Response to Comment from West et al. on "Soil core study indicates limited CO_2 removal by enhanced weathering in dry croplands in the UK".

We thank West et al. 2023 for their interest in our paper (Buckingham et al. 2022), and we share their view that assessing the potential for enhanced weathering (EW) as an approach to greenhouse gas removal (GGR) is important. We refute their assertion, however, that our observational study is flawed. Carefully measured and fully-reported observational studies of EW, such as that in our study, are critical for accurate assessment of this GGR technique, and to refine models used to calculate its wider potential.

We structure our response in four sections to address the issues raised by West et al. and to identify future research areas for further assessment of the potential for EW in the UK.

1. Hydrology and water flux

1.1. How were water fluxes assessed in Buckingham et al. 2022?

West et al. (2023) are concerned that the experimental design of our study leads to incorrect water fluxes. We are confident that the water fluxes through our cores are well constrained, similar to nearby agricultural fields, and with an accurate Q value (i.e. precipitation minus evaporation and transpiration). Prior to our EW study, the water flux through a representative soil core, located at the same roof-top location, was measured gravimetrically for a period of three months. The mass of the core, the mass of rainfall falling on the core, and the mass of effluent water leaving the core at its base were measured. Mass balance then constrains evapotranspiration (i.e., ET = rainfall – effluent – change in mass of core). These measured evapotranspiration values for our core were comparable (±2%) to a nearby grassland site, Chimney Meadows (CM), regularly monitored by UKCEH. This suggests the experimental set-up did not significantly enhance evaporative losses relative to the field site and are well constrained at 57 mm/yr. This value is also consistent with the volume of waters collected from the cores at their base and by rhizon samplers. This triple approach (i.e., by mass, by proxy field data, and by direct water volume) make the Q value unusually well constrained in the Buckingham et al. (2022) study.

1.2. Is the Buckingham et al. (2022) water flux reasonable for a typical UK cropland?

The UK experiences a wide range of rainfall and evapotranspiration fluxes. The resulting range of UK Q values is plotted in Figure 1 (by cropland because it is normally assumed that EW will be conducted on farmed land), and mapped in Figure 2 to show spatial variation. Values of Q range from 0 to >1,000 mm/yr in cropland areas, with a 95 percentile range of 46 to 1042 mm/yr. The value of 57 mm/yr for the Buckingham et al. study is therefore at the dry end of UK water flux, as described in the title and extensively elsewhere in that paper, but is within the normal range of UK cropland. This is particularly true for cropland in the southeast of England. We note with interest, for instance, that the observationally constrained Q value for the Harpenden site (shown in Fig 1 of West et al.) is even drier than our study, with an average of 37 mm/yr for the period 1971 to 2000 (Perryman et al., 2019). Overall, we believe that the water flux for our study is well within the range of UK farmland and that our study is therefore a useful observational constraint on the potential for EW in the UK, particularly for drier areas such as SE England where there is a particular concentration of farmland.

