Enhanced rock weathering - evidence on potential environmental impacts and social implications

Chief Scientist's Group report

September 2025

SC230003/R9

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Dr Robert Bradburne
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Introduction

This research is part of a series of reports which aim to collate and review current evidence on the potential environmental impacts and social implications of five greenhouse gas (GHG) removal technologies: ocean alkalinity enhancement, enhanced rock weathering (ERW), biochar, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS). This report synthesises the evidence of environmental impacts and social implications of ERW and highlights any evidence gaps. The carbon removal efficacy of each GHG removal technology, and the economic impacts of their implementation, are not explored in this research.

The structure of the report is as follows:

- A description of how the ERW technological process functions and main considerations for its application
- Synthesised evidence on potential environmental impacts of ERW
- Synthesised evidence on potential social implications of ERW
- A summary of the key findings and identification of evidence gaps
- An overview of the methodology followed to undertake the research

A non-technical summary of this research is also provided as a separate document.

Overview of enhanced rock weathering

This section provides a description of how the process of ERW delivers CO_2 removal from the atmosphere, details of the various forms of the technology, spatial constraints on the implementation of the technology, and context on its current maturity in the UK and globally.

Description

Enhanced Rock Weathering (ERW) is a greenhouse gas removal (GGR) technology that involves crushing rocks into a fine "rock dust" and dispersing it over terrestrial landscapes, such as agricultural fields. The rock dust, once spread, interacts with atmospheric carbon dioxide (CO_2) to form stable carbonate minerals. These minerals effectively lock-away carbon, for long-term carbon sequestration, either within the terrestrial environment or marine sediments from anions transported through waterflows. It usually uses silicate rock material. It is also known as Enhanced Terrestrial Weathering or simply Enhanced Weathering, but will be referred to as ERW in this report.

At its core, ERW accelerates a naturally occurring chemical rock weathering process, which, under normal circumstances, proceeds slowly over geological timescales. Figure 1 provides an overview of the process of ERW. Naturally occurring chemical rock weathering results in the global capture of approximately 1.1Gt of CO_2 from the atmosphere annually, as part of the global carbon cycle (Strefler et al., 2018, Vienne et al., 2022). By crushing silicate rocks into a powder form, the ERW process significantly increases the specific surface area that is available to interact with CO_2, thereby accelerating the rate of CO_2 removal from the atmosphere. There is a theoretical potential to capture up to a maximum of an additional 4 Gt of CO_2 per year globally by 2100, if 900 Mha of the most productive cropland soils are treated with basalt dust at 10-30 t per hectare (Royal Society, 2018), requiring a total application of 27 Gt of basalt dust per annum. In the UK, estimates of the GGR potential vary widely, in part due to the high spatial variability of local soils, but it has been estimated that ERW could sequester 12-21 $MtCO_2$ per annum for moderate application rates (10-20 t per ha per annum), and 19-27 $MtCO_2$ per annum for high application rates (30 t per ha per annum) (Royal Society, 2018).

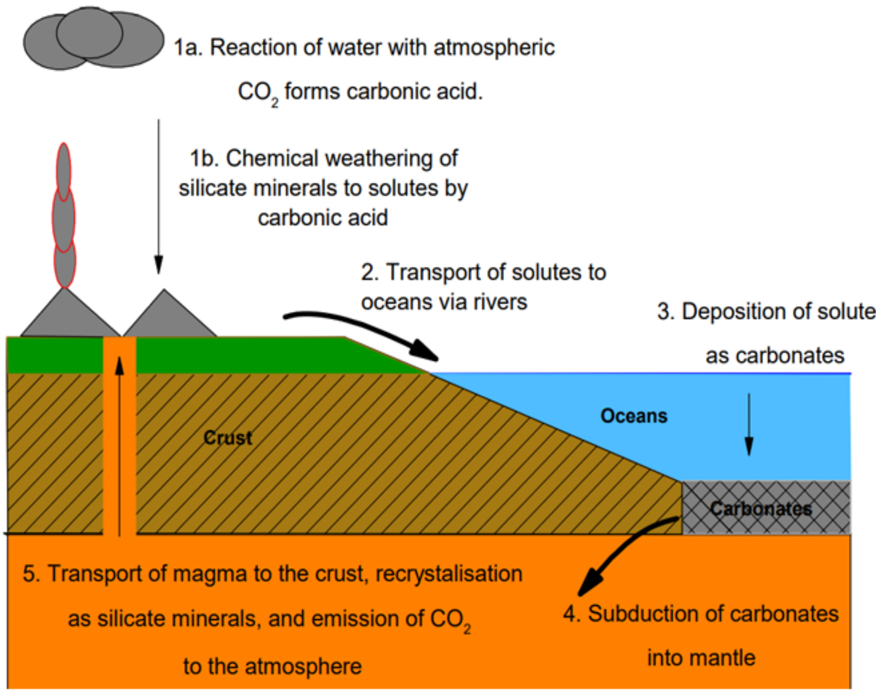

Figure 1 Enhanced Rock Weathering process (Hayes, 2019)

The geochemical processes involved in rock weathering start with rain water, that reacts with atmospheric carbon dioxide (CO_2) to produce carbonic acid (H_2CO_3), as shown in equation 1. This is a reversible reaction, so in acidic soils the carbon dioxide can be re-released to the atmosphere. In the following equations, material types for each compound are shown as atmospheric (atm), aqueous liquid (aq) and solids (s).

(Eq. 1) $$CO_{2\,(atm)} + H_2O_{(aq)} <-> H_2CO_{3\,(aq)}$$

The carbonic acid reacts with the crushed rock mineral, generally producing metal ions and bicarbonate ions (HCO_3^-). Equation 2 shows this process with wollastonite, a silicate material. Other materials can be used, producing different ions. The silicate (Si) hydrates in stages to orthosilicic acid (Spitzmuller, et al., 2023).

(Eq. 2) $CaSiO_{3\,(s)} + 3H_2CO_{3\,(aq)} \rightarrow Ca^{2+}{}_{(aq)} + 2HCO_3^-{}_{(aq)} + H_4SiO_{4\,(aq)}$

Over time, the metal and bicarbonate ions can bind to other components in soil pore water, or local freshwater. They eventually reach the ocean, where the bicarbonate ions or other compounds are used by organisms to form carbonate shells or skeletons (Equation 3). These carbonate materials eventually sink to the ocean floor, and largely re-dissolve in the deep ocean.

(Eq 3) Ca^{2+} (aq) + $2HCO_3^-$ (aq) → $CaCO_3$ (?) + CO_2 (?) + H_2O (aq)

The rate of these reactions depends largely on ambient temperature (Zuhaili Kashim et al., 2020), and water availability. Due to this, the GGR potential of ERW will vary depending on the climate of the environment in which it is applied (Strefler et al., 2018). Other key factors that influence the weathering rate include the silicate composition of the rock and its particle size. Deng et al. (2023) reported that the ideal grain size for CO_2 removal using forsterite (a magnesium rich olivine) was less than 10 microns (μm), in a modelled laboratory experiment.

Ultramafic rocks are categorised as being low [<45%] in silicon dioxide (SiO_2), such as dunite. They exhibit high potential for CO_2 sequestration, with the potential to capture 1.1 tonnes of CO_2 for every tonne of dunite applied in ERW and full weathering after a year at a grain size of 10-100 μm (Strefler et al., 2018). Mafic rocks are characterised by a higher [45-50%] SiO_2 content, most notably basalt which is the most common volcanic rock globally. Mafic rocks also have significant carbon capture capability, with 0.3 tonnes of CO_2 sequestered per tonne of basalt applied in ERW and full weathering after a year at a grain size of 1-10 μm (Strefler et al., 2018). In the UK, a range of mafic and ultramafic rocks, can be used to produce different weathering products. These rocks are most commonly found in the north of England, Scotland and Northern Ireland. The logistical implications of this are explored in further detail in Section *Environmental impacts: Feedstock sourcing and transportation.*

An exception to the preferred use of mafic or ultramafic rock for ERW is dolomite, a calcium, magnesium and carbonate rich limestone that occasionally contains wollastonite. Wollastonite is a silicate mineral with a high silica (56%) and calcium content (26%), and is one of the most studied and promising minerals for ERW (Paulo, et al., 2021). Wollastonite is primarily mined in the U.S, Finland, and China as an alternative for fibre glass in plastic products (USGS, 2022). As it would not be mined within the UK, wollastonite is not further expanded upon as a potential feedstock but is mentioned as one of the promising options for future ERW applications abroad.

