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Global meta-analysis of soil hydraulic properties on the same soils with differing land use

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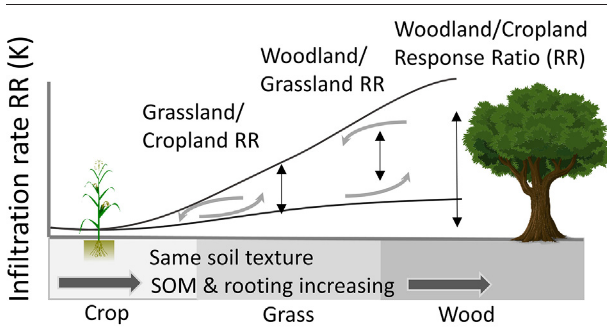
HIGHLIGHTS

- Biotic factors increase soil infiltration rates over and above pedotransfer function predictions based on soil texture.
- On the same soil type infiltration rate increases from cropland to grassland to woodland.
- Forest doubles infiltration rate compared to cropland.
- Dependence on biotic factors means infiltration rates are dynamic and depend on land use and change.

GRAPHICAL ABSTRACT



ARTICLE INFO

ABSTRACT

Global land use change has resulted in more pasture and cropland, largely at the expense of woodlands, over the last 300 years. How this change affects soil hydraulic function with regard to feedbacks to the hydrological cycle is unclear for earth system modelling (ESM). Pedotransfer functions (PTFs) used to predict soil hydraulic conductivity (K) take no account of land use. Here, we synthesize >800 measurements from around the globe from sites that measured near-saturated soil hydraulic conductivity, or infiltration, at the soil surface, on the same soil type at each location, but with differing land use, woodland (W), grassland (G) and cropland (C). We found that texture based PTFs predict K reasonably well for cropland giving unbiased results, but increasingly underestimate K in grassland and woodland. In native woodland and grassland differences in K can usually be accounted for by differences in bulk density. However, heavy grazing K responses can be much lower indicating compaction likely reduces connectivity. We show that the K response ratios (RR) between land uses vary with cropland (C/W = 0.45 [W/C = 2.2]) and grassland (G/W = 0.63 [W/G = 1.6]) having about half the K of woodland.

1. Introduction

Soil hydraulic conductivity near saturation (K) alters infiltration-runoff partitioning at the land surface and is thus an important component in

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Earth System Models (ESM) (Fatichi et al., 2020). For the last four decades, K has been increasingly determined from pedotransfer functions (PTFs) based on laboratory measurements of simple soil properties (Van Looy et al., 2017), primarily soil texture, bulk density and/or organic carbon content (Schaap et al., 2001; Zhang and Schaap, 2019). These derived K values can differ substantially, orders of magnitude, from field measurements (Gupta et al., 2021). The databases of soil hydraulic properties used globally tend to be heavily populated by measurements from agricultural soils (Rahmati et al., 2018). This has generated a bias towards measurements from cropland soils (Batjes, 2008; Rahmati et al., 2018; Weynants et al., 2013). As a result, K determined from PTFs is largely unresponsive to the effects of land use and climate change, especially where vegetation changes occur.

Fig. 1 illustrates the problem; the amount of water retained in soil, expressed as a volumetric water content, depends on the soil suction (h) and can be modelled using a classical Van Genuchten (1980) retention (Fig. 1A) or hydraulic conductivity (Fig. 1B) model. The grey lines in both figures are models for a clay loam soil and estimate a porosity ~0.4 m^3 m^{-3} and K ~ 6 cm/day. This response is largely controlled by soil texture, however, other processes generate macropores, cracks, worm burrows, and the root systems of vegetation that tend not to be captured by a data set mostly focused on tilled, homogenised cropland soils. These macropores generate what is termed structural porosity which can be modelled using a dual porosity approach. Together the textural and structural porosity make up the total soil porosity. While PTFs were largely used for agricultural modelling, texture based PTFs proved adequate. However, PTFs are increasingly utilised for ecological modelling and ESMs to predict earth system function for the vast majority of land that is not covered by crops. Emerging research shows that land use is an important factor in determining soil hydraulic properties (Jarvis et al., 2013).