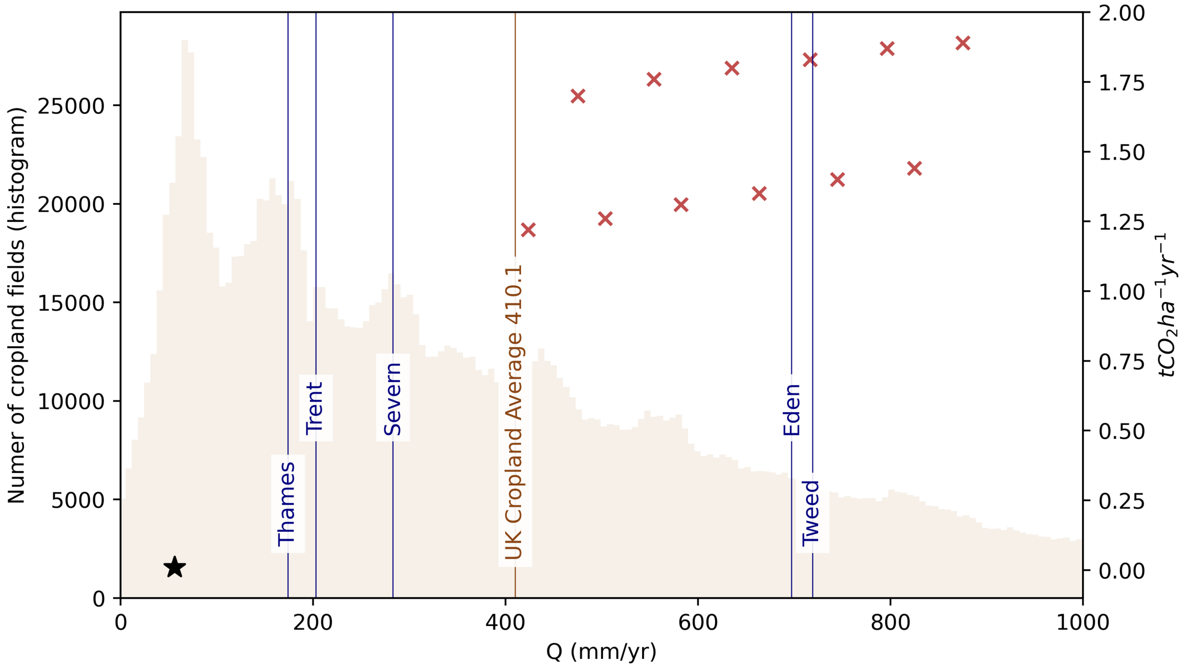

Figure 1: A histogram of Q values for UK fields, compared with modelled and observed CO_2 removal fluxes. The histogram is calculated from 5-km gridded mean annual precipitation data (Met Office et al. 2022) and mean annual potential evapotranspiration (Tanguy et al. 2017) for the period 2010 – 2015. For total UK land area, precipitation, evapotranspiration, and P-E were consistent with the values reported in Blyth et al., (2019). Cropland spatial data was sourced from UKCEH Land Cover plus Crops (2021) for Great Britain and UKCEH Land Cover Map for Northern Ireland (Marston et al., 2021), and P-E information are interpolated for the centroid of each field (n > 1,600,000 points). Average Q values for the UK and five example catchments are shown for reference. CO_2 removal fluxes are plotted as crosses (the modelled sensitivity analysis presented in Kantzas et al. for higher Q values) and as a star (the observed value for drier conditions of Buckingham et al. 2022).

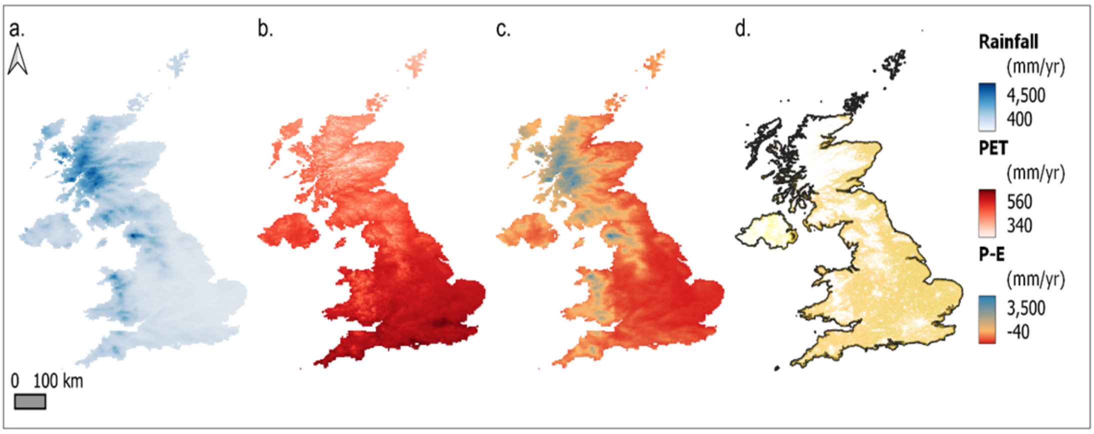

Figure 2: Geospatial distribution of a) UK precipitation from 5-km grid cells (Met Office et al. 2022), b) UK potential evapotranspiration (PET) from 5-km grid cells (Tanguy et al. 2017), c) precipitation minus potential evapotranspiration (P-E), and d) cropland at field scale resolution, sourced from UKCEH Land Cover plus Crops (2021) for Great Britain and UKCEH Land Cover Map for Northern Ireland (Marston et al., 2022).

1.3. What is the average water flux for UK farmland?

We have been puzzled about this question because West et al. (2023) cite a typical Q value for central UK farmland of 700±30 mm/yr, based on NFRA data, while Buckingham et al. (2022) used the same NFRA data to assess a UK cropland value of 235 mm/yr. We have carefully recalculated our previously published number using all UK river catchments. In doing so, we found a systematic error due to the fact that river fluxes are sometimes constrained by a measurement station not at the coast. This means that NFRA river data slightly under-estimates the total water flux leaving the UK because it omits flow from the most coastal parts of some catchments. We now correct for this effect by using reduced catchment areas, representing the catchment area above the last measurement station for each river. This more correct calculation assesses average Q values, by area, for UK farmland of 345 mm/yr. We believe this value is the most accurate observational constraint on average UK Q, though it omits the reasonably small amount of water which flows to groundwater.

We compare this value with two modelling approaches; precipitation minus evaporation results from the CLM5 model (i.e. the hydrology model used in Kantzas et al., 2022) and the GIS-based calculations described above (for which results are shown in Figure 1 and Figure 2). Average values for these two models bracket the observational value from riverine fluxes (Table 1). We note that all values for average Q for UK farmland are significantly lower than the 700 mm/yr values of West et al. and question the origin of that number.

Buckingham et al. reached the conclusion that water fluxes were a critical control on potential for EW. We believe it will be particularly important to constrain water fluxes accurately in all future observational and modelling studies. As the data in Table 1 indicates, such constraint can be difficult to achieve at both local and national level, with assessment for Q varying between models, and relative to observations.

It will also be important to conduct observational studies in wet UK conditions, to complement that in the dry conditions of Buckingham et al. 2022.

	a) Calculated Q (GIS)	**b) Measured P-E**	**c) Calculated Q (CLM5)**	**d) Inferred flux, Rothamsted (2010-2015)**
Harpenden	130.9	37	9.8	221
Brooms Barn	19.4	-	6.5	51
Woburn	43.9	-	6.4	166
Oxford	99.8	57	10.3	-
UK cropland	410.1	345	153	-

Table 1: Water flux, Q (i.e. precipitation minus evapotranspiration; mm/yr) for key sites and for average UK farmland. a) Q, calculated from gridded precipitation and potential evapotranspiration data as in Figure 1. b) Q, measured at Harpenden, averaged between 1971-2000 (Perryman et al., 2019); measured at Oxford, between Feb 2019 to Jan 2022 (Buckingham et al., 2022); averaged over UK cropland using river flow data from the entire NRFA database (NRFA, 2022), with a median of 46 years of observations available for each river. River flux is calculated as the annual river volume at the most seaward measurement station, divided by the area of catchment above that measurement station. c) Q, calculated from CLM5, as used in Kantzas et al. (2022). d) Inferred water flux, using precipitation data and inferred actual evapotranspiration collected from Rothamsted between 2010-2015 (Perryman et al., 2019).

2. Secondary impacts on soils

West et al. (2023) point to the observation, made in Buckingham et al (2022), that some carbonate formation might occur at the base of the soil cores. We conducted post-experiment measurements (XRD and PHREEQC) but were unable to directly observe any such additional carbonate formation. This is challenging to observe after only one year of experiment and is also challenging to model because kinetic inhibition is well known to slow calcium-carbonate precipitation in natural waters. Such carbonate formation is an important question for future research because, as West et al. (2023) state, it represents an additional form of GGR (though only about half as effective as that from Ca^{2+} that remains in solution), but also because carbonate formation in soils will alter the long-term chemistry of the soil with potential implications for crop growth.

It is also important to assess the chemical adsorption of ions released during enhanced weathering, and the growth of secondary silicates, both of which lead to long-term changes in the soil. Our soil-core experiment demonstrate that, in dry UK conditions, dissolution of silicate is slow, leading to significant residual silicate in the soil for many years. The combination of remaining silicate, and the formation of secondary minerals (carbonates and silicates), will lead to fundamental changes in soil chemistry and structure if EW is pursued for multiple years. Our study indicates how critical it will be to the long-term security of crop growth to further assess these changes in the soil.

3. Model-data comparison

The Buckingham et al. (2022) soil-core experiment was not set up to test any specific model, and was initiated 4 years before publication of the modelling study of Kantzas et al (2022). Our study does, however, provide valuable input for such models. Important variables that are measured and reported include:

- The grain size and surface area of the added basalt
- Water flux
- Soil chemistry
- Ion chemistry of water in the soil and exiting the base of the cores

We expect that these measurements will provide a valuable test of the performance of many models seeking to assess enhanced weathering. It would, for instance, be interesting to test the performance of the 1-D geochemical reaction-transport model underpinning Kantzas et al. (2022) against the observations made in our study.

4. Extrapolation to the UK

We fully accept that extrapolation from any one site to the whole UK is challenging and uncertain. The limitations of doing so are clearly stated in Buckingham et al. (2022). As stated in that paper, further observational assessments will be required in a range of soil-types, climate conditions and water fluxes to better test and refine such extrapolations. This is demonstrated in Figure 1, which shows the wide range of Q values to be assessed, and the potential for mismatch between modelled and observed CO_2 fluxes, which will be influenced by the choices of mineral chemistry, grain size, spreading rates, and soil type amongst other variables.

A key conclusion of Buckingham et al., is that the water flux is of fundamental importance in controlling the rate of EW, and therefore particularly important to consider in any extrapolation. In the absence of other constraints, we used a simple relationship and assumed that weathering rate increases linearly with water flux. We defend this as a reasonable first approach to extrapolate from our observational assessment of EW. We recognise, however, that the relationship is likely to be more complex. This is another question where a combination of models and observations will be important to provide tighter and more robust assessments of the potential for EW as a GGR approach for the UK (and more widely).

Assuming that the revised Q value for UK cropland , as described above (345 mm/yr; NRFA, 2022), is the most representative water flux for EW, we re-calculate the UK CDR potential to be 1.9 ± 0.1 $MtCO_2\ yr^{-1}$ (rather than the 1.3 ± 0.1 $MtCO_2$ reported in that paper). This higher value uses a linear relationship between weathering and water flux, as in Buckingham et al. 2022, and therefore includes the same limitations identified in this response and in Buckingham et al. (2022). It is worth noting, however, that strategic EW deployment will need to consider the play-off between water flux, carbon removal and lifecycle emissions to fully assess the contribution of EW to UK net-zero targets. For example, practical application of crushed particulates may initially focus on large arable areas to reduce emissions associated with transport and distribution; but >20% UK arable land spans five river basins which have an average Q below the UK average (241 mm/yr; NRFA 2022), and may therefore have a slower weathering rate relative to other arable sites with a greater water flux.

5. Conclusion

We have addressed key concerns raised by West et al. (2023) and are confident the experimental methods and interpretation of results in Buckingham et al. (2022) were fully appropriate for the objectives of the study. Water flux was identified as a fundamental control on the CDR potential of EW in Buckingham et al., (2022). In this response we use GIS-based and CLM5 model data to demonstrate that the well-constrained water flux of Buckingham et al. is within the normal range for UK cropland. The average water flux over UK farmland has been carefully recalculated to 345 mm/yr, and application of this to findings in Buckingham et al. (2022) results in a similarly low rate of carbon removal (1.9 ± 0.1 $MtCO_2$). Our work provides a rigourous observational constraint on the drawdown potential for EW in dry UK croplands and highlights the need for a combination of observational and model-based studies in a range of hydrological and soil conditions to provide robust assessments of the GGR potential of EW in the UK.

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