Spreading rock dust over arable agricultural land can improve the GGR potential of ERW, as well as bringing additional co-benefits. The enhanced GGR potential is partly due to the plant roots which help the weathering process. The higher soil acidity (due to the application of nitrogen fertiliser) and higher CO_2 levels (due to soil microbiota respiration) in this environment also further accelerate the process, as they facilitate the stabilisation of solid organic matter in the soil. When plants roots and microorganisms respire, they produce CO_2, which, through secondary reactions, can be turned into solid carbonates in the soil (Buss et al., 2023). Studies have shown that this may have a beneficial co-impact of increasing crop productivity (i.e., yield), which is discussed in the *Environmental impacts* and *Social implications* sections of this report. However, there are also concerns that inhalation of dust may present a health risk to farmers applying the dust and to local communities, as discussed in the Environmental Impacts section.

Technological development

ERW is a promising GGR technology from a technological readiness standpoint, partly because the technology required for each aspect of the process, from extraction of rock to spreading on fields, already exists. The mechanism utilised for carbon storage enhances a naturally occurring process, and therefore requires no novel forms of infrastructure (Buckingham and Henderson, 2024). it has undergone few large-scale demonstrations compared to other GGR technologies such as biochar and BECCS, possibly due to concerns over costs and energy requirements (Mission Innovation, 2022), with a technology readiness level (TRL) of 3-5 (Figure 2).

Researchers at the University of Sheffield recently conducted a four-year field trial on an experimental farm in the US, into the sequestration potential and impact on crop yields, which demonstrated significant carbon removal potential, as well as increased soil fertility for maize and soybean yields, reproducible across farm fields (Beerling et al., 2024). Similar trials are currently underway in the UK, including a study at Consett steel works in Durham that aims to quantify CO_2 removal rates through geochemical reactions, as well as alkalinity changes in a nearby stream (Knapp, et al., 2023), and there are ongoing multi-year trials of ERW on arable and agricultural land (University of Sheffield GGR demonstrator project, 2025). The Carbon Drawdown Initiative recently conducted the first complete pilot demonstration of the complete value chain of an ERW project, from basalt mine to agricultural farmland, in Germany, demonstrating the potential profitability of ERW projects through the sale of carbon credits (Carbon Drawdown Project, 2022). Nevertheless, as noted below, further research is needed into the wider, and especially long term, environmental and social implications of ERW before it is deployed on a large commercial scale.

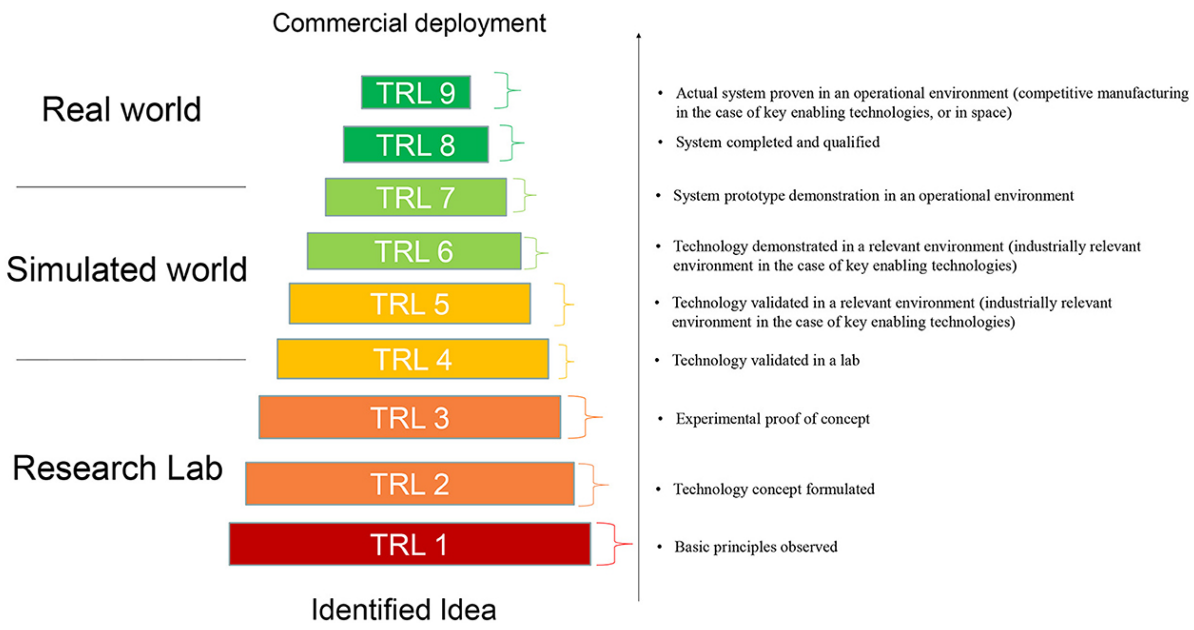

Figure 2 Technology Readiness Levels (Arnouts et al., 2022)

The large-scale deployment of ERW also depends on its economic viability, with cost estimates for ERW varying widely. Much of the costs are attributed to the high energy consumption associated with rock grinding processes, and with transport costs. Models developed by Kantzas et al. (2022) projected that initial costs were likely to range from £200-250 per tCO_2 sequestered p.a., falling to £80-100 per tCO_2 by 2070, as carbon drawdown rates increase with repeated rock applications and renewable energy prices decline. The most significant costs stem from the energy required for rock grinding and the costs of fuel for spreading rock dust on farmland.

Logistical considerations

The transport distances of transporting mined feedstocks may significantly impact on the cost and GGR efficiency of ERW (Fuss et al., 2018, Kantzas et al., 2022, Madankan and Renforth, 2023). There are also potential environmental implications from the sourcing and transportation of material for ERW.

Feedstock sources and availability

Mafic and ultramafic rock is currently predominantly extracted in the UK for use in the construction industry at the active commercial mines shown in Figure 3(a). From current production of 14.8 Mt p.a., around 3.7 Mt p.a. of basic silicate fines could be produced for early-stage deployment of ERW (Madankan and Renforth, 2023). However, extraction and rock dust production will need to be expanded by between 30 to 170 times to remove a total of 6-30 Mt CO_2 from the atmosphere by 2050, which is equivalent to 45% of the total atmospheric carbon removal needed nationally to meet net-zero (Kantzas et al., 2022). This increased demand could be met with the currently identified reserves of basic silicate rock with valid planning permission for extraction (490 Mt) and waste quarry fines until 2034, without disrupting crushed rock supply to the construction industry (Madankan and Renforth, 2023). However, new permit applications for the construction of new associated infrastructure for extraction and processing of rock will be needed to secure further demand beyond this date, without disrupting supply to the construction industry.

The material required for ERW can also be sourced from by-products of other industrial processes such as residual slag[1] or construction rubble - secondary material sources. However, the majority of construction waste material is currently recycled into secondary aggregate, so supply may be limited. It is likely to require additional treatment and processing before application on croplands to avoid soil contamination, e.g. metals, surface treatments (Madankan and Renforth, 2023). While there is potential for mafic and ultramafic rock to also introduce unwanted compounds into the soil, these potentially toxic elements are less understood in application of construction waste. Further commentary on the potential environmental impacts relating to contamination by trace metals is provided in Section *Environmental impacts: Human health impacts*.

