International Journal of Greenhouse Gas Control 130 (2023) 104010

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

An inventory of UK mineral resources suitable for enhanced rock weathering

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ARTICLE INFO

Keywords:
Enhanced weathering
Geochemical carbon dioxide removal
Alkaline minerals
Resource inventory
United Kingdom

ABSTRACT

Enhanced Rock Weathering (ERW), a technology based on amending soils with crushed calcium- and magnesium-rich silicate minerals has substantial CO_2 removal potential. Evaluation of the available resources of these minerals and current production capacity is crucial for early-stage deployment of this approach. A robust understanding of the potential limitations in exploiting these resources is also required to ensure the scalability of ERW. This paper provides a spatial inventory of basic silicate rock resources in the UK along with current production capacity and permitted reserves. We also integrate spatial data to assess the potential environmental and social impacts of current rock extraction. 68 active and 100 inactive quarries were identified within outcrops of basic silicate rocks which are mainly distributed in Northern Ireland and in the central belt of Scotland. 14.8 Mt yr^{-1} of basic silicate rock are estimated to be extracted from which up to 3.7 Mt yr^{-1} of basic silicate waste fines is estimated to be produced which may be available for ERW in the UK. 490 Mt of permitted reserves is associated with active and inactive queries. Spatial distribution of artificial alkaline minerals including Construction and Demolition Wastes (CDW) and legacy slags in the UK have also been included in the inventory. Transport distances are calculated between all resources and the UK's croplands where these materials may be applied for ERW. The relative appropriateness of the UK's croplands for CDR are also calculated based on their proximity to mineral resources and climate parameters controlling the rate of EW.

1. Introduction

Limiting the impacts of dangerous climate change will require extensive and rapid emissions reduction combined with large-scale removal of carbon dioxide from the atmosphere ('CDR' IPCC 2018, NASEM, 2019, IPCC, 2022). Geochemical CDR, a group of methods that remove CO2 from the atmosphere by chemical reaction with natural or artificial minerals (Campbell et al., 2022; Kolosz et al., 2022) have substantial potential (Bullock et al., 2023; Renforth, 2019). Enhanced Rock Weathering (ERW), a geochemical CDR technology based on amending soils with crushed calcium- and magnesium-rich silicate rocks, may be able to remove ~2 billion tonnes (Gt) of CO_2 yr^{-1} globally (Beerling et al., 2020). The availability and accessibility of rock resources, their heterogeneity, environmental context, and public acceptance for deployment are aspects that require consideration (Bullock et al., 2023, 2023; Eufrasio et al., 2022; Krevor et al., 2009; Renforth, 2012; Riley et al., 2020; Spence et al., 2021)

Basic and ultrabasic igneous silicate rocks contain 45–55% and <45% silicate respectively, and are potential resources for ERW. These rocks which are abundant in the earth's surface mainly consists of calcium (Ca), iron (Fe) and magnesium (Mg) rich minerals such as olivine, pyroxene, ca plagioclase and augite. Their potential for CDR varies based on their chemical composition but typically ~0.2 to 0.8 tCO_2 t^{-1} rock can be expected in basic and some ultrabasic rocks respectively (Renforth, 2012). While the abundance of these resources does not seem to limit the deployment of ERW, potential technical, environmental, and social constraints may affect accessibility to these materials. For instance, from the resources of rocks suitable for ERW in the UK (1668 Gt estimated by Renforth, 2012), a considerable proportion are under land-use with an environmental designation (Renforth, 2012). The recent annual production of total igneous rocks in the UK is estimated to be 37.5 million tonnes (Mt) for 2018 (BGS Mineral Yearbook, 2018). But details on the proportion of basic and ultrabasic silicate rock production and permitted reserves are not readily available.

Other potential resources for ERW are artificial silicates that are rich in Mg or Ca such as construction and demolition waste (CDW), cement kiln dusts (CKD), steel slag and mine tailings (Campbell et al., 2022). These materials are found to have a large global CDR potential of

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https://doi.org/10.1016/j.ijggc.2023.104010
Received 30 May 2023; Received in revised form 5 October 2023; Accepted 7 November 2023
Available online 30 November 2023

2.9–8.5 $GtCO_2$ per year by 2100 (Renforth 2019). In the UK, 190 million tonnes of iron and steel slag are located in legacy deposits, and their cumulative CDR potential is estimated to be 57–138 $MtCO_2$ (Riley et al., 2020). Some estimates (Department for Communities and Local Government, 2005) suggest the total production of CDW to be around 80 Mt yr^{-1} in the UK, however its spatial distribution is not well documented. In this study we constrain CDW spatial distribution using locations of built areas as a proxy.

In addition to natural and artificial alkaline materials, land for mineral application is also an important resource for deployment of ERW. Agricultural land has received more research for the application of alkaline materials given the potential co-benefits of these materials for improved food and soil security (Beerling et al., 2020) as well as available infrastructure for spreading the materials. The UK has over 10 M ha of croplands distributed across the country. The CDR potential in croplands is expected to vary in different locations due to the spatial variation of factors that control the rate of ERW such as temperature and water availability.

The transport distance of alkaline materials from sources to application area can significantly influence the cost and the CO_2 emissions of ERW. Given the asymmetrical distribution of alkaline material resources across the UK, a range of transport distances are expected between these resources and the UK's agricultural land.

Previous work suggests that ERW may have significant CDR potential in the UK (Kantzas et al., 2022; Renforth, 2012). A modelling assessment suggests that ERW may be able to deliver a net CDR of 6–30 $MtCO_2$ yr^{-1} for the UK by 2050 which represents up to 45% of the atmospheric carbon removal needed to meet the national net-zero emission targets (Kantzas et al., 2022). This study explores the deployment of ERW through a detailed assessment of the available resources in the UK. Particularly by i) identifying locations of current rock extraction, production volumes, and consented reserves ii) identifying sources of artificial alkaline materials for ERW (cement-based waste), iii) assessing the proximity of these production sites to agricultural land and possible transport distances, iv) determining methods for assessing the social and environmental impact of rock extraction.

