies suggest that if the process is explained clearly, including how hazards are mitigated, this may help to alleviate any concerns to help acceptance of ERW.[164,184–186] Stakeholder involvement on the local, as well as regional, scale will help negotiate the impacts of scaling up ERW, such as opening new greenfield quarries, affecting other land uses.[42]

Farmer involvement

Individual farmers are currently motivated to get involved in ERW through the potential to help address climate change by removing carbon dioxide on their land.[187] They may also be motivated by the potential supplement of fertilisers to improve their soil quality and increase future crop yields.[45]

Farmers currently receive rock dust for free.[45] However, some stakeholders suggest that a public or market-based financial incentive[ss] may be required to implement ERW at scale, particularly if farmers are unsure about potential co-benefits and other unknown risks associated with ERW. This incentive could include being paid to spread the rock dust. There is also the question of carbon credit ownership and responsibility. If the ERW process takes several years to capture the maximum amount of carbon, there may be constraints on land use during that time.

[rr] Australia, n = 1,006; New Zealand, n = 1,022

[ss] Providing publicly funded incentives to farmers to spread rock dust in the countries of the UK would be a devolved decision.

Table 5: A summary of key policy considerations

Logistics & scaling up	A detailed life cycle analysis of any potential greenhouse gas emissions and potential costs during the ERW process will help to determine whether ERW is appropriate to the context, and to verify the expected net CO_2 removal.[123,124,134] The logistics considerations for the emissions involved in: • Extraction, which could involve expanding current quarries, re-opening closed quarriers, or applying for a permit for new quarries[22,120,188] • Crushing rock to an optimal size, where 10-100 μm will take ~1-200 years to fully dissolve, depending on rock type, which is a significant factor[50] • Maximum transport distance from quarry to field, including the type of transport (train, lorry, ship) and fuel, and spreading on fields (Figure 4) • The logistics of spreading in some landscapes, such as upland grassland, can be a challenging (and possibly expensive) undertaking
Regulating environmental considerations	Regulating the type of rocks added to farmland may help to reduce any negative impact on soil or crop health and improve food security. Currently, impacts on species in adjacent environments, such as peatland, rivers, and the ocean, are understudied.[139,162] For example, an increase in pH could lead to a shift away from peatland native acid flora and fauna.
Social impacts	Recent studies into UK public perception into ERW found that small-scale trials in controlled environments are generally accepted.[23] However, if ERW scales up, there may be social concerns about: • Impact on farmers' livelihoods, if they do not receive possible carbon credits • Air quality near quarries[176] • Potential environmental impacts such as the opening of new quarries[139] • Other unknown social impacts, which could be investigated and alleviated through discussion with local stakeholders[179]
Addressing scientific uncertainties	Stakeholders suggest that data from current (Table 3) and future field trials, laboratory studies and computer modelling may improve knowledge on: • Conditions that control the rate and efficiency of CO_2 removal, such as grain size, soil conditions, and climate, and how to best optimise the process[40,49,50,52,135–137] • Timescales & mechanisms for CO_2 removal and subsequent transport from the soil, through soil pore waters, rivers and to the ocean[53] • Potential mechanisms for re-emitting carbon during transport, which would decrease the net effectiveness of any CO_2 removal[55] • Timescales & mechanisms for increasing crop yields, improving soil chemistry, or soil nutrients[39,67] • Agreed cost-effective standardised Monitoring, Reporting & Verification (MRV) of carbon dioxide removal[138]

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