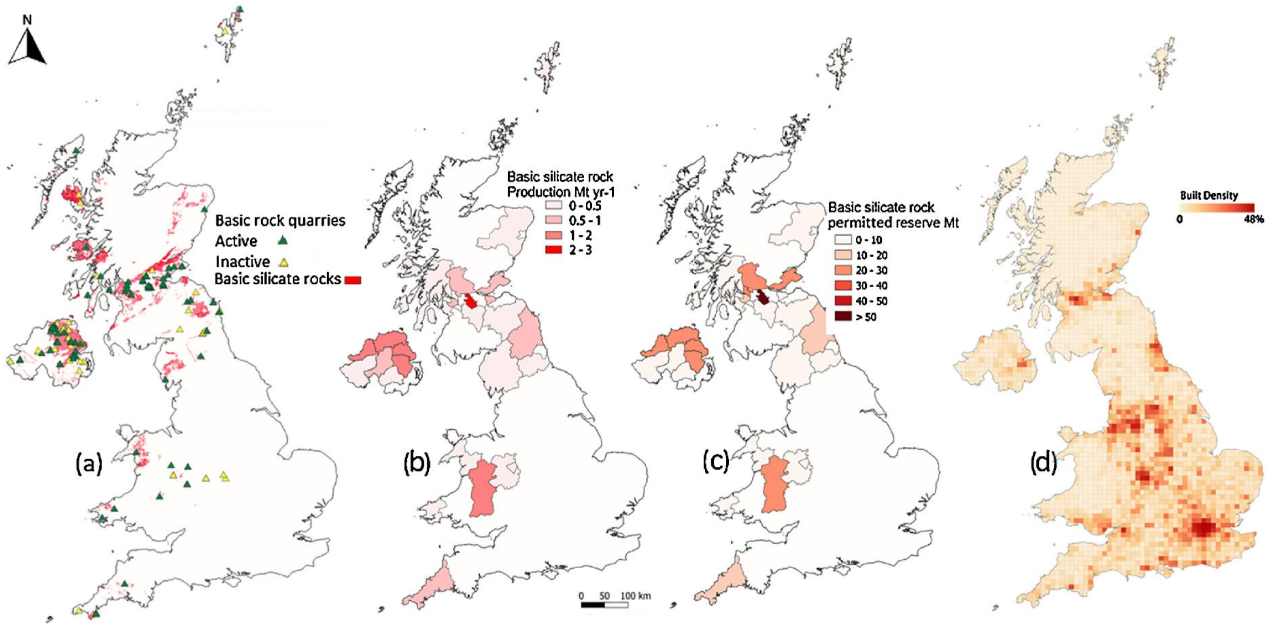

Figure 3 The distribution of a) of active and inactive mafic rock extraction sites, b) production of mafic rock by region, c) permitted reserves by region and d) build density indicating the main potential locations of construction and demolition waste production (Madankan and Renforth, 2023).

More research into the potential environmental costs and benefits of using waste materials is needed to ascertain their long term potential as an alternative feedstock source. Moreover, it is unlikely that these waste products alone would be sufficient to produce enough fines to contribute significantly to ERW as a GGR technology. In 2012, the UK produced around 86 Mt of suitable waste materials per year, but it is estimated that 125 Mt

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[1] Refuse slag is the coarse aggregate and impurities produced as a residue following the melting of non-metallic materials with a high melting point

of such material would be needed per year to draw down around 12% of UK carbon emissions each year (Renforth, 2012).

ERW application locations

Research into ERW has focussed on its deployment on arable cropland, which is highly suitable for application of rock dust and tends to be intensively managed. Moreover, there may be potential co-benefits for crop yield from the application of rock dust, such as the reversal of soil acidification and replacing the use of fertilisers, as discussed further below.

The UK has over 10 million hectares of arable agricultural land, but for ERW application, croplands are likely to be selected for optimal CO_2 sequestration. As noted above, the rate of weathering and therefore CO_2 sequestration is highly dependent on the type of rock applied and local environmental conditions, such as temperature, pH, particle size and soil biology (Madankan and Renforth, 2023). Figure 4 indicates potentially appropriate locations based on GGR efficiency of ERW for a) mafic silicate rocks; b) legacy slags (in England, predominantly in the North West and North East (Riley et al., 2020)); and c) construction and demolition waste. Appropriateness of arable land was calculated using temperature, soil pH, transport distance and normalised scores of input factors.

To reduce transport costs, distance from sources of rock dust should be taken into consideration when selecting application sites (environmental implications of transport distances from the source of rock dust are discussed further in the *Environmental Impacts* section below). Maps created by Madankan and Renforth (2023) (Figure 4) indicate that there are areas of overlap between the location of source material and the location of suitable cropland, for example west central Scotland, northwest England and northwest Wales, which should reduce transport costs and emissions associated with ERW. In total, this study found that over 2 million hectares of arable lands are located within less than 40 km road transport distance of the material resources of all groups. It estimated that 10-20 Mt of crushed rocks would need to be applied to about 0.25-0.5 million hectares of these arable lands to deliver a net CDR of 6-30 $MtCO_2$ per annum for the UK by 2040 (Madankan and Renforth, 2023).

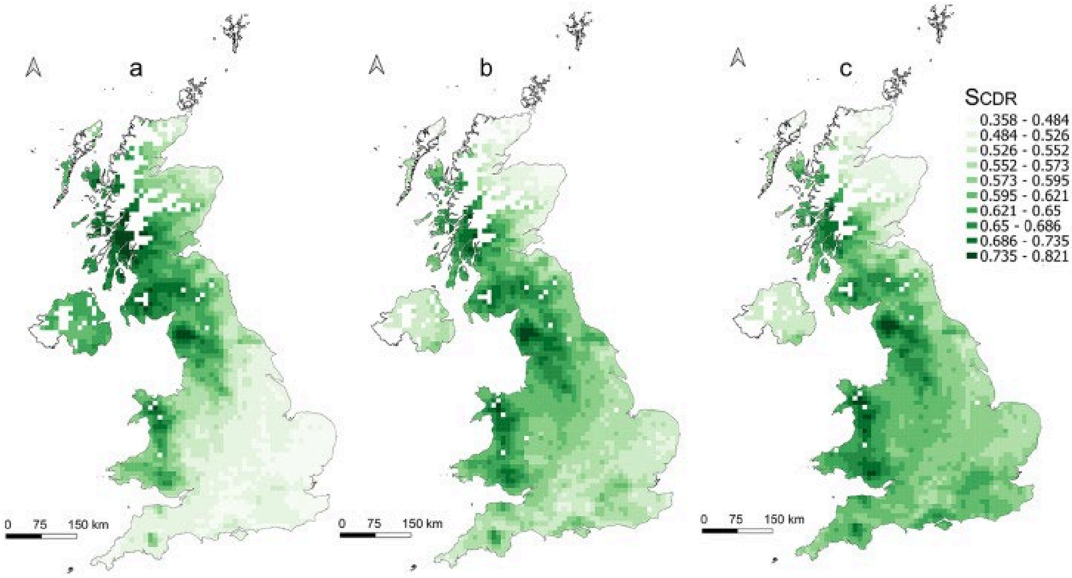

Figure 4 Relative appropriateness of the UK's croplands (10 × 10 km grids) for ERW based on greenhouse gas potential (SCDR) via application of basic silicate rocks (a), legacy slags (b) and construction and demolition waste (c) on arable agricultural land (Madankan and Renforth, 2023).

The long-term storage of CO_2 as stable carbonate minerals is the goal of ERW. Factors that can increase the natural weathering process of rock, and in parallel the sequestration of CO_2, include the choice of solid materials, increased temperatures, increased exposure to rainwater, and increasing the reactive surface area of minerals (Vandeginste et al., 2024). Because of this, tropical climates are especially efficient at increasing the reactivity of basic rocks due to their frequent rainfall and higher average soil temperatures. In addition, the screening of ERW locations prior to implementation will increase the success rate of carbon reduction. The UK is not the optimal place globally for ERW, but the efficiency of ERW in the UK may increase in the coming decades, as climate change increases the frequency of extreme rainfall events and temperatures.

- The choice of mineral bearing rock or waste material for ERW in combination with the acidity of the soil in the target cropland can enhance the weathering process (Deng, et al., 2023). The most researched and highest CO_2 yielding minerals are; wollastonite, a silicate mineral found in the sedimentary rock dolomite: and olivine, an iron-magnesium silicate found in mafic rocks such as basalt (Te Pas et al., 2022).
- More acidic soils, measuring a pH of less than 7, promote the formation of acidic aqueous solutions that increase the rate of dissolution of minerals applied to the soil. Upland soils in the North and West of England generally have a lower pH than lowland arable habitats, although there is high spatial variability in soil pH across the country (Henrys et al., 2012).
- Temperatures control the rate at which minerals are dissolved and precipitated from the host rock. For example, it has been observed than an increase in ambient

temperature from 10 to 40°C may produce a tenfold increase in carbon sequestration due to increased mineral dissolution rates (Vandeginste et al., 2024), though the upper end of this range is not likely in the UK.