2. Methods

2.1. Material resources identification

2.1.1. Basic silicate rocks

Production sites for silicate rocks that are suitable for ERW were determined by relating entries in the BritPits (BGS, 2022) dataset, a database that includes a total of 254,584 entries detailing location, history, type of rock, and current status of mineral workings. As the database covered all current and previous mineral working including, active, inactive, ceased and dormant sites, entries were filtered to include active quarries which are currently extracting rock and inactive quarries which are sites that currently do not extract but retain planning permission. Data filtration was carried out using the 'select features using an expression' feature of QGIS 3.22. Then, entries were filtered again based on their 'commodity type' and only quarries with commodities of 'Igneous and Metamorphic rocks' ('Basalt' in Northern Ireland) and 'Crushed rocks' were retained.

Given that the lithology of the quarry's product is not identified in BritPits, the dataset was cross referenced with the 1:50,000 geological map of the Great Britain (BGS, 2016) and 1:250,000 Geological map of the Northern Ireland (BGS, 2021). For this purpose, first, the map of geological units with potentially desired lithology for ERW were extracted from the geological map in QGIS. The details of selected geological units is provided in supporting information Fig. S1 and table. S1. Then, using the 'join attributes by location' feature of QGIS 3.22, each entry (quarry) of the filtered BritPits dataset obtained a corresponding lithology data from the lithology unit that spatially overlapped with it. The quarry entries which did not spatially overlap with the desired lithological units were omitted from the dataset.

Annual production from the identified quarries and their total reserve were compiled from local authorities planning databases (Argyll and Bute Council, personal communication; Falkirk Council, personal communication) and commercial reports of the UK's aggregate industry (BDS Marketing Research report, 2021). While this annual production data of basic silicate rocks contains the current production only (most data were for 2021), data of previous annual total crushed rock production in the UK were collected from (BGS Mineral Yearbook, 2018) in which the production data for three groups of rocks including sandstone, limestone and igneous rock are provided. Using the annual igneous rock production data and the BritPits dataset, we estimated the amount of basic silicate rock produced annually in the past. This was done by calculating the proportion of area of quarry working corresponding to the basic silicate rock sites to the area of all igneous rock quarries in the UK (using QGIS) and multiplying this proportion to the annual igneous rock production.

2.1.2. Artificial materials

The potential locations of production of CDW were estimated using a 10 × 10 km gridded building density map created by using the UK's building boundaries map (Ordnance Survey OS, 2022). In the building density map, each grid cell has a value representing the ratio of the total building area in each grid to the total area of that grid. Grids with higher than 10% building density are assumed to be the main locations of CDW resources in the UK. The location of legacy slag deposits which are present in proximity of current and former iron and steel working in the UK, were obtained from (Riley et al., 2020).

2.2. Transport distance of material from source to the application lands

The locations of basic silicate rocks (and their production sites) and legacy slags resources (Riley et al., 2020) are known. Centroid of 10 × 10 km grid cells with larger than 10% building density are assumed to be the primary locations of CDW production in the UK. The maps of Great Britain's croplands (Land Cover plus: Crops, 2021) and Northern Ireland's arable lands, extracted from the 20 m pixel rasterized land cover map (UKCEH, 2019) are used to extract the coordinates of the UK's croplands. Due the large number of entries in these maps which makes the transport distance calculations computationally intensive, we created a 10 × 10 km gridded map of the UK's croplands in which the area of croplands for each grid is known. The centroid coordinates of these grids are used for transport distance calculation purposes.

The road transport distance of individual material resources to each of the cropland grids were extracted by applying URL requests for routs (road transport was chosen as transportation mode) from the Bing Maps (www.bingmapsportal.com). An Application Programming Interface (API) was used for an automated data extracting process. In addition, distance between each cropland grid and the nearest resource of each group of material was similarly obtained.

2.3. Relative appropriateness of cropland grids for ERW

The transport distance between resources and croplands, temperature, water availability and the soil pH were considered as four factors that can control the net CDR potential in each cropland. 10 × 10 km gridded maps of temperature, rainfall and evapotranspiration were prepared for the UK based on (Buckingham et al., 2023). To estimate the water flux through different croplands, potential evapotranspiration was subtracted from the precipitation value (P – E) for each grid using the 'raster calculator' in QGIS. The 10 × 10 km gridded map of the soil pH was also generated using the soil pH map of the UK (Henrys et al., 2012). All calculated values of the four factors were normalised between 0 and 1 so that the higher normalised value represent more favourable condition for CDR namely the shorter transport distance, higher P-E, lower soil pH value (more acidic soil) and higher temperature. The relative appropriateness of cropland grids for ERW was calculated as S_{CDR} using Eq. (1), which describes the average of normalised scores of all factors including P-E (α), temperature (β), soil pH (δ)and transport distance (γ).

$$S_{CDR} = (\alpha + \beta + \gamma + \delta)/4 \quad (1)$$

The S_{CDR} was calculated and assigned to each cropland grid indicating the relative appropriateness of each cropland for CDR through the EW. Each factor was equally weighted (α, β, δ and γ equal to 1), but variations of weighting were considered in a sensitivity analysis (see supporting information Fig. S2)

2.4. Scoring environmental and social impacts of rock extraction

Scalable deployment of ERW in the UK will require the allocation of basic silicate rock resources, which may require a considerable increase in the rock extraction. To achieve this, we quantify the potential relative social and environmental impacts of current rock extraction sites through the attribution of environmental and social score.

Proximity of the quarries to the protected and designated areas in the UK may be a limiting factor for expansion of a quarry in future. To assess this potential environmental limitation, we employed a scoring approach consistent with the framework that BGS uses (Bee et al., 2010a) to evaluate decisions for aggregates working in designated areas. In this approach, quarries are classified based on their proximity to each of the protected and designated areas in the UK. Here, the distance of all active quarries with any of the designated areas in the UK was calculated in QGIS. For this purpose, we used the map of designated protected boundaries in the UK (See supporting information Fig. S3 and table. S2 for links to the data). Buffer zones of 1, 5 and 10 km were created around the boundaries of protected areas. Based on the distance of each quarry to each of the designation boundaries, arbitrary scores of 1 to 10,000 in a logarithmic scale were assigned to that quarry (see table. S3 in supporting information). The logarithmic distance score is consistent with dust concentrations from air-pollution dispersion models (Zhou et al., 2022). The total score of each quarry was calculated by summing the scores associated to the distance of that quarry to all designation boundaries. In this way, the quarries which are located very close to the protected areas will have higher score which indicates their lower chance to get approval for expansion in future. Given the relative nature of these scores, a comparison with a broader range of data can provide a better idea of the scale of these scores. For this purpose, the same approach was repeated to calculate the score for all the active mineral workings in the UK which were about 2123 quarries (extracted from BritPits dataset). The min, max and mean environmental scores associated with UK's active quarries, active and inactive basic silicate rock quarries are presented in table. S4 (supporting information).