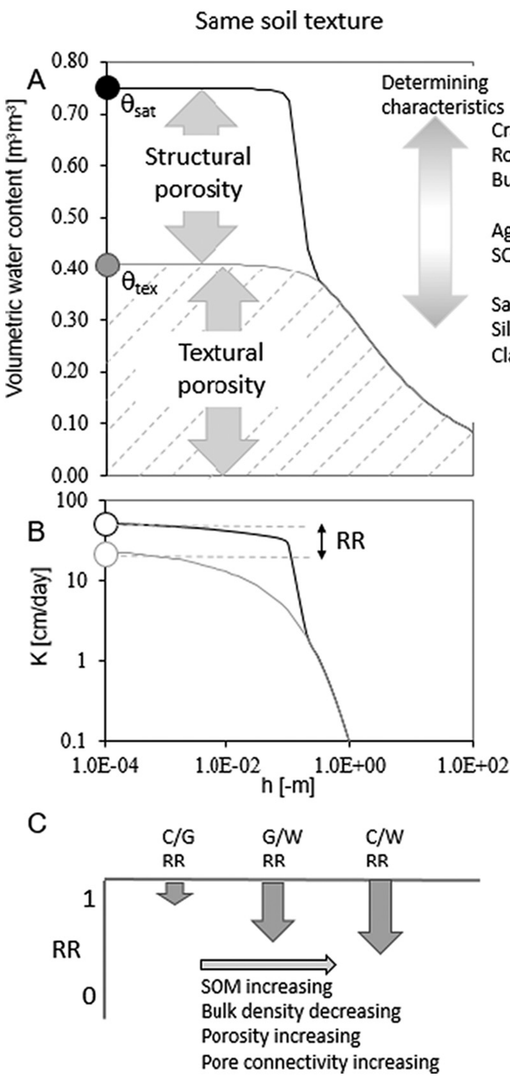

Fig. 1. A, water retention curve with suction, h (-m) along the x-axis for A&B, showing the textural and structural hydraulic regions with the dominant characteristics that determine the properties of each region listed on the right. B, the corresponding hydraulic conductivity (K) with the grey line indicating the textural contribution to K and the black line the structural contribution. The expected change in response ratio (RR) when comparing cropland, grassland and woodland (RR of 1 indicates numerator and denominator are the same, values <1 that the denominator is greater).

Moreover, researchers recently found that the structural soil porosity, defined as the macro-porosity or effective porosity, is more dynamic than previously thought; responding to climate change on a decadal time scale, with mechanisms, yet to be identified driving this (Hirmas et al., 2018). Fatichi et al. (2020) have shown that incorporating soil structure into ESMs is important, as it significantly alters the infiltration-runoff partitioning and recharge in wet and vegetated regions of the earth; moreover with implications for processes impacted by run-off such as erosion (Borrelli et al., 2021; Borrelli et al., 2017). This presents a substantial challenge because while PTFs provide reasonable prediction of textural porosity and hydraulic properties, structural porosity must be added through bulk density which is often unknown and changes due to biological activity and hence land use (Robinson et al., 2022). To incorporate soil structural effects into ESMs, Bonetti et al. (2021) proposed a framework using vegetation metrics obtained from earth observation. Whereas, of the handful of land surface models developed globally, the Joint UK Land Environment Simulator (JULES) (Best et al., 2011; Blyth et al., 2010; Clark et al., 2011) tries to account for land use on K by altering its effect on infiltration through the introduction of empirical correction factors based on modelling experience. This provides some sense of the direction and magnitude of the expected impact.