- Hydraulic conductivity, the ease that a liquid can move between particles, in combination with rainfall, will increase the dissolution of rock by allowing more surface area to become reactive. This increases the amount of available ions in solution to bond and form new carbonate minerals in the soil.
- Increasing the reactive surface area allows for the reactive aqueous solution to dissolve the particles of basic rock, releasing ions capable of forming bonds with one another and precipitating new minerals.

Environmental impacts

The effects of enhanced rock weathering (ERW) on the environment are addressed in this section, including improved soil health and potential impacts in surrounding ecosystems, land, water, and air. The processes and impacts associated with ERW, which may have both positive and negative environmental consequences, include:

Transportation Emissions– the generated emissions from transporting fined material from the source to the area where it is spread, and the impacts associated with different transit options.

Change to Soil and Water Chemistry – the effects of ERW on the geochemistry, organic carbon, and microorganisms within soils and how runoff of inorganic carbon impacts surrounding ecosystems; from subsurface to the ocean.

Leaching of Potentially Toxic compounds – the effects of ERW material dissolution on the migration of heavy metals and other potentially toxic compounds.

This section includes a synthesis of available evidence on the observed and likely environmental impacts of ERW, and commentary on areas of knowledge that need to be further explored to ensure environmental and human safety. As a technology that is still in the process of broader implementation, the long-term impacts of ERW interactions with the environment are still being understood, and most of the research relating to ERW comes from research studies and demonstrations rather than full-scale trials. This section is structured according to the life cycle of the technology (from feedstock sourcing to transportation and impacts on the surrounding environment when and where the ERW process occurs).

Feedstock sourcing and transportation

ERW starts with a feedstock. This can include residual mine tailings as a by-product of the aggregates industry or construction and demolition waste. The mining or collection of these materials begin the life cycle of ERW. Each material has a different processing pathway due to its contents and a different particle size for maximum weathering efficiency. The material is collected at the source and transported to be crushed using commercially available equipment to a powder, which is screened to produce rock dust (The Future Forest Company / BEIS, 2021). Finer material will have a higher energy requirement from longer operation of crushing equipment; which can also be associated with prolonged exposure to noise and emission of rock dust. Decreasing basic silicate rocks to the suggested particle size of less than 10 micrometres is an energy intensive process that increases the reactive surface area, but can appear to be counterproductive to the reduction of CO_2 due to energy related emissions. The process of mining, grinding and processing rocks can lead to the generation of GHG emissions which can be mitigated by using mining tailings, cement, ash and slags, to create a circular solution to the production of industrial waste (Royal Society, 2018). However, previous expansion of mining efforts globally have been linked to deforestation and leaching of heavy metals into the soil and local waterways (WBCSD, 2023).

Transportation of rock dust material to the site of application will produce an upfront cost of CO_2 emissions due to the burning of fossil fuels and release of GHGs from vehicles, however these are expected to be minimal in comparison to the crushing process which alters the density of the material (The Future Forest Company / BEIS, 2021). In addition, the carbon sequestered over time by ERW is calculated to be significantly greater than emissions associated with transport. As a baseline, the expected emissions for UK transport of biomass from source to conversion for BECCS is 1% of the total sequestered carbon (MacDowell, 2021). These emissions are similar to those calculated by Moosdorf et al. (2014), which predicted that CO_2 emissions from transport should only account for an average of 0.5-3% of the potentially sequestered CO_2 from ERW. The distance from source to croplands varies throughout the UK, therefore varying the emissions associated with each site.

Similarly, it is possible that feedstock could be imported from overseas, which would likewise bring an associated emissions and environmental footprint. The minimum transport distances from croplands to nearby resources (basic silicate rocks, legacy slags and construction and demolition waste) are illustrated in Figure 5. In the UK 2 M ha of arable lands are located within a close proximity (below 40 km road transport distance) of the material resources of all groups. Using an estimated CO_2 sequestration rate of 0.77 t CO_2/ha from a PHREEQC 1-D reactive transport model, the total 2 M ha of arable land could sequester 1.54 M t CO_2 in the initial year of application given 50 t/ha was applied (Vienne et al., 2022). However, the available supply from UK quarries alone might not be enough to meet the demand of nearby croplands. Using three of the basic silicate rock quarries in southwest England from Figure 3a as an example, the total rock production of 600 kt/year would not be enough to cover the arable land within 100 km, equivalent to 10,000 ha, given a rate of 40 t/ha a year was applied (Madankan and Renforth, 2023). In cases of insufficient supply, Figure 5 d-f shows the mean transport distance between UK croplands and all resources of target type of rock. Although some areas have a high mean transport distance it is estimated that post-subtraction of emissions from mining, grinding and spreading leaves enough CO_2 for 50,00-17,000 km of road transport (Moosdorf et al., 2014). Even within the lower estimate of 5,000 km, the furthest transport distance for the UK is 1,600 km, meaning ERW has the potential to sequester a large amount of carbon. A switch from road to rail could emit 76% less CO_2 per tonne (Rail Partners, 2023), however, due to the amount sequestered by ERW, the budget allows for either mode of transport. Furthermore, in a scenario where railways are the predominant system of transport, the rock would still need to be transported by road at least part of the way (from railway to the deployment site) and so emission reduction would fall below the 76% mark. The electrification of transportation systems in the future could increase the net sequestration potential of ERW (Eufrasio et al., 2022). To date, life-cycle assessments have not explored the potential of electric vehicles as an alternative transportation method of rock in the UK, however the energy mix of the UK is an important factor to consider when attempting to quantify this difference. Other impacts from transport may include increased shedding of tyre particles and impacts on air quality from increased vehicle traffic.