The proximity of quarries to populated areas can directly contribute to potential social limitations that may arise in the event of quarry expansion. A similar process was used to investigate the potential social impact of each quarry by estimating the population living within 1, 2.5, 5 and 10 km from quarries using 'zonal statistics' feature in QGIS and the 1 × 1 km gridded population map of the UK (Reis et al., 2017). The final score for each quarry was then calculated by multiplying the number of people living in 1, 2.5, 5 and 10 km distance zones by arbitrary logarithmic scale scores of 1000, 100, 10 and 1 respectively. In this way, higher score will be an indicator of quarry's proximity to the populated area which indicates the higher chance for social limitations on quarry expansion.

To understand the social and environmental impact of rock extraction from other potential locations across the basic rock silicate rock outcrops in the UK, the 1 × 1 km gridded map of outcrops of these rocks were prepared. The social and environmental scores were then calculated (as explained above) and assigned to each grid.

3. Results

3.1. Spatial distribution of CDW resources

The spatial distribution of building density is shown in Fig. 1a. A small proportion of grid cells (below 2%) accounts for over 21% of the total built area. Handling and reuse of CDW is assumed to be constrained to the area with highest built density (assumed here to be >10%).

3.2. Inventory of basic rock quarries

68 active and 100 inactive quarries were identified as quarries with the desired commodity product for ERW. Fig. 1a shows the location of retained active and inactive quarries and how they spatially overlap with basic silicate rock outcrops. Most of the quarries are located in Northern Ireland and the central belt of Scotland. Numerous inactive quarries are situated in proximity to active quarries, which may indicate that they are not distinct sites but an artefact of registration with BritPits (e.g., organisations extracting rock from a common site at different times).

Annual production of active quarries and the size of their permitted reserve is presented in Table 1, Fig. 1b and c. Due to confidentiality, the data are not presented for each individual quarry but by district and country. 14.8 Mt of basic silicate rock are estimated to be extracted from the 68 active quarries in 2021 with a total of 352.6 Mt of permitted reserves. This estimated production value is consistent with annual production estimate based on the yearbook data (BGS Minerals Yearbook, 2018) of igneous rock production which suggests an approximately 16.6 Mt of basic rock produced in 2018. 12 top-producing counties account for about 80% and 77% of the total production and total permitted reserve of basic silicate rocks in the UK respectively.

The recent (2021) production capacity of active quarries shows considerable variation ranging from 6000 to over 800,000 tonnes of rock extracted (see supporting information Fig. S5). 18 quarries (out of the 68 active quarries) with production capacity range of 250 to 500 thousand tonne of rock per annum, account for about half of the total basic silicate rock production in the UK. The top 24 quarries with capacity of over 250 thousand tonnes of rock per annum account for about 70% of both the total production and total permitted reserve of basic silicate rocks in the UK. While the UK hosts several 'super quarries' (>1Mt yr^{-1}), none extract basic silicate rock.

The extracted basic silicate rocks are currently used for various construction application including road base, track ballast or as aggregate in asphalt and concrete. Quarry fines are typically produced during crushing and screening, which consist of small particles that are typically smaller than 5 mm, and have low market value and utilisation. Mitchell, (2009) indicated that the ratio of the fines to the total crushed rock produced in the igneous crushed rock quarries in the UK is around 25%, which suggests around 3.7 Mt yr^{-1} of basic silicate waste fines may already be available for ERW in the UK.

The maximum CDR potential of rocks via enhanced weathering which is defined as R_{CO2} (tCO_2 captured per t of rock) is dependant on their geochemistry. The resources of basic silicate rocks in the UK are associated with different geological units with varying geochemistry and lithology which are summarised in table. S1 of supporting information. The major lithologies are basalt, dolerite, gabbro and micro-gabbro which are primarily composed of olivine, plagioclase, clinopyroxene, orthopyroxene and augite. A wide range of R_{CO2} (0.23 – 0.82 tCO_2 $tRock^{-1}$) is calculated for these rock units (Renforth, 2012). These values rely solely on geochemical indices and do not necessarily indicate the material's reactivity.

3.3. Transport distance of material from source to the application lands

The distance between the sources of materials and the application sites (croplands), directly influences the costs and amount of CO_2