While these approaches attempt to deal with the potential impact of vegetation and management on K there is still no empirically based assessment of the impact of land use on K for a given soil across land uses. In order to address this, a general hypothesis is proposed:

H_0. The ratio of hydraulic conductivity for highly managed land use to native land use will be = 1 for a given soil type, where the soil type is the same under each land use.

With the alternative hypothesis:

H_1. Ratio of hydraulic conductivity for highly managed land use to native land use will be $\ll 1$ for a given soil type, where the soil type is the same under each land use.

The effect of land use management is expected to decrease progressing from cropland > grassland > woodland, hence seeing K increase with, cropland < grassland < woodland, accordingly.

A global meta-analysis is presented to test the hypothesis. For the purposes of this study woodland (W), includes native broadleaf, evergreen and plantations; grassland (G) includes native and pasture systems and cropland (C) was dominated by arable crops such as corn and maize. ESM's tend not to differentiate beyond these high level groupings hence we adopt a similar approach. Thus an analysis approach compatible with JULES was chosen, using response ratios (RR) to determine the extent to which land use alters K. The RR approach is widely used in ecological studies (Hedges et al., 1999) with the natural logarithm transformed response ratio (Ln(RR)). The denominator is the land use expected to have the higher infiltration rate (e.g. W). This approach was chosen for the analysis to try to constrain the results to between 0 and 1, although individual ratios can, and do, occur above 1. However, in some results reported and discussed, the inverse, which is a multiplication factor and is more intuitive in practical applications is used. Note that the land use pairs used to calculate the RR of K do not reflect the direction of land use change i.e. cropland to grassland, or

Table 1
Matrix for the hypothesised impact of land use on soil hydraulic conductivity ratios. (G/W); (C/W) & (C/G) (~ indicating about the same).

			Grassland (G)			Cropland (C)	
			G1	G2	G3	C1	C2
			Native grassland	Extensive pasture	Intensive pasture	No/min tillage	Deep tillage
Woodland (W)	W1	Native woodland	1 (G/W)	<1	≪1	<1 (C/W)	≪1
	W2	Silvo pasture/savannah	>1	1	<1	1	≪1
	W3	Managed orchards/plantations	≫1	>1	1	1	<1
Grassland (G)	G1	Native grassland				<1 (C/G)	<1
	G2	Extensive pasture				~1	~1
	G3	Intensive pasture				~>1	~>1

grassland to cropland; nor in most cases do they report grazing intensity which will lead to compaction. Fig. 1B proposes that RR reflect a change in the proportion of structural K (associated with macroporosity) and textural K (associated with the *meso* and micro porosity), and that cropland soils dominantly present textural K, while in grassland and woodland soils the structural K is expressed to a greater extent. As a result, the RR for K are expected to diverge for grassland and woodland from cropland, as proposed in Fig. 1C. Table 1 presents a conceptual framework in the form of a matrix in this regard, indicating the expected change in RR for K for different land use combinations. Values of 1 indicate no difference between land uses, while values of <1 indicate a higher K for the denominator, usually woodland. Native woodland and grassland are expected to express structural K to a greater extent leading to a similar RR; while, RR are expected to diverge to lower than 1 as management increases under cropland. Note, the expectation that intensively managed woodland, such as orchards, are also expected to have less structural porosity compared to native grassland or woodland, and hence may present higher RR. Initial survey of the global literature indicated that there were insufficient studies to fully test the matrix including management, thus, a pragmatic approach was adopted and the studies were aggregated into woodland (W), grassland (G) and cropland (C). The dominant characteristics of the studies found were, native woodland, extensive pasture and tilled cropland; with corn, maize and wheat being the dominant crop types represented. Studies with cropping were considered during the growing season when crop growth was active. Hence, three RR were determined between the different major land uses (Fig. 1C). By determining the RR for K, based on firm observational evidence, for different land uses, factors can be obtained to adjust K predicted from textural PTFs for different land uses, thus improving process description of surface hydrology made with ESMs.