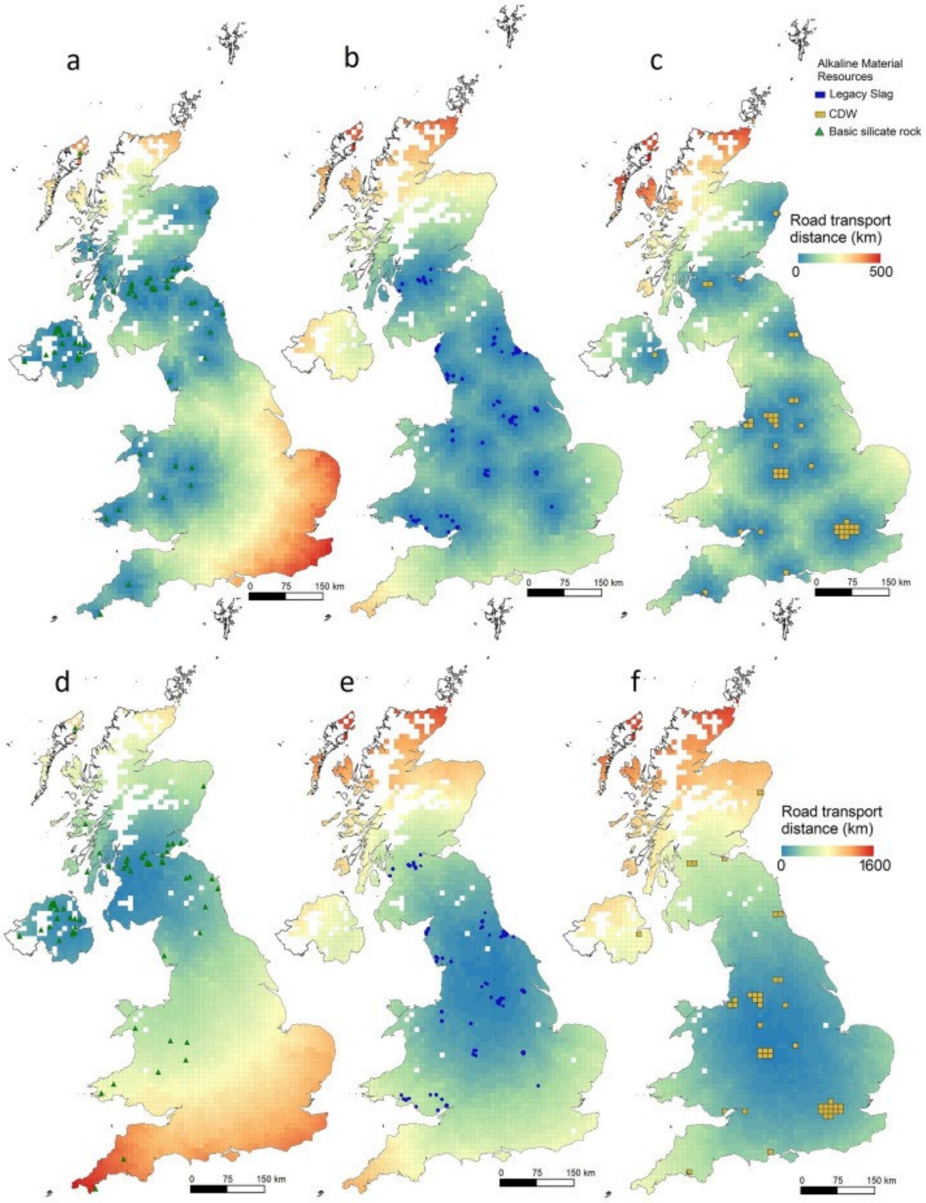

Figure 5 Minimum transport distance between the UK's croplands and nearby resources of (a) basic silicate rocks, (b) legacy slags and (c) CDW. Mean transport distance between the UK's croplands and all resources of (d) basic silicate rocks, (e) legacy slags and (f) construction and demolition waste (Madankan and Renforth, 2023).

Summary: Though the GHG emissions associated with the transportation of rock dust to sites of application should be considered as part of the life cycle emissions calculation of ERW, the estimated volume of carbon sequestered is significantly higher than the emissions from transport, even where local feedstock is unavailable.

Application of rock dust

Soil biochemistry

Research shows that the deployment of silicate materials on land changes the chemical properties of soil by increasing its pH (Royal Society, 2018; Kantzas et al., 2022). Specifically, soils with a lower pH will see more significant increases in pH following mineral application (Madankan & Renforth, 2023; Hartmann et al., 2013). Farmlands, especially those where farming has been the predominant land use for a long period of time, can have a lower pH, which can present an issue in terms of soil nutrient availability. The established practice to reverse this process is liming, where a solid mineral such as calcium carbonate is applied to farmland to increase its soil pH. ERW could be used as an alternative to liming, as it has the same intended effect.

However, suitability for application depends on the materials used and the chemical properties of the soil (Dietzen et al., 2018). A study by Buckingham et al. (2022) into the potential of CO_2 removal by soil, indicated that modelled assessments have previously overestimated the efficacy of ERW in the UK, most likely due to the complexity of soil systems. Additional variables in the soil system such as long-term compaction and biodiversity of micro-organisms can complicate applying modelled approaches.

The increased nitrogen retention and addition of P and SiO_2 can reduce the need for fertilisers, however, arable soils in the UK tend to contain excessive phosphorous and so there may be a reduction in soil health should ERW be deployed at scale (Edwards et al, 2017, Charlton et al, 2018). On the other hand, a study by Deng et al. (2023) demonstrates how higher soil water content and increased microbial activity increases rates of forsterite weathering. Studies in this area are limited, and both Buckingham et al. (2022) and Deng et al. (2023) recommend further research into the relationship between ERW rates and different soil chemistries. One specific area of focus is the equilibrium dynamics between the rate of aluminosilicate rock dissolution to produce silicic acid in pore water, which can have a halting impact on mineral weathering (Exley et al., 2019).

ERW can capture and store atmospheric carbon dioxide in soils, in solid organic matter. ERW can increase the process of respiration, by creating favourable conditions for plants and microorganisms, such as increased soil water retention (The Future Forest Company / BEIS, 2021). This is evidenced by several studies (Kantola et al., 2017; Taylor et al., 2009), including a study by Buss et al. (2023) where mineral-associated organic matter increased by 22% following the application of secondary minerals. The CO_2 produced through photosynthesis is then stored as solid organic matter. Then, carbon can be sequestered from the atmosphere at an enhanced rate and stored in the soil long-term as carbonate minerals, or washed into local waterways and eventually reaching the ocean.

However, if too much rock powder is added to a given area, the plants may suffer from anoxia (complete lack of oxygen) as the soil could become flooded from increased soil water retention. A major effect of anoxia is increased carbon dioxide production, which would reverse the intended effect of ERW (Sairam, 2008). Little research has been conducted into the oversaturation of soil water following ERW application, and so the upper limit of powder application for optimal soil water levels is unknown. ERW could reduce carbon and N_2O emissions from soils and release nutrients such as phosphorous (P) and silica (SiO_2) (Fuss et al., 2018), making it a potential alternative to traditional agricultural fertilizers such as nitrogen. The cause of N_2O reduction through ERW is not fully understood, however, it may be caused by increased microbial production of enzymes which reduce N_2O to N_2 at a neutral pH (Kantola et al., 2017), and may depend on soil types and other dynamics.

Summary: The relationship between soil chemistry and ERW is complex, and although this CDR technology could improve soil chemistry by increasing its pH, improving soil water retention and releasing nutrients into the soil, other research has produced differing results dependent on soil chemistry and quantity/type of application material.

Surface waters

Following the deployment of ERW on land, a fraction of the dissolution products from the chemical weathering process would be transported to the ocean via rivers, with potential local impacts. In addition, if the amount of solute in the river water exceeds the threshold of calcium carbonate saturation, CO_2 will be released back into the atmosphere (Zhang et al., 2023). The risk of this occurring is dependent on the calcite content of the river, which tends to be higher than in soils (Knapp & Tipper, 2022). The oversaturation of calcite results in the formation of large amounts of secondary carbonate during transport and releases the CO_2 sequestered by soil dissolution back into the atmosphere.

The mobilisation of rock dust by wind can also lead to water pollution, potentially causing higher sedimentation and turbidity in rivers. This could have adverse effects on the health of fish populations, as reproduction and recruitment may decrease. However, this should be balanced with the potential benefits of reduced eutrophication in rivers. Current agricultural fertilising practices have caused large phytoplankton blooms to form, as fertiliser is washed into riverine systems, increasing N and P concentrations in the water. ERW practices may reduce the risk of eutrophication if applied instead of fertiliser, as P : Si and N : Si ratios would decrease. Higher Si concentrations remove the nutrients from rivers that stimulate phytoplankton bloom growth (Edwards et al., 2017). Therefore, a transition from fertiliser practices to ERW in agricultural settings could improve the health of fish populations in rivers. However it is also possible that ERW and fertiliser may be co-applied on an area of land.

Ocean alkalinity

The final stage of ERW is the movement of solutes from waterways to oceanic systems where they will be stored; this process could help to reverse ocean acidification. Once the solute has made its way into the ocean, the alkalising substance is deposited as a carbonate or bicarbonate by sequestering atmospheric CO_2. This would increase the ocean pH and speed up the removal of CO_2 from the atmosphere. Modelling studies to date suggest that by 2100, surface seawater alkalinity could be increased by ~100 to >2,000 μm kg^{-1} from ERW / OAE practices (Bach et al., 2019).

The use of ERW to reverse ocean acidification could have adverse effects on marine ecosystems, as it relies on seawater being equilibrated with air after the addition of ERW feedstocks. If this equilibration does not happen, due to inadequate mixing between the surface seawater and the air, CO_2 limitation in the water can occur, causing ocean primary production (photosynthesis) to become limited. This can have varying effects on different species. For example, when CO_2 levels drop below ~100uatm phytoplankton growth rates may be reduced, whereas some larger species are better suited to low CO_2 conditions (Bach et al., 2019).

Conversely, in a scenario where equilibration does occur, a higher ocean pH would improve conditions for calcifying marine organisms, which have been adversely affected by ocean acidification. This would result in a shift in the ocean food chain, and alter species compositions (Bach et al., 2019). An increase in calcifying marine organism populations could however reverse the intended effect of ocean alkalinisation, as solid $CaCO_3$ minerals would increase. The carbonate would likely sink to the deep ocean, rather than dissolve at the surface where it would otherwise be more effective for storing atmospheric CO_2 (Bach et al., 2019). However, this could speed up the process of locking organic carbon in the deep ocean for long term storage, as the carbonate mass would help sink the carbon sequestered at the surface of the ocean (Bach et al., 2019). Further research is required to better understand how different species would respond differently to changes in alkalinity, and how the associated positive and negative feedback systems would affect the efficacy of ERW.