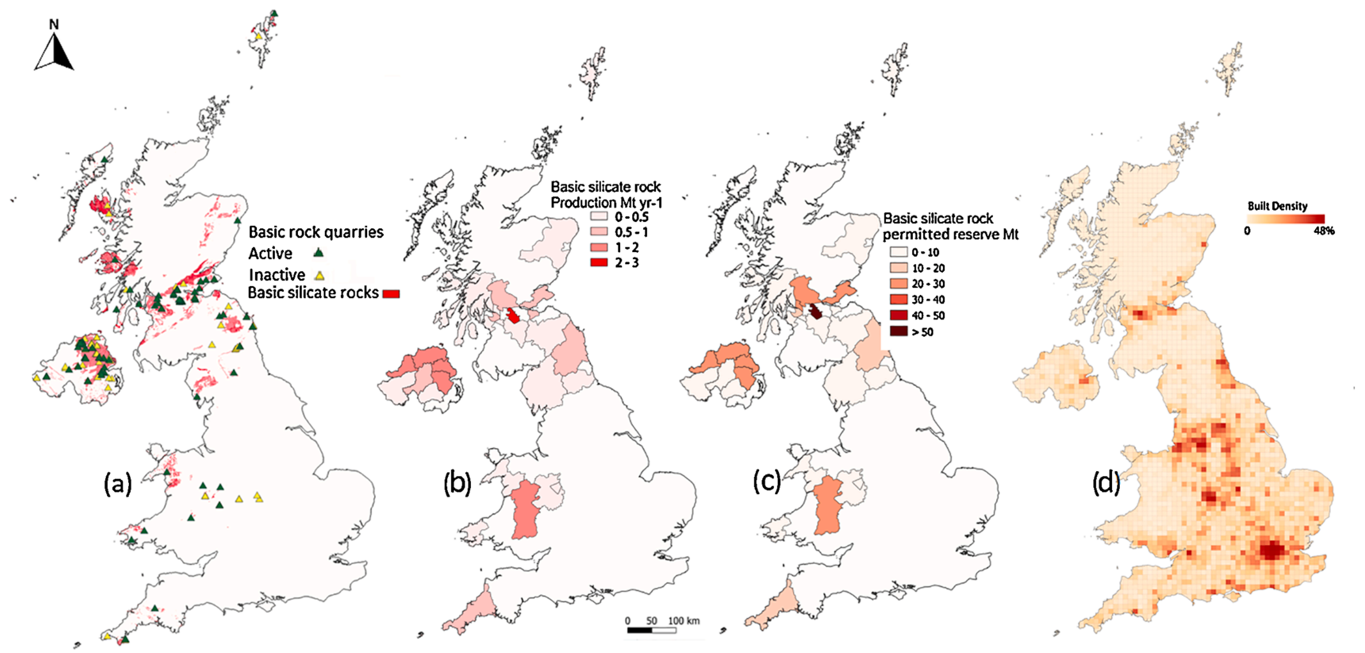

Fig. 1. The distribution of a) of active and inactive basic rock extraction sites, b) production of basic rock by region, c) permitted reserves by region and d) built density indicating the main potential locations of CDW production.

Table 1
Basic silicate rock production and permitted reserve in the UK by region.

Country	Active*			Inactive		District Name	Production Mt	Active Reserve Mt	Inactive Reserve Mt
	No. of quarries	Production Mt	Reserve Mt	No. of quarries	Reserve Mt				
England	9	2.06	49.7	19	93.55	Cornwall	0.60	13.1	34.3
						Northumberland	0.71	11.75	57.85
						Warwickshire			1.4
						others	0.77	24.85	
Scotland	31	6.78	193.99	21	43.2	Argyll and Bute	0.06	2.0	
						Edinburgh	0.80	7.0	15
						Fife	0.42	12.62	
						North Lanarkshire	4.91	81.3	
						Renfrewshire	0.97	16.19	
						Scottish Borders	0.22	8.9	4.8
						Stirling	0.98	24.8	23.4
						Others	1.06	38.57	
Wales	5	1.68	33.13	2		Powys	1.11	20.2	
						Pembrokeshire	0.32	8.03	
						Others	0.26	4.9	
NorthernIreland	23	4.35	75.23	58		Antrim	1.38	26.73	
						Mid and East Antrim	1.14	20.77	
						Causeway Coast and Glens	1.47	22.61	
						Others	0.35	5.12	
UK	68	14.87	352.6	100	136.75				

'active' refers to sites which are actively extracting a mineral.
'Inactive' refers to sites which are not extracting minerals, but which still have a valid planning permission to do so, and can restart at any time.

emissions associated with their transportation. The minimum and the mean transport distances are shown in Fig 2. The nearest resource map (Fig 2a-c) shows how the alkaline materials may be supplied from the nearby resources to minimise the transport distance and its corresponding cost and CO_2 emission as a result. The cumulative area of arable lands located in varying distances from the material resources is also calculated (Fig. 3). Based on these results, the area of arable lands that can be accessible by a given transport distance from the quarries can be quickly extracted. For instance, over 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. However, feasibility of sourcing all the needed materials from nearest resources is dependant on the supply capacity of each resource and the ability to upscale if needed. For example, the supplying capacity of only a few basic silicate rock quarries (total production of 600 kt yr^{-1}) in the southwest of England may not meet the demand of crushed rock for ERW in all the nearby croplands (e.g. 10,000 ha within 100 km, would require 400 kt yr^{-1} for an application rate of 40 t ha^{-1}), while meeting the existing demands from the local rock aggregate market. As such, the average transport distance from each cropland grid to the location of all resources within each group of material is also shown (Fig. 2.d-f). The map indicates that in case of insufficient supply from the nearby resources, some areas (e.g.,

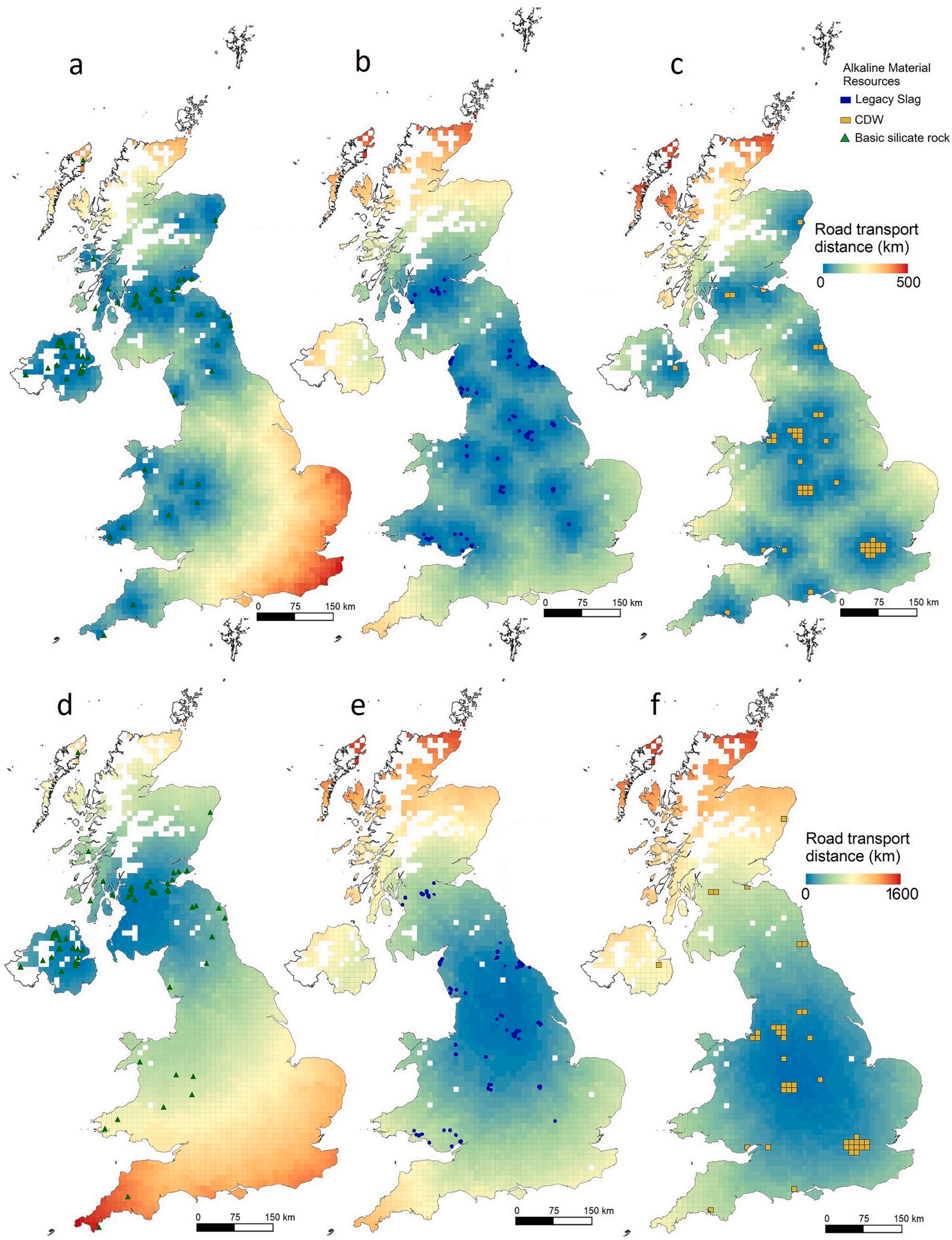

Fig. 2. Minimum transport distance between the UK's croplands and nearby resources of basic silicate rocks (a), legacy slags (b) and CDW (c). Mean transport distance between the UK's croplands and all resources of basic silicate rocks (d), legacy slags (e) and CDW (f).

South Wales, South West England) may not be suitable for ERW. It also highlights that South East England may be unsuitable for basic rock spreading, but potentially appropriate for CDW materials. These discrepancies suggest that there may be a need for alternative methods of transport for scalable operation of ERW (e.g., dedicated shipping) between Northern Ireland or Scotland, and the South West and South East of England.

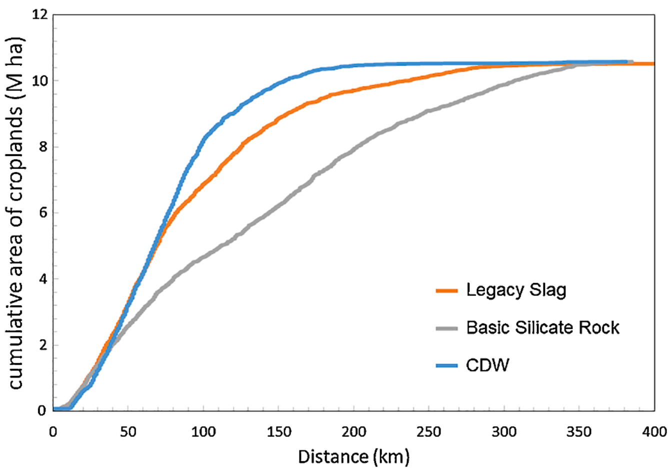

Fig. 3. Cumulative area of arable lands located in varying radius distances from resources of basic silicate rock, legacy slag and CDW.

3.4. Environmental and social impacts of scaled-up rock extraction

Social and environmental scores of 68 active and 100 inactive quarries of basic silicate rocks are presented in Fig 4. The scores associated with all UK's active quarries are also plotted along with a dashed line indicating their average scores. Environmental or social scores above the UK's average scores may be considered as a potential environmental or social constraint, especially in cases of quarry expansion. As shown in Fig 4.a, inactive quarries have slightly higher environmental score than active basic silicate rock quarries, but both have generally smaller environmental score compared to the UK's active quarries. Approximately over 80 percent of basic rock quarries have environmental score smaller than average score of UK's active quarries. Somehow same trend can be observed for social scores with over 90 percent of basic rock quarries having social score smaller than UK's average score (Fig. 4.b). Fig. 4.c,d shows the scores plotted versus the associated production and permitted reserve of basic silicate rock quarries. It is observed that over 85 and 95 percent of current production and reserve of basic silicate rocks are associated with quarries with below-the-UK's-average environmental and social scores respectively. The scores attributed to the outcrops of basic silicate rocks are also plotted vs the cumulative outcrop area in Fig. 4.a,b. From 10,180 km^2 of outcrops, only ~4200 km^2 have environmental scores below the UK's average score. On the other hand, the outcrops have significantly smaller social score compared to all quarries. The average (area weighted) social score of all outcrops is ~420,000 which is far lower than the UK's quarries average score (2717,620). Only a small proportion of the outcrops area (~400 km^2) has above-the-UK's-average social score.

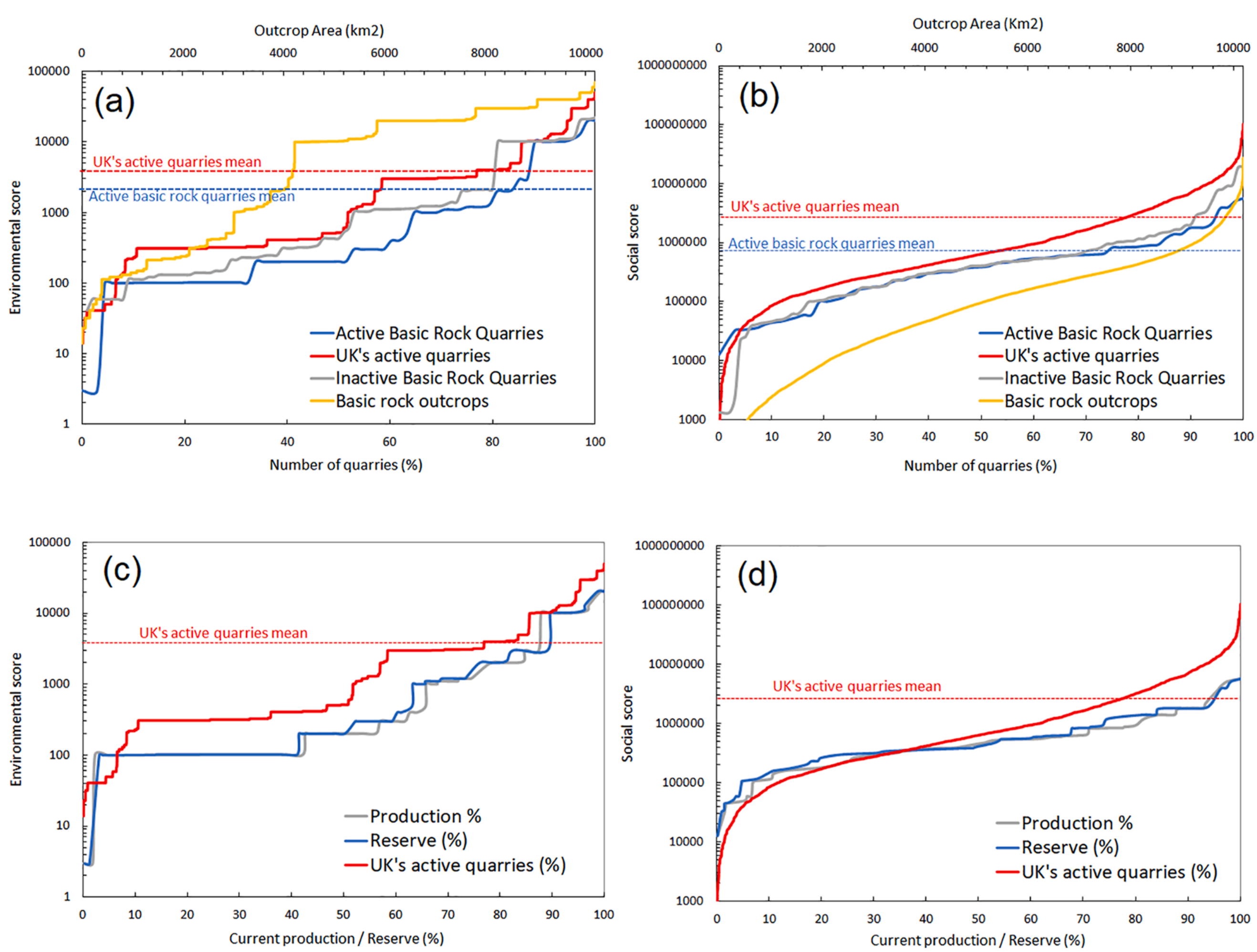

Fig. 4. Environmental (a) and social (b) scores associated UK's active quarries, active and inactive basic rock quarries and the outcrops of basic rocks in the UK. The average scores of UK's quarries and currently active basic rock quarries are indicated by dashed red and blue lines respectively for comparison. Environmental (c) and social scores plotted vs production and reserves. All x axis represents cumulative values.

3.5. Relative appropriateness of UK croplands for CDR through EW

The UK has about 10.5 million hectares of croplands which are not evenly distributed across the UK (see supporting document Fig. S6). Given the recommended amount of crushed rock applied per hectare of cropland is around 40 tonnes per year, and by assuming a 10 - 20 Mt of rocks to be applied annually (Kantzas et al., 2022) for EW in the UK, about 0.25–0.5 million hectares of croplands would be required which is only a small proportion of the UK's croplands. This may provide an opportunity to optimise deployment for those croplands that can provide higher CDR efficiency. Giving equal weighting to factors that might influence the CDR potential of ERW including temperature, P-E, soil pH and transport distance, the relative appropriateness of the UK croplands is shown in Fig 5. As shown in Fig. 5, croplands located in the west central Scotland, northwest of England and northwest of Wales appear to be the most appropriate locations for application. Croplands on the north of Scotland, west and south west of England appear to be the least appropriate.

A sensitivity analysis of changes in the relative weighting of factors is included in the supporting information. The results (see supporting information Fig. S2) suggest a sensitivity to different weights both in terms of the absolute scores and spatial distribution of scores. For instance, croplands in the south, south east and south west of England return higher scores when the greater weight is assigned to the temperature. Apart from a few exceptions, generally a similar distribution of scores can be found for most of the weighting configurations.

4. Discussion

4.1. Scalability of basic silicate rock supply

Based on mineral yearbook (BGS Mineral Yearbook, 2018) data (see supporting information Fig. S7.a), the annual production of crushed rock in the UK has decreased from ~200 Mt to ~125 Mt since 1990. This trend exists for all categories of crushed rocks including igneous crushed rock (equating to a decrease from ~1 to 0.56 t/capita year). Also, based on the data from Annual Mineral Statement provided by the Department for Economy of Northern Ireland (DfE, 2021) the annual production of basalt and igneous rock (excluding granite) has decreased from ~ 6.5 Mt to ~ 3 Mt in since 2001 (see supporting information Fig. S7.b). Assuming that per capita rock extraction decreases by a further 50% by 2050, and that the UK's population grows to approximately 76 M by 2050, spare capacity within the sector for ERW may be approximately 6.5 Mt yr^{-1}. Combined with waste fine production of about 25% (~2 Mt yr^{-1}), the total basic silicate rock production without expanding capacity may be approximately 8.5 Mt yr^{-1} by 2050. While current waste fines production (~3.7 Mt yr^{-1}) can partially fulfil the short-term demand of crushed rock for EW in the UK, the production of basic silicate rocks would need to increase by ~ 30 - 170 to meet the extraction scenarios outlined in (Kantzas et al., 2022). This may require production intensities in quarries to be expanded, inactive quarries to be reopened, or new extraction sites to be developed The environmental and social impact scores calculated in this study (Fig. 4), can be useful in this decision-making process. In fact, a wide range of scores calculated for social and environmental impact (Fig. 4) of quarries and outcrops offers an opportunity to optimise the scalability of rock production in a way to minimise the social and environmental impact.

The mineral reserve with existing planning permission is an important factor in insuring the feasibility of up-scaled supply of crushed rock. Great Britain has approximately 2 Gt of igneous rock reserves (out of approximately 5 Gt for all rock types), and 140 Mt of igneous rock reserves received planning permission between 2017 and 2021 (BDS Marketing Research report, 2021). Currently, 352.6 Mt of reserve is associated with active basic silicate rock quarries identified in the UK (equivalent to approximately 23 years of production). Only 10 out of 100 inactive quarries have data available for permitted reserves with a total reserve of 136.7 (but potentially >1Gt if undocumented inactive quarries retained similar amounts of reserves) Mt. But these are only small proportion of the total resources of basic silicate rocks in the UK which is estimated to be around 1700 Gt (Renforth, 2012). Planning authorities are required to maintain consent for 10 years demand. Assuming that current rates of granted extraction permissions are retained until 2050 (e.g., 15 Mt yr^{-1}), an additional cumulative 390 Mt of rock may have received planning permission.

The currently identified permitted reserve of ~490 Mt can meet the cumulative demand of basic silicate rocks for EW for all extraction

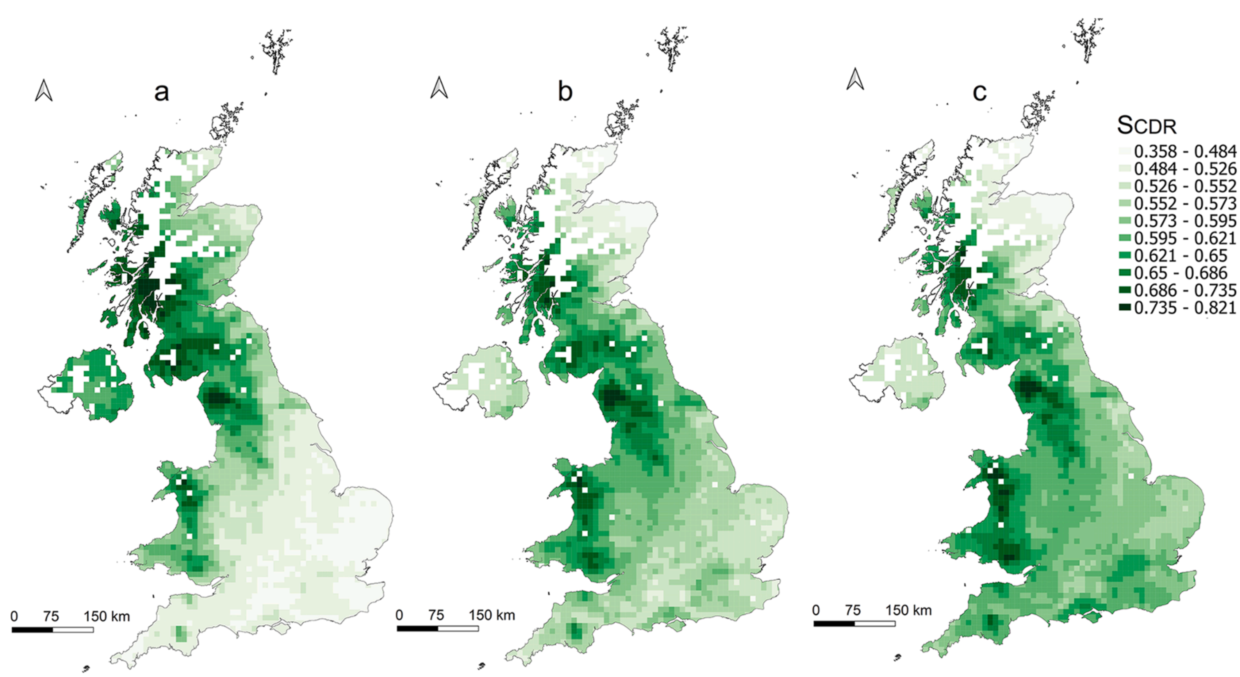

Fig. 5. Relative appropriateness of the UK's croplands (10 × 10 km grids) for ERW via application of basic silicate rocks (a), legacy slags (b) and CDW (c) on croplands.

scenarios of (S1, S2 and S3) suggested by (Kantzas et al., 2022)until 2034 by assuming a constant demand of ~14.8 Mt yr^{-1} for other consumption. This means that new permit applications need to be made as soon as possible to insure the fulfilment of incremental demand thereafter.

The quantity of basic silicate rock resources does not seem to limit the deployment of EW however, environmental and social limitations might exist in exploitation. Findings of this paper indicate that over 58% the basic rocks' outcrop area (~5980 km^2 of ~10.180 km^2) has an environmental score higher than the mean score associated with UK's active quarries. It should be noted that the slight discrepancy in estimated area of basic silicate rocks outcrop between this study (10.180 km^2) and Renforth (2012) (11,152 km^2) is due to using the geological maps of different scale (1:50 k & 1:250 K maps in this study and 1:625k map used in Renforth, 2012). But our finding is consistent with (Renforth, 2012) in which considerable proportion of these resources are identified to be under land-use with an environmental designation. We expect this as a potential limitation in obtaining planning permission for exploitation those proportion of outcrops. The remaining ~4200 km^2 of basic silicate rock outcrops with lower than mean environmental score is still considerable amount and can provide up to ~ 630 Gt of basic silicate rock resources given a density of rock of 3 t m^{-3} (Sloane, 1991) and assuming a 50 m mining depth. It is noteworthy that more than 95% of these outcrops exhibit social scores that fall below the mean social score attributed to UK's active quarries, thus suggesting a comparatively lower incidence of social constraints pertaining to their exploitation.

The cost of rock extraction as another possible limitation for exploiting these resources is not discussed here and the reader is referred to (Beerling et al., 2020; Renforth, 2012). While the current permitted reserve can meet the short-term demand for EW in the UK, the up-scaled supply of crushed rock for EW require obtaining new planning permission which requires consideration of possible environmental and social limitations.

4.2. Potential social and environmental constraint for rock extraction

As shown in the results, over 85 percent of current production and reserve of basic silicate rock in the UK are associated with quarries that have social and environmental scores below the average score of the UK's active quarries. This suggests that potential environmental and social constraints have already been considered during the authorization of planning permission for rock extraction. As suggested by (Bloodworth et al., 2009), increasing pressure from demographic factors in the UK affect the public perception and acceptability of mining and quarrying activities which result the spatial planning system to be influenced by these concerns, as well as the relationship between mining, other land uses, and official designations. Most of quarries extracting aggregate tend to be located close to the demands area, usually at distances less than 50 km (Escavy et al., 2022). We speculate that this might be a reason for most of the active basic rock quarries to have higher environmental score compared to the average social score associated with basic rock outcrops. It is possible that locations of current rock extraction are somewhat optimised for lower environmental and social impact, and pathways for scalability may also focus on opening new sites given the very low social scores associated with most of the outcrop's grids.

The environmental scoring approach is consistent with categories used by BGS (Bee et al., 2010) in planning decisions, and can be used an indicator of relative favourability of approval for future planning permission applications. Social impact scoring of rock extraction has been simplified by quantifying only the population affected by rock extraction activities and not accounting for the nature of the relationships between quarries and their communities. Given the incremental demand of communities in being involved in decision-making of quarries' operations, the nature of the relationships between quarries and their communities may need to be well considered to obtain the social licence to operate (Moffat et al., 2016) for up-scaled production of basic silicate rocks. It is also important to note that the social and environmental impacts assessed in this study pertain exclusively to the process of rock extraction and do not take into account the impact of the entire ERW cycle.

4.3. CDW and slag resources in the UK

Total current production of CDW (Department for Communities and Local Government, 2005) is around 80 Mt yr^{-1} in the UK, the majority of which is recycled into secondary aggregate. The potential locations of resources of CDW are associated with high building density. While the grid cells with higher than 10% building density cover just over 21% of UK's built areas, it is expected that these grid cells account for higher proportion of UK's building volume given the higher average building heights in these regions (https://buildingheights.emu-analytics.net). Also, as seen in Fig 1d, the built density gradually decreases with distance from the highest values. Accordingly, the location of these grid cells may be a good representation of the spatial distribution of the majority of CDW resources in the UK.

The feasibility of exploiting the CDR potentials of CDW resources in the UK will be however dependant on the availability of materials, their chemistry and potential contamination risk, processing requirements, and economic viability. High economic costs and embodied carbon costs (due to producing large amounts of new materials) of building new structures may be resisting factors against demolition (Power, 2008) that can constrain the availability of CDW. Recovering cement from CDW through post demolition processing may be costly and energy consuming. However, growing interest in recycling these materials for producing aggregate (Lawson et al., 2001; Contreras Llanes et al., 2021, Silva and Brito, 2015) may have an important role in reducing the cost and carbon footprint of recovering cement from CDW to be used for ERW. For instance, waste fines produced during recycling CDW for aggregate production, (0 - 4 mm) for which there is no considerable high-quality application at present (Lotfi and Rem, 2016). The cementitious powder that needs to be separated from the coarser particles to provide a high-quality aggregate may be used for ERW at very low economic and carbon cost.

4.4. Appropriateness of croplands for CDR

Here, the temperature and rainfall are considered to be directly related to the rate of weathering while the soil pH and evapotranspiration is considered to be reversely related to the rate of weathering. The effect of temperature on silicate weathering has been studied in laboratory experiments (Brady and Carrol, 1994) and field studies (Turner et al., 2010). Furthermore, the higher the moisture content of soil, the greater the rate of silicate weathering due to increased water availability for chemical reactions to occur. Quantifying the precise impact of temperature or moisture content on the rate of weathering in field is challenging due to the multiple variables interplay. For instance, the effect of temperature on natural silicate weathering is found to be substantial (Turner et al., 2010)over a temperature range of 3° to 22 °C only where the topographic conditions are favourable to weathering, rainfall amounts are high, and evapotranspiration is low. The appropriateness score for CDR of the UK's cropland presented in this study were found to be sensitive to the weight given to influencing parameters like temperature and moisture content. However, the general pattern in distribution of CDR scores presented in Fig. 5 is found representative of most of the weight configurations.

It should be noted that the maximum CDR potential of rocks (R_{CO2}) can play a role in net CDR via ERW. In fact, it controls the amount of rock to be used to achieve a given CO_2 removal target. Given the wide range of R_{CO2} of basic silicate rock units in the UK, the net CDR via ERW for the unit mass of rock extracted and transported from different quarries would be different. For instance, utilizing an equivalent amount of rock extracted from the Lizard Gabbro unit (RCO2 of 0.7) can yield more than twice the CDR compared to rock from the Antrim Lava Group (RCO2 of 0.3). This can influence the net CDR and its associated cost by controlling the amount of rock extracted and transported per unit mass of CO_2 removed. While this aspect is not specifically considered in this study, it can be an interesting area for future research. The exploration of these factors can have implications for the optimisation of rock extraction expansion strategies which is crucial for up-scaled ERW in the future.

5. Conclusions

A high-resolution spatial inventory of the basic silicate rock resources in the UK along with the current production capacity and permitted reserves is presented in this paper. From the current basic silicate rock production of approximately 14.8 Mt yr^{-1}, estimated waste fine production of 3.7Mt yr^{-1} could be exploited for early stage ERW deployment in the UK. Some production capacity could be allocated for ERW without impacting current aggregate supply due to the potential decrease in demands for crushed rock in the coming decades, which together with waste fines could deliver up to 8.5 Mt yr^{-1} of basic silicate rock by 2050. While this can partially meet the UK's demand of silicate rock for ERW, the up-scaled deployment of ERW will require expansion in rock extraction. The currently identified permitted reserve of ~490 Mt can meet the cumulative demand of basic silicate rocks for EW for all extraction scenarios of (S1, S2 and S3) suggested by (Kantzas et al., 2022) until 2034 by assuming a constant demand of ~14.8 Mt yr^{-1} for other consumption. This means that new permit applications need to be made as soon as possible to insure the fulfilment of incremental demand afterwards.

Assessing the potential environmental and social impacts of expanded rock extraction revealed a relatively low environmental and social impact associated with basic silicate rock extraction compared to average impact associated with all active mineral workings in the UK. This means that most of basic silicate rock extraction sites are located further from protected environments and densely populated areas. This also suggested potential for approval for future extension applications.

A significant spatial variation was found in CDR potential across the UK's croplands. Equal weighting of factors influencing CDR potential, such as temperature, P-E, soil pH and transport distance, revealed that croplands in west central Scotland, northwest England, and northwest Wales are potentially the most appropriate locations for ERW application, while croplands in the north of Scotland, west, and southwest England have lowest potential. This significant spatial variation highlighted the opportunity for optimizing deployment for higher CDR efficiency. Applying ERW on croplands with highest CDR potential may be possible given that only a small proportion (~ 2 - 4%) of the UK's croplands will be needed for deployment of ERW based on 10–20 Mt yr^1 rate of rock application scenarios in (Kantzas et al., 2022). Overall, the result of this study highlights the necessity of granular studies of national potential of ERW in which aspect of deployment from rock extraction to the application as well as potential limitation are assessed in high spatial resolution.

CRediT authorship contribution statement

Mohammad Madankan: Conceptualization, Investigation, Methodology, Software, Formal analysis, Validation, Visualization, Writing – original draft. **Phil Renforth:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mohammad Madankan reports financial support was provided by UK Research and Innovation. Phil Renforth reports financial support was provided by UK Research and Innovation. Phil Renforth reports a relationship with UK Research and Innovation that includes: funding grants.

Data availability

Data will be made available on request.

Acknowledgment

PR and MM acknowledge funding from UKRI for the Industrial Decarbonisation Research and Innovation Centre (EP/V027050/1), and Greenhouse gas removal with UK agriculture via enhanced rock weathering project (BB/V011359/1).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2023.104010.

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