2. Methods

The analysis framework presented follows from the hypotheses using a comparison of RR to test for the presence of an effect size for K when comparing the following pooled land use combinations C/W; G/W and C/G. Given the aggregation of the studies, a single effect size was not anticipated, but that there will be a range of effect sizes, hence, the analysis was constrained to mixed effect models and not fixed effect models (See supplementary for details of statistical methods). Soil K is highly dependent on soil type, ranging from >450 cm day^{-1} in organic or sandy soils to <8 cm day^{-1} in clay soils (Gupta et al., 2021). Measurements of K or infiltration are made using a number of different methods and at different degrees of soil saturation. Exploratory data analysis was conducted using the reported K values for each land use. However, in order to minimize differences due to measurement methods and soil types RR were used. Structural porosity across a transition is expected to be hysteretic, with degradation reducing structural pores much quicker than biological activity is able to regenerate them, hence, Fig. 1C indicates only the expected trajectory. Evidence for this is supported by similar changes in soil organic matter (Or et al., 2021), compiled for cropland/grassland transitions.

In order to complete the meta-analysis, a global database, comprising over 800 measurements of soil K or infiltration rate, was compiled from 58 papers, published in the last four decades. The database includes both studies where K or infiltration measurements were reported and were co-located and made on the same soil texture and classification type but for different land uses i.e. C, G or W. The database also contains ancillary data, where reported, such as latitude, climate (MAT & MAP), soil type, texture, organic matter, crop type and whether the trees were broadleaf or needle leaf. While other databases have been compiled for K measurements (Rahmati et al., 2018), for each soil the data are on single land uses and thus do not easily support a study on determining how land use affects K independently of soil texture and without additional assumptions. The data reported here represents a latitudinal spread, diversity in soil type for soil textures ranging from 75 % sand to 75 % clay; porosity between 0.30 and 0.93 m^3 m^{-3} and soil organic carbon (SOC) between 1 and 25 g 100 g soil^{-1}, where reported. Some of the organic soils did not have SOC reported and are likely to be close to 55 g 100 g soil^{-1}.

3. Results and discussion

The meta-analysis shows that land use modifies K, given the same soil. Texture based PTFs are shown to hold reasonably well for cropland, but diverge for grassland and woodland. This is important because for global ESMs cropland covers only ~7 % of the land surface; while grassland covers 27 % and woodland 26 % (Ritchie and Roser, 2013) (others, Glaciers 20 %; Barren land 19 %; shrubland 8 %; urban 1 %). Analysis supports the use of PTFs to determine K for cropland soils, which tend to be mineral soils with relatively low organic matter content; the determination of RR with other land uses therefore offers the possibility to adjust K in a simple manner for the same soil type. The study provides a first approximation of the expected difference in K for different land uses using global data and it equips ESM modellers with simple ratios as a starting point to adjust hydraulic behaviour based on land use.

3.1. Global measurements of soil hydraulic conductivity and infiltration

The analysis extracted measurements from 58 papers from across the globe (Fig. 2). All papers contained data that allowed the calculation of RR values for at least G/W (182 *Qualitative WG*), whereas 30 papers yielded 79 G/W RR with numbers and error terms (*Quantitative WG*). Finally, 13 papers contained measurements for C/G/W providing 34 RR, often with different woodland densities or crop types (*Quantitative WGC*). Of those 13 studies, three used rainfall simulators to determine infiltration. Noticeably, no data was found from the northern latitudes in Russia and few in Canada or Australia. The data set gives a reasonable global coverage but appears to show a bias, as expected, towards areas where land use change is a reported issue, South America, Europe and the Eastern USA.

Initial data analysis compared the measured K with that predicted based on a popular global PTF for study sites where soil texture was available. PTFs were generated using the Rosetta1 program (Skaggs, 2022. https://www.handbook60.org/home/) which uses machine learning based on a large soil database (Zhang and Schaap, 2017). Rosetta-predicted PTFs based on sand, silt and clay, model H2 were then compared with measured K values from the literature. Using a sensitivity plot (Fig. 3) the median value of the difference between measured vs predicted K will be zero if the PTF predictions do not show bias compared with the measured data.