The impacts on ocean alkalinity from ERW are similar to the impacts that are likely from ocean alkalinity enhancement (OAE) in terms of increasing calcifying organism populations, and the associated positive and negative feedback systems affecting ocean alkalinity. However, as ERW relies on the transportation of feedstocks via rivers, rather than targeted deposition within the oceans, the efficacy of the two technologies on increasing ocean alkalinity may differ. Furthermore, OAE would sequester more carbon dioxide from the ocean than ERW, as the dissolution of OAE minerals occurs in the marine environment, whereas the majority of ERW chemical weathering occurs in soils. Whilst ERW / OAE are largely discussed separately in research, it should be noted that the effects of both on ocean environments share significant similarities.

Summary: The implementation of ERW could have both positive and negative effects on ocean alkalinity, and therefore on the health and abundance of marine species. The transport of silicate materials can increase ocean pH, which can cause CO_2 limitation in the water leading to a limitation in ocean primary production. But higher ocean pH can also increase marine organism calcification and alter the balance between carbonate surface dissolution and deep ocean organic carbon sequestration.

Human health impacts

There is a lack of research demonstrating the short and long-term health impacts of ERW. However, hypotheses about possible health hazards have been proposed based on health conditions associated with a) the inhalation of rock dust and b) the contamination of the soil with trace compounds.

Inhalation of rock dust

Concerns have been raised about the potential risk of respirable rock dust particles (less than 75 microns in diameter). They could have a negative impact on air quality and pose a risk to the health of local populations near application sites, to the farmers applying the particles, and if inhaled during mining or mineral processing (Taylor et al., 2016). Of these stages, occupational exposure during quarrying and grinding operations may represent the greatest hazard, exposing workers to long-term lung diseases such as silicosis (Vandeginste et al., 2024; NHS, n.d.). However, to date, research on the health impacts of rock dust inhalation directly linked to ERW has focussed on the possible impacts on communities in areas where rock dust is applied to agricultural land.

Inhalation of crystalline silica particles such as those found in basic and ultramafic rocks can cause silicosis, and it is likely that other potential health risks exist, stemming from the toxicity of metals contained within certain materials (Royal Society, 2018). The health risks posed are likely to vary significantly depending on the mineral used to produce rock dust, and local wind and weather conditions. For example, fast-weathering harzburgite includes asbestos-related materials, which may pose a long-term health risk if particles are inhaled by local populations (Taylor et al., 2016). Health risks may also vary depending on local weather conditions. For example, in dry seasons, particles are more likely to be dispersed by wind than in more wet or humid conditions (Edwards et al. 2017; Goll et al. 2021). As droughts increase in frequency due to climate change, dust-spreading may increasingly present health issues for local populations.

Mitigation techniques to reduce potential health risks may include increasing particle size (although this will affect the rate of weathering), or dust mitigation techniques such as creating a suspension or “slurry” prior to application (Strefler et al., 2018), or the application of repeated smaller doses. However, further research is needed to assess the effectiveness of these potential mitigation techniques, and to consider any trade-offs that exist between reducing health impacts and maximising GGR potential, before ERW is deployed at scale. Moreover, using construction and demolition waste as a replacement for rock dust, and thereby reducing the extraction and grinding of rock dust, could reduce some of the occupational hazards associated with ERW (Eufrasio et al., 2022). However, ERW materials produced from construction and demolition waste may contain contaminants that pose harm to human health when applied to fields, either through dust particles or via contamination of soil or waterways. There is not currently a substantial body of research examining the potential health impacts of the application of waste materials for ERW.

Summary: There are several areas of potential concern around health hazards that may lead local communities to oppose mining and application of rock dust for ERW. Where rock dust is inhaled, it may have health implications for local communities, and possibly for the general public at large, which need to be further quantified before the technology is deployed at scale.

Trace compounds

There are several areas of potential concern around health hazards of ERW. Where rock dust is inhaled, it may have health implications for local communities, and possibly the wider public, which need to be further quantified, and mitigation techniques employed as necessary, before the technology is deployed at scale. Potentially toxic elements and compounds in the parent material of ERW rock dust could cause the accumulation of contaminants in soils when applied to agricultural land. These have the potential to accumulate in the food chain, presenting a possible long-term health risk to humans. The main factor controlling soil concentrations is the composition of the applied material and the rate that this material is applied (Suhrhoff, 2022). The use of mafic rocks, like basalt, over ultra-mafic rocks reduces the risk. Mafic rock weathering is associated with nickel and chromium contamination, either as secondary minerals, those derived from the dissolution of olivine and other primary minerals in the host rock, or adsorption, observed as a crustal layer at the surface (Suhrhoff, 2022; Dupla et al., 2022).

For basalt, a trial was conducted with a single application of 20 tonnes per hectare of basalt powder on soil with a bulk density of 1100 kg/m^3. The heavy metals of concern (Table 1) were monitored and found to remain within 5% of background values after a week of initial application (The Future Forest Company / BEIS, 2021). The largest increase in concentrations was from cadmium (4.8%) with secondary increases in copper and cobalt (2.8%). One potential mechanism for increased rates and mobility of contaminants is the adsorption of these elements by iron phases and clays (Cabral Pinto et al, 2017). Further monitoring and research is needed to conclude the long-term release mechanisms from potential feedstock sources, especially to account for repeat applications over multiple years. Other potential contaminants associated with rock feedstocks are outlined in Table 1.

Material source	Feedstock	Primary Composition	Potential Contaminants
Mafic rock	Basalt	High Mg and Fe with low silica	• Cadmium • Chromium • Cobalt • Copper • Lead • Mercury • Nickel • Zinc
Ultramafic rocks	Serpentinite	Serpentine minerals- mostly Mg silicates	• Chromium • Chrysotile (asbestos) • Cobalt • Copper • Iron • Magnesium • Nickel
Legacy slags	Iron and steel slag	Iron and Calcium-silicate	• Hyperalkaline oxyanions • Rare Earth Elements (RREs) • Chromium • Vanadium
Construction waste	Concrete	Cement (calcium-silicates) and other materials	• Cadmium • Chromium • Cobalt • Copper • Lead • Manganese • Zinc

Table 1 Potential material sources for ERW feedstocks and the associated contaminants that derive from the dissolution of the feedstock's primary compositional elements. Toxicity and concentrations will vary depending on the dissolution rate of the feedstock material, in combination with soil geochemistry (Ismail, et al., 2023; Riley, et al., 2020; Bini, et al., 2017).

While the contaminant content of rock dust must be further considered for its implications for human health and food safety when applied to agricultural land, the concentrations can be managed to remain at safe levels in soil and plant biomass through effective monitoring and remediation strategies. One such strategy, proposed by Hou et al. (2020) includes phytoremediation to reduce the accumulation of trace metals in the soil by planting willow trees that intake trace metals through their root systems. This technique has not been proven on ERW affected soils, requires additional research into the efficiency and additional benefits of these crops, and would add an additional crop rotation for land managers.

The use of ERW as a carbon removal technology may be limited by legal requirements for potentially toxic elements (PTEs) in soil; with safe threshold values for nickel, chromium, zinc, and copper found in almost all soil protection legislation (Dupla et al., 2022). The UK for example has set out a minimum level of chromium allowed in soils for industrial use at 5,000 mg/kg and a minimum level of nickel in 'agricultural and after sewage sludge application' at 50 mg/kg for soils with a pH of 5-5.4 (ALS Environmental, 2017). Further research is needed for each potential feedstock to conclude the maximum amounts that can be utilised relative to the national permissible PTE values in soil.

During a study conducted by Suhrhoff (2022), the limitations of olivine as an ERW feedstock was assessed to be 95 tonnes per hectare for a single application. Beyond this rate, the soil retention rate of leached nickel and chromium reached 99% and the measured values went beyond the permissible levels under Swiss regulations. Chromium and nickel contained in harzburgite may also have detrimental health impacts on the wider population if they are taken up by crops via the soil and accumulate in the food chain but the rate of this is uncertain (Beerling et al, 2018). It is possible to use materials like basalt with lower metals content, though it would still have some metal content.

Summary: There is a risk that the rock dust spread for ERW contains potentially toxic elements which could lead to the accumulation of soil contaminants which could have implications for human health and food safety. This will be regulated by legal limits on PTEs in soil.

Social implications

This section explores the actual and potential social implications of ERW identified within the existing evidence and identifies where research currently falls short of exploring these impacts.

As many social aspects are intertwined, with industry, community and governance often interdependent and influencing one another, each identified social impact of ERW is likely to apply to a broad range of stakeholders, as well as being intrinsically linked to the environmental impacts identified within the other sections of this report. However, for the purposes of this review, and to identify where evidence gaps exist, the following social implications identified within the available evidence are explored:

Social acceptance and acceptability – explores public opinion of ERW and the factors that can influence this both positively and negatively.

Implications for local communities – explores the impacts of ERW on those who work or reside within the immediate vicinity.

Other implications – brief exploration into the wider social implications of ERW, including the potential impacts of policy and governance.

Social acceptability

Research into social acceptance of ERW has demonstrated that awareness of this technology amongst the general public is extremely low (Spence et al., 2021; Pidgeon & Spence, 2017; Goll et al., 2021). In comparison to other CDR technologies, such as BECCS (bioenergy with carbon capture and storage) and DACCS (direct air carbon capture and storage), ERW is not 'distinct', meaning the public generally find it difficult to visualise the process. Therefore it is less likely to draw their attention (Wright et al., 2014). This could contribute to the limited public reaction to ERW.

However, when made aware of ERW as a potential GGR technology, some studies suggest that the public are supportive of research into the area, particularly small-scale trials and scientific experiments (Spence et al., 2021; Pidgeon & Spence, 2017). This is mostly due to concerns about climate change and its associated environmental impacts, including the impacts on animals and humans. In a study on social acceptance of ERW in the UK, using a stratified sample of the British public (n=935), 53.3% of respondents stated that research into the area should be allowed, whereas only 9% disagreed (Pidgeon & Spence., 2017). When presented with the potential risks of ERW, respondents demonstrated concern, and stated that development within the area should be allowed, provided that scientific independence, appropriate monitoring, risk assessment and transparency of results are ensured (Pidgeon & Spence., 2017).

Support for the wider deployment of ERW is lower, with significantly more respondents supporting the research into ERW than the scaled-up use of the technology itself. Public concern into the scaling-up of ERW is largely associated with the mining and extraction of materials required for weathering (Royal Society, 2018; Kantzas et al., 2022). Another study into public attitudes towards this technology, found that across Australia, the USA and the UK, most respondents were unsure whether they would support ERW (42.8%, 45% and 49.7% respectively) (Spence et al., 2021). Nature-based solutions such as afforestation tend to be more widely socially accepted over engineered GGR technologies such as ERW (Kantzas et al., 2022). There is a general consensus amongst social scientists that further research into the development of low emission innovative solutions for material extraction would be required, in order for the technology to be fully accepted (Pidgeon & Spence, 2017; Spence et al., 2021).

At this stage, it is difficult to determine global public perception of ERW. This is because studies have been conducted at a small-scale and in a limited number of countries. Further research should look to expand these studies, in particular focusing on areas where ERW activities would take place. Public understanding of ERW is limited, as the technology is still poorly defined as a concept (Royal Society, 2018). To gain a better understanding of social implications, public awareness campaigns with a focus on implications for each local community should take place, alongside monitoring of public perception.

It is also important to note that to date there are no studies exploring the level of industry acceptance of this CDR technology. This is perhaps because of the overlap between ERW and established fertilising practices which are already widely accepted in the farming industry. However, further research into farmers' perceptions of ERW as a CDR technology will help to shape future government policy and enable the process to be scaled up.

Summary: Public awareness of ERW is low, although there is support for further research into the technology at a small-scale. Social acceptance of deployment is lower than for development, however more research should be conducted within the communities directly impacted by ERW.

Implications for local communities

The expansion of mining operations for ERW may have both positive and negative impacts on local communities. It may provide local employment opportunities in remote areas, boosting local economies and reducing rural depopulation. However, communities may raise concerns about whether wealth created in large mining businesses will be fairly distributed within the local community, and whether quarries will be abandoned without a sustainable management plan following extraction (Kantzas et al., 2022).

There may also be local opposition on the grounds of negative impacts on biodiversity and human health, as discussed in the *Environmental impacts* section, which may limit the selection of application sites away from population centres or sensitive ecosystems (Hartmann et al., 2013). There is a consensus that mining companies and local authorities will need to engage extensively with local communities to facilitate acceptance of extraction, processing and application of rock dust for ERW (Kantzas et al., 2022; Royal Society, 2018). However, unlike some GGR technologies ERW does not compete with other uses for land so will not have significant implications in terms of food production under the current division of land use for food production (Deng et al., 2023).

Socio-economic implications

Studies into the socio-economic implications of ERW indicate that the agriculture and mining sectors may benefit from the scaling-up of this technology. This would benefit those working in the sectors by increasing employment and improving agricultural productivity. However, these benefits may be counterbalanced by the social implications of the health and environmental impacts already discussed.

Increased productivity and reduced requirements for synthetic fertilisers could potentially lower overheads for farmers (Royal Society, 2018). Changes to soil, through the release of nutrients such as silica, increase the alkalinity of cropland and not only improve crop yields, but increase the area of viable land on which crops can be grown. Therefore, the integration of ERW into agricultural practices has the potential to improve the economic viability of the farming sector (Skov et al., 2023; Beerling et al., 2024). Research is required into how the economic benefits of improved crop yield will balance with the costs of deployment as the technology matures.

Currently, ERW practices are mostly financed by the voluntary carbon market, where private entities buy and sell carbon credits representing a reduction in atmospheric carbon. To create natural capital from ERW, credible monitoring, reporting and verification (MRV) is essential for valuing each project. As ERW is still in the development stage and questions remain around the efficacy of this technology, MRV approaches are not yet rigorous enough to support the growth of ERW in the global carbon market (Almaraz et al., 2022). This represents a significant barrier to scale, as funding is required to ensure quality of MRV at the field level (NASEM, 2019). Once questions around ERW have been answered, farmers will be able to access revenue through these carbon markets to further improve the economic viability of this sector.

A thorough cost-benefit analysis of ERW in the farming sector has not yet been conducted, and considerations such as retrofitting costs and productivity improvements in climates where ERW can be deployed are not fully understood (Royal Society, 2018). Therefore, further research into ERW at a global scale with a particular focus on viable farmland for deployment is needed to realise its full potential.

The mining sector could also see benefits from the scaling-up of ERW. Areas rich in silicate deposits tend to be rural (e.g. basalt in the Scottish Highlands) and may benefit economically from new mining industries. However, transport costs from rural areas would be higher and the relationship between mining quarries and local communities must be carefully managed (Madankan & Renforth, 2023). ERW could also provide a new market for areas where the mining industry is oversaturated and are currently facing problems with accumulating overburden material. Furthermore, a just transition to a green economy could be assisted by replacing jobs in the declining coal mining industry with jobs which would require a similar skill set (Goll et al., 2021).

There are several social barriers to achieving this, due to environmental and health concerns in public perceptions of the mining industry. Another important factor for social acceptance is distributional and procedural justice, which would require studies into public engagement and the potential benefits which could be realised by local communities engaging in mining activities. These studies would therefore have to look beyond the primary socio-economic benefits of job creation and retention, and seek to understand how these opportunities could be distributed fairly amongst communities. The development of regulations to manage the relationship between mining for silicates and the wellbeing of local communities should take this into consideration before the technology is scaled-up.

Whilst it is clear that ERW has the potential to deliver socio-economic benefits to the mining and agricultural sectors, studies into these benefits may be limited and are currently largely theoretical. There is a significant research gap on industry acceptance of ERW, including acceptance amongst farmers, and the practicalities of spreading silicate materials may differ greatly between i) small and large, ii) urban and rural, iii) temperate and tropical farms (Edwards et al., 2017; Haque et al., 2021). Therefore, further research should focus on the economies of the countries where mining and deployment of ERW would take place to understand how communities could realise the benefits of this CDR approach.

Summary: There is significant potential for the deployment of ERW to deliver socio-economic benefits on a national and global scale, however these benefits are complex and may have adverse effects on some communities. Research should focus on the industries and communities which are likely to be affected by ERW in order to gain a well-rounded understanding of its socio-economic implications.

Conclusions

Summary of environmental and social implications

ERW has the potential to deliver social and environmental benefits to various communities and industries, particularly as this technology is already being deployed at a small-scale by farmers for soil fertilisation. The transition from development to deployment of ERW could see increased productivity in croplands, new employment in the mining industry and wider environmental benefits based around carbon dioxide removal. However, possible adverse social and environmental impacts of this technology are not yet well understood or more widely considered.

The long-term goal for this technology is to permanently capture and store carbon dioxide in the form of carbonate minerals. This mineral formation is dependent on the dissolution of host rocks, typically basic silicate rocks, as well as environmental controls such as temperature, rainfall, and soil chemistry. The primary concerns surrounding ERW are focused on the extraction of rock as feedstock, and how the application of this feedstock may interact with the surrounding ecosystems. Some of the issues to monitor are trace metal leaching and particle migration via air and waterways from the initial application site.

Public approval of this technology is largely based on views on climate change. However, a poor understanding of ERW means that it is difficult to gauge how ERW is perceived to be of specific benefit to different groups in society. Concerns around the health and environmental implications of the mining and grinding process further limit its potential for scaling-up.

There are many research gaps in the area, which may provide an explanation for the limited policies and regulations surrounding ERW and its associated risks globally. Government bodies should begin to develop policy frameworks to support the deployment of ERW, whilst monitoring ongoing research developments. In addition, detailed management and screening of the local environment (water and soil) should be conducted prior to implementation, to minimise environmental risks and keep in line with current regulation surrounding the environment in other industries.

Evidence gaps and research priorities

ERW shows theoretical potential in terms of carbon drawdown, but it is currently an immature GGR technology that has yet to be demonstrated widely and at scale. Uncertainties relating to environmental and health impacts highlight a need for further research into the use of ERW as a GGR technology.

The primary knowledge gaps pertaining to large-scale ERW implementation are the lack of real-world trials, currently depending mostly on laboratory experiments and computer models. To establish ERW as a carbon removal technology, measuring the impacts of the technology on surrounding environmental systems is needed. Currently, there are ongoing trials in the UK researching the interactions between ERW application on croplands and geochemical changes in local waterways and soil health, with some of these trials completing and publishing findings in the near future. From the initial findings of these studies and others globally, evidence of the environmental impacts of enhanced weathering in soils has been generally positive; observing improved soil health and increased pH in water. However, the long-term environmental effects of ERW application are difficult to predict and to monitor, as this is a natural process that is being enhanced and managed anthropogenically; with diffuse potential impacts on soils and waterways.

Another significant research gap of this technology is how the weathering of mafic rocks can lead to the leaching of heavy metals, such as nickel and chromium, and the ratio of PTE concentrations per tonnage of rock applied. This will assist in setting environmentally suitable regulations for the application of ERW, to mitigate environmental and health impacts that these elements may have if carried away from the application point by rain runoff.

Other gaps in environmental impact research include:

- The impact of ERW on organic carbon in soils.
- The timeline for mineral sequestration of ERW, especially compared to CCS.
- The impact of ERW feedstock runoff on ocean microorganisms.
- The change in pH on soil from the deployment of silicate materials, which factors influence the speed of this, and whether the impact is the same from other liming materials.
- The particle size that returns the best ERW results for various mafic minerals.
- Quantifying the human health hazards associated with ERW.
    - For example, understanding the impacts of mechanical perturbation (such as harvesting and ploughing) on dust particle dispersal, and the associated health risks.
    - As well as the health risks of exposure to various toxic and hazardous components of rock dust, which have not yet been fully investigated and quantified.

There is limited evidence relating to the potential social implications of ERW. Existing research is predominantly focussed on social acceptance and acceptability. However, even within this area, significant research gaps exist. Research is focussed on acceptability by the general public, but more evidence is needed to better understand acceptability and potential uptake of ERW within the UK, with a particular focus on key stakeholders such as farmers, who are crucial to ERW deployment in the UK. There is also a need to improve public understanding of ERW. Research into the potential impact of public awareness campaigns surrounding ERW should improve the efficacy of such engagement.

Other gaps in social implications research include:

- The socio-economic impacts affecting the industries associated with ERW, such as farming and mining; and
- The socio-economic impacts affecting the communities where extraction and deployment of ERW would take place.

Most pressingly, there is some concern that negative health impacts may exist, based on knowledge of studies examining the health impacts of related mineral substances and particulate matter. However, there is a lack of quantitative evidence linking rock dust applied to croplands to relevant clinical or lab-based health research. Taylor et al. (2016) suggests that concerns around the foreseeable and unforeseen consequences of ERW, including potential health impacts, may be a significant barrier to the deployment of ERW. It is therefore important that research into potential health hazards associated with each stage of the process, from mining and grinding, to application on croplands, along with possible dust mitigation strategies, is initiated without delay.

Appendices

Methodology

Parameters for including suitable sources in the review were devised according to academic best practice based on the timeliness, accuracy, authority and objectivity of the research, thereby excluding sources of insufficient quality to contribute to the required quality of results. All sources used as part of this research were assessed against this source reliability protocol (included in Table 2 overleaf).

Relevant literature was identified, including 'grey' literature (e.g., conference papers, government publications, social surveys, industry standards, market reports, and policy statements) and scientific papers, using a range of search strings on both public and academic platforms.

A framework of research questions was used to form the basis for collating information. Following the assessment of all relevant literature, a gap analysis was undertaken to identify research gaps in the available evidence. A final search relating to these specific gaps was conducted to ensure that no relevant literature was missed.

Table 2 The source reliability protocol used to assess the and suitability reliability of sources used in the research.

Criteria	Red	Amber	Green	Grey
1. Currentness				
How up to date is the information?	20-30 years' old	10-20 years' old	0-10 years' old	Date not identifiable
2. Accuracy				
Does the item have a clearly stated aim or brief? Is it detailed and factual? Does the work contradict itself? Does the work appear to be carefully prepared (e.g. well-written or designed, mostly free of errors, easy to navigate)? Does it have a stated methodology?	No clear aims or methodology, contains several errors, contradicts itself	Aims and methodology explored in less detail, some errors	Detailed aims and clear methodology, very few errors	N/A

Criteria	Red	Amber	Green	Grey
3. Authority				
Is the author associated with a reputable organisation? Do they have relevant professional qualifications or experience? Are they cited by others? If published by an organisation, is the organisation reputable? Is the organisation an authority in the field? Does the item have a detailed, credible reference list? Has it been peer reviewed? Has it been edited by a reputable authority?	No clear expertise and / or not reputable organisation, no reference list, no reference to review/editing process,	Some relevant expertise, review/editing process unclear	Reputable organisation, considerable expertise, reviewed and / or edited by technical experts and well-supported by credible sources,	N/A
4. Objectivity				
Is the author presenting their opinion or factual evidence? Is the goal of the work to inform or persuade? Does the work seem to be balanced and consistent? Independent expert or vested interest? Who funded/sponsored the work?	Clear vested interest, strong opinions presented, written to persuade rather than inform	Possible vested interest, opinion-driven	Independent expert, balanced views / factual evidence presented, clearly identified funding source with lack of vested interest	No evidence of funding source

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List of abbreviations

Abbreviation	Definition
BECCS	Bioenergy with carbon capture and storage
CO_2	Carbon dioxide
DACCS	Direct air carbon capture and storage
ERW	Enhanced Rock Weathering
GGR	Greenhouse gas removal
GHG	Greenhouse gas
Gt	Gigatonne
Ha	Hectare
H_2O	Water (chemical formula)
Mt	Megatonne
t	Tonne
TRL	Technology readiness level

Glossary

Term	Definition
Carbon sequestration	The process of capturing and storing atmospheric carbon dioxide.
Enhanced rock weathering	A geoengineering method that involves the application of basic rock dust to soil, accelerating the natural drawdown of CO_2 by the chemical weathering of silicate minerals.
Geoengineering	Large-scale manipulation of an environmental process that affects climate, to counteract the effects of global warming.
Greenhouse gas	Gases in the atmosphere that raise earth's surface temperature; including CO_2, CH_4, N_2O, HFCs and PFCs.
Greenhouse gas removal	Also known as negative emissions technologies, greenhouse gas removal technologies encompass a range of techniques for reducing the concentration of GHGs in earth's atmosphere.

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