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Making mistakes in estimating the CO_2 sequestration potential of UK croplands with enhanced weathering

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Determining the potential of UK croplands to sequester CO_2 via enhanced rock weathering (ERW) is important for government, policymakers, NGOs, and other stakeholders aiming to deliver UK net-zero by 2050. This goal requires drawing on a range of approaches, from process modelling to field trials, to arrive at realistic quantification. Buckingham *et al.* (2022) report results from an alkaline soil 'tubes on a roof' ERW experiment with coarse basalt dust attempting to address this aim. We highlight unfortunate fundamental errors in the execution of the experiment, reporting and interpretation of the results. These ERW results for a chalk soil under dry conditions are then erroneously extrapolated across millions of hectares of UK croplands to misrepresent UK cropland CO_2 removal potential by ERW.

Experimental design flaws and hydrology errors

Fundamental flaws in experimental design stem from conducting the trials with the cores filled with alkaline soil and amended with coarse basalt located on the roof of a building. Bound together in a rectangular block (see Buckingham *et al.* Fig. 1), the cores were subjected to unnatural heating by solar insolation onto the sides of the tubes, and relatively high wind speeds due to their rooftop location. This resulted in more evaporative drying than occurred *in situ* at the field location, both during the trials, and for several years previously (since 2018).

This higher drying explains why the measured pot-based drainage flux from the tubes (Q), based on the weights of the tubes (Buckingham *et al.* pers. comm.), was so low (57mm/yr). They claimed that their water fluxes aligned well with P-PE data at Chimney Meadows across the same time interval (± 2%). However, we believe this comparison is spurious and based on a misunderstanding of how hydrologists calculate evapotranspiration. Hydrologists calculate Q as

Precipitation (P) minus Actual Evaporation (AE). Buckingham et al. erroneously use potential evapotranspiration (PE), which is calculated from solar radiation and temperature assuming soil water content is non-limiting, instead of AE. We confirmed this inaccuracy by checking the CEH data for the Chimney Meadows site https://cosmos.ceh.ac.uk/sites/CHIMN). Buckingham et al. (2022) assumed an evaporation of 600 mm/yr (the PET value), combined with rainfall of 657 mm/yr, to obtain a Q of only 57 mm/yr.

However, the potential evapotranspiration (PE) is that which would occur from vegetated saturated soil - the actual value of evapotranspiration over a year is smaller, because evaporation rates only reach their potential values when soil water is abundant and non-limiting. In the UK, the annual AE is less than the PE because the soil is relatively dry in the summer months. Annual AE is typically between 25% and 80% of PE worldwide (Anabalón & Sharma, 2017; their Table 3) and based on an example of UK short-grassed cropland given by Hiscock & Bense (2021) may typically be around half of PE for UK croplands, so in the case of the Chimney Meadows dataset for Feb 19 – Jan 20, a value of 300 mm/yr. Using such a value would give Q fluxes at Chimney Meadows much closer to values typical for Central England croplands which are 40% of the UK average of 700 +/- 30 mm/yr (CLM5, Lawrence et al., 2019), . A Q flux 57 mm/yr is thus well below average values seen within the Thames catchment, when P-AE (rather than P – PE values) are used, as is correct practice. Although inter-annual variability means that such low values will occur in some years, it is not justifiable to use experiments representing such years for scaling up to multi-year timescales.

The very low Q value indicates that the tube-soil was considerably drier than that at the field site and will have retarded weathering, and also meant little water flowed from the tube bases. In order to obtain samples, the authors needed to repeatedly added large aliquots of rainwater each equal to a month's rainfall all in one go. Artificially manipulating rainfall in this way to correct for problematic dry soil creates preferential flow paths along the smooth hydrophobic walls of tubes, with water bypassing the *in-situ* pore fluids reducing the water residence time with rapid drainage. To find weathering fluxes, the authors assumed that the added water flushed out any weathering products (Buckingham et al. pers. comm.); this is highly unlikely due to preferential flow conditions (Evans & Banwart, 2006). Thus, the authors' statement that the approach 'proved the most efficient maintaining natural hydrological conditions throughout much of the time-series' is incorrect. Their extrapolation of CO_2 removal flux results to field Q values is thus also incorrect.

Buckingham *et al.* (2022) suggest that their Q of 57 mm/yr is 4x below the UK average (actually only 8% based on the CLM5 average of 700 mm/yr, Lawrence et al., 2019), and then extrapolate using assumption of a linear relationship between water-flux Q and CO_2 removal flux. This assumption itself is not valid, given that the original experiments were conducted both far from natural hydrological conditions and incorrectly sampled.

Numerical errors in scaling up CDR fluxes

Buckingham *et al.* (2022) compound the errors in the design and execution of their experiment noted above with gross errors in scaling their results to estimate ERW CDR for millions of hectares of UK croplands.

The first error is failing to report CDR via possible soil carbonate formation in extrapolating from the 'tubes on a roof' study to estimate the CDR potential of millions of hectares of UK croplands. Pedogenic carbonate formation, the second pathway of ERW CDR, is expected in the dry alkaline soil used in the trial. Indeed, possible calcite precipitation is indicated by their results (e.g., Buckingham *et al.* (2022) Fig. 3, shows Ca depletion near the base of the cores). Additionally, average alkalinity from major-ion weathering at different depths in the cores is used to calculate CO_2 removal. However, their data indicates release of Ca by dissolution of basalt rock at the top and substantial loss of Ca at the base of the column, the most likely explanation, acknowledged by the authors, being precipitation of carbonate at the bottom (Fig. 3). This CO_2 removal pathway was not quantified, contributing to an incorrect calculation CDR, resulting in an underestimate of removal.

The second error is in scaling from a 'tubes on a roof' trial with a single year's basalt amendment to estimate the CDR rate over five years. ERW CDR rates per unit area increase over time with successive annual applications of rock dust because the basalt added in earlier years continues to capture CO_2 as the slower-weathering mineral constituents dissolve over time scales greater than a single year. Numerical recipes for correctly scaling from a single rock dust application to multi-year applications to include this effect have been derived (Beerling *et al.*, 2020; Kanzaki *et al.*, 2022) but were not used. Omitting this repeat application effect incorrectly determines the potential for CDR by ERW when scaled over the five-year time horizon they used.

The third error is extrapolating incorrect CDR numbers obtained from the columns with a single and unrepresentative arable soil type (alkaline soil) under unusually dry conditions to millions of hectares of arable land. This calculation falsely represents UK croplands across which soil types and weathering conditions vary substantially and soil drainage fluxes (P-AE) are typically several hundred mm/yr (CLM5, Lawrence et al., 2019). It is not scientifically valid to scale to UK-wide conditions using unrepresentative water fluxes and incorrect calculation of CDR, due to the errors noted above. Publishing the extrapolated value for UK CDR potential is therefore unwarranted.

In consequence, comparing an erroneously extrapolated UK cropland CDR number with the UK-wide simulation-based EW study of Kantzas *et al.* (2022) leads to a false conclusion by Buckingham et al. (2022). The study of Kantzas *et al.* (2022) undertook detailed calculations with a geospatially resolved process model and considered the ERW CDR via *both* pathways (alkalinity production and soil carbonate formation) with geospatially variable inputs of soil pH and monthly climate (including P-AE). It simulated ERW CDR for UK croplands *over 50 years of repeated rock dust application* with appropriate multi-year numerical calculations, soil types, UK basalt mineralogies and future climates.

Getting land surface hydrology correct for ERW calculations is important for experiments, field trials and model-based approaches. The 1-D soil profile geospatial weathering model of Kantzas *et al.* (2022) is driven by variables from the land surface model CLM5 (Lawrence et al., 2019), including monthly P-AE, i.e., water flux through the soil, Q. Comparison of CLM5 simulated monthly P-AE values with observations for an arable field site (Harpenden) in central England and a grassland field site (North Wyke) in Wales between 2005 and 2014 gives strong agreement, validating the model (Figure 1). These provide strong support for CLM5-based monthly modelled Q values used in weathering calculations of Kantzas *et al.* (2022).

The Buckingham *et al.* (2022) study differs from Kantzas *et al.* (2022) in terms of measured and modelled CDR pathways, fails to encompass the variability of soil types and climates, and fails to account correctly for the effects of consecutive years of rock dust applications on CDR. Consequently, the comparison between the CDR value for UK arable land by Buckingham *et al.* (2022) and that of Kantzas *et al.* (2022) is not valid and mis-leading.

Conclusion

In short, Buckingham *et al.* (2022) located the tubes for their ERW trial on the roof where they were subjected to heating and drying (and hence much higher evapotranspiration than at typical UK field locations), for year before and during the experiment. They artificially manipulated the hydrology of the dry soils this created, which invalidates their results as being representative of weathering at a field site, and subsequently failed to report ERW CDR via both potential pathways (alkalinity and soil carbonates). With flawed results obtained from using an alkaline soil unrepresentative of typically acidic UK farmland soils, amended coarse basalt (fine fast-reacting rock dust was removed prior amending the soil), they propagated scientific and numerical errors in extrapolating to estimate the ERW CDR for millions of hectares of UK farmland.

Determining the potential of UK croplands to sequester CO_2 via ERW is important for government, policymakers, NGOs, and other stakeholders aiming to deliver UK net-zero by 2050. However, this paper's flaws and incorrect findings fundamentally compromise its integrity and falsely represent the CO_2 sequestration potential of UK croplands with ERW.

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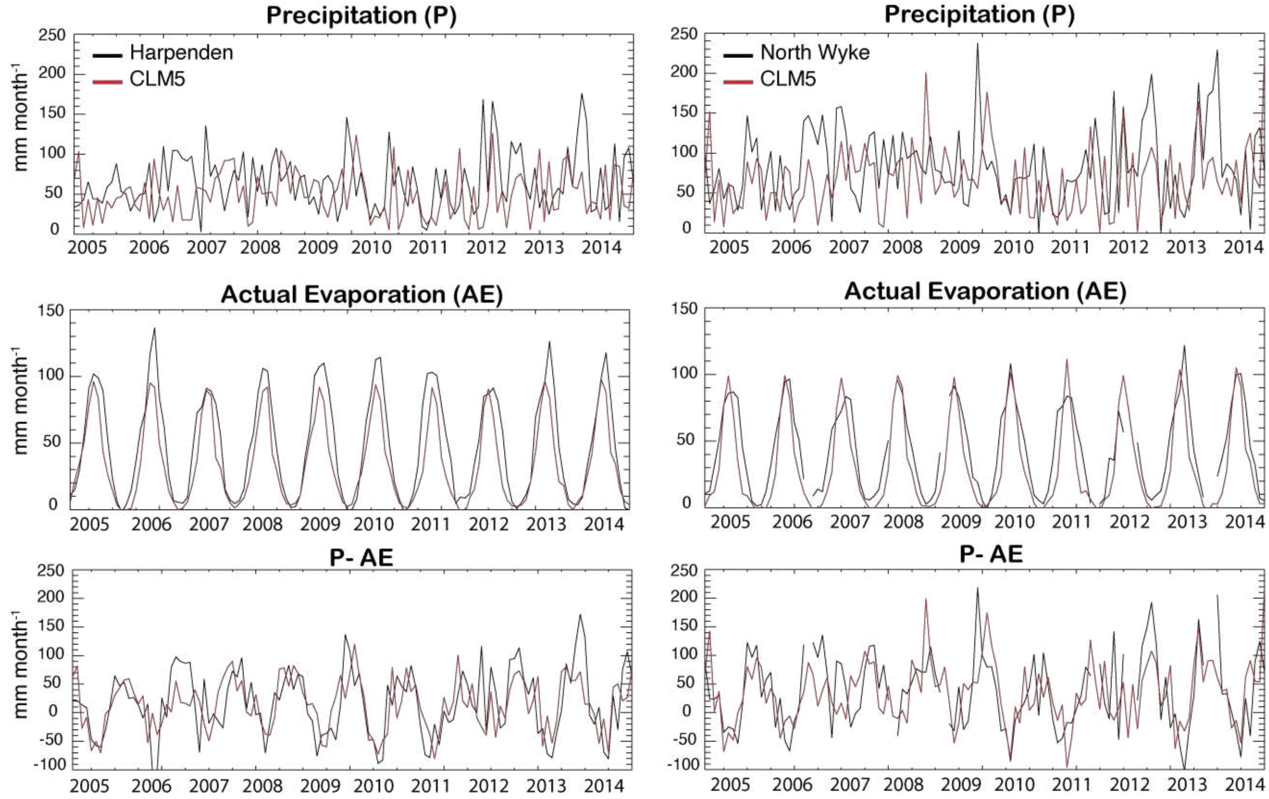

Figure 1. Model-data comparison of land-surface hydrology for a UK arable field site in central England (left, Harpenden, 51.80 N -0.36 E) and a grassland field site in Wales (right, North Wyke, 50.77 N, -3.90 E) from 2005 to 2014. Shown is the decadal monthly precipitation (P), actual evaporation (AP) and precipitation minus actual evaporation (P-AE) for CLM5 (red) and the Rothamsted Research sites (black). Information about the hydrological measurements at the Rothamsted Research sites are found in Perryman et al., (2021) and the CLM5 simulations in Kantzas et al, (2022).

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