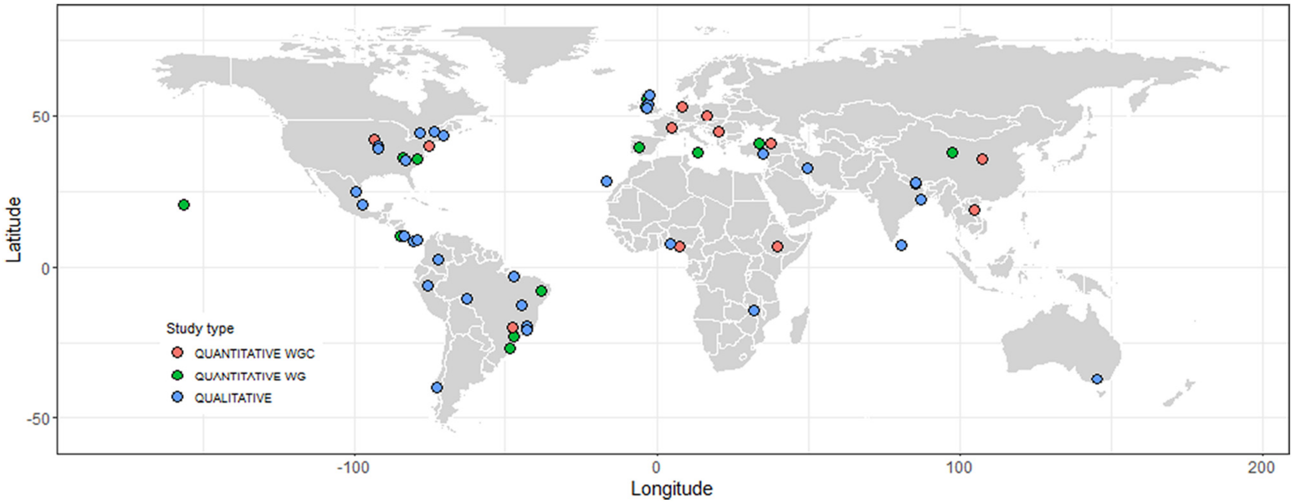

Fig. 2. Locations of the 58 study sites where published hydraulic conductivity and infiltration data allowed the calculation of response ratios (RR). The red dots show sites where information was available for woodland, grassland and cropland; green dots are where only woodland and grassland data were available, and the blue dots show the rest of the dataset that provides qualitative supporting data on response ratios but lacked details on the variance and number of replicates to be included in this meta-analysis.

It can be seen that the cropland soil K measurements in the database minus the predicted PTF values are similar, with a median deviation of 10 cm day^{-1}, (n = 19, arithmetic mean measured K = 239 cm day^{-1} or 63 cm day^{-1} when 2 outliers removed), i.e. the median deviation is within an order of magnitude. The median deviations for grassland and woodland are progressively greater than zero with the grassland median deviation being 46 cm day^{-1} (n = 64; mean measured K = 203 cm day^{-1}) and the woodland median deviation being 183 cm day^{-1} (n = 73, mean measured K = 1058 cm day^{-1}), both with right skew, i.e. tending towards greater values. The data supports the use of PTFs for estimating K for cropland soils that dominate the underlying global database and other similar commonly used databases (Weynants et al., 2013; Wösten, 2000). This also means cropland soil K predicted from global PTFs potentially serve as a lower boundary for K in grasslands and woodlands, however, the magnitudes of K in land uses other than cropland are clearly different based on Fig. 3 and require the structural porosity to be accounted for in some way.

Response ratios are ideal for determining differences between K for different land uses independent of soil type and are summarized in Fig. 4. A value of 1 indicates no difference in RR between two land uses, whereas values <1 indicate higher K in the denominator. Starting with croplands and grasslands (C/G), grasslands clearly have higher K values than the same soil under cultivation. There are some distinct outliers with RR >3, these refer to a study in Nigeria on an Ultisol where the grass was heavily grazed by cattle, likely reducing the grassland K compared to cultivated and woodland soils (Mbagwu, 1997). The RR for croplands and woodlands (C/W) shows that three quartiles have values with RR below 1, indicating higher K values in the woodlands. The median for the grassland and woodland sites falls between the C/G and C/W RR. Boxplot D in Fig. 4 plots the G/W RR (*Quantitative WG*, n = 79), while boxplot E contains all the RR found (*Qualitative WG* n = 182). Incorporating more studies from C to D reduces the spread of data while marginally decreasing the median of the

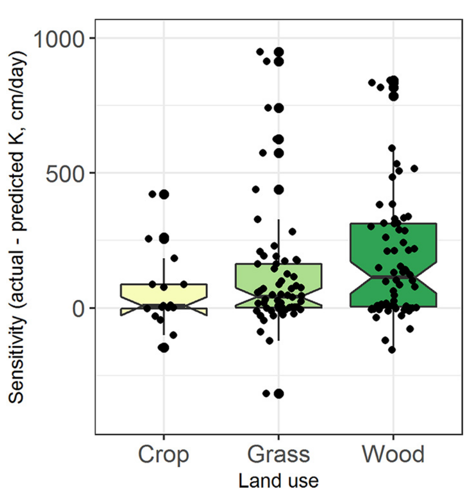

Fig. 3. Sensitivity plot showing the actual (measured) K minus the predicted K using PTF and soil texture information. The data show that the median K for cropland is close to zero indicating unbiased correspondence between the measured and predicted K. Measured and predicted K increasingly diverge for grassland and woodland, indicating that these land uses have higher K values than predicted using the PTF.

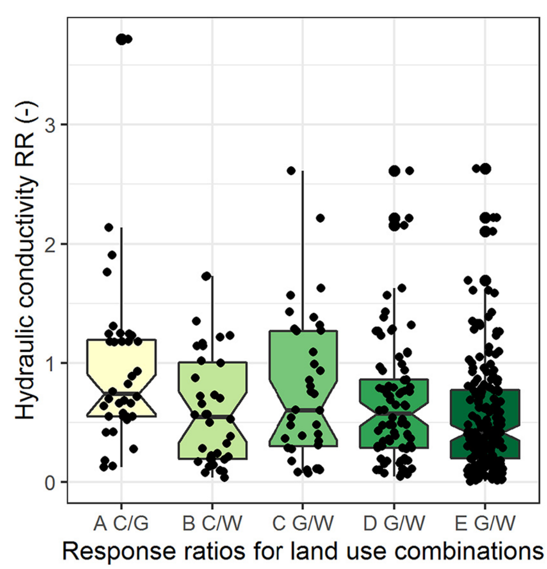

Fig. 4. Hydraulic conductivity response ratios (RR) as a function of the different land use comparisons as published. Medians of RR <1 indicate that the hydraulic conductivity (K) of the denominator is higher than the numerator. A, B and C are the main data set for C/G/W. D is the larger data set for G/W and E is the extended grassland/woodland data set with all available RR.

bigger study (D). Increasing the number of studies from D to E maintains a similar spread but decreases the median of E more. The data provide good evidence that K is higher in woodlands than in other land uses on the same soil type. RR between 2 and 3 correspond mostly to a study in China on loess soils (Yu et al., 2015). The study site was part of an afforestation scheme where the woodland was planted in the 1980's with black locust, while the grassland was abandoned cropland and allowed to regenerate, both without human management. The researchers measured fine root density, showing that in the surface horizons density was almost twice as high under the grassland as under woodland or cropland. They also observed that the woodland was compacted when afforested and structural porosity didn't rebound. Therefore, those woodland sites had similar bulk densities to those in cropland, explaining the higher infiltration rates observed in the grasslands.

Meta-analysis was conducted on the data to determine the mean effect size using the "meta" package in R (Schwarzer et al., 2015) which is a more robust analysis that uses more of the data than simply comparing medians; however, it means limiting the analysis to the *quantitative WGC* and *WG* data sets, given they contained the required replicate numbers and error terms for analysis. A random effects model was chosen because the assumption of the fixed effects model, that all studies come from the same population, is unlikely, as previously discussed. Hence, interpretation using the results of the random effects model is emphasised. The results are summarized in Table 2. All studies indicated high degrees of heterogeneity using the I^2 measure, which indicates the percentage of variation across studies; due to heterogeneity and not chance (Higgins and Thompson, 2002). This being the case, the random-effects model used was more appropriate as it doesn't assume that sampling error alone explains the effect size, but that there is another source of variance given that the studies are drawn from a distribution of populations (environments, etc.). High heterogeneity is to be expected with measurements of K where it is considered that effect size, in reality, is from a distribution of effect sizes. This makes physical sense because different soils may have the same porosity but different levels of connectivity and tortuosity yielding a distribution of K values. Moreover, the direction of land use change for most studies is unknown, with an anticipated change in K being hysteretic, giving a spread of K for similar physical conditions depending on whether the soil is degrading or regenerating. This will depend on a variety of intrinsic biological (e.g. root growth, bioturbation), physical (e.g. particle shape, orientation and arrangement) and management factors. This is intuitively why H_1 makes sense, in that there should be differences in land use RR, as these factors, especially rooting and direction of transition, are generally unaccounted for.

Looking at the *quantitative* data set of all C/G/W, soil K between cropland and woodland on the same soil type (C/W) ($n = 13$) showed an effect size of 0.45 and a moderate heterogeneity if outliers were removed as calculated by the random effect model (Table 2). The reciprocal value for the mean random effect size (1/0.45) gives a slightly more intuitive

Table 2
Meta-analysis results for soil hydraulic conductivity Response Ratios (RR) for comparison of K on cropland (C), grassland (G) and woodland (W) soils. The smaller the number the more dominant the denominator. Inverse response ratios are given in round brackets e.g. woodland is 2.21 times higher than crops. The pale grey rows are prior to outlier removal and the black numbers in bold are obtained after outlier removal. Outlier removal reduced the heterogeneity (I^2) in the dataset from substantial to moderate.

Land use response ratio	Random effects model Effect size, lower CI, upper CI, and inverse in round brackets to 2d.p.	Heterogeneity (I^2) [lower CI, upper CI]	Median 2d.p.	Number of studies
1) RR C/W	0.4337 [0.3301; 0.5698]	91.4% [89.1%; 93.2%]	0.54	13 studies 34 RR combinations
2) RR C/W Outliers removed	**0.4535** [0.3553; 0.5788] (1/0.45 = 2.21) Expt n = 187; Control n = 219	65.5% [44.7%; 78.5%]	0.54	7 studies after outliers removed 20 RR combinations
3) RR C/G No outliers	**0.7696** [0.5860; 1.0107] (1/0.77 = 1.30) Expt n = 228; Control n = 230	90.2% [87.1%; 92.6%]	0.84	13 studies 28 RR combinations
4) RR G/W	0.5416 [0.4039; 0.7263]	96.8% [96.2%; 97.3%]	0.60	13 studies 34 RR combinations
5) RR G/W Outliers removed	**0.6327** [0.5019; 0.7977] (1/0.63 = 1.59) Expt n = 198; Control n = 171	52.9% [20.6%; 72.0%]	0.60	7 studies after outliers removed 19 RR combinations
6) RR G/W	**0.4898** [0.4127; 0.5813] (1/0.49 = 2.04)	99.9%	0.60	30 studies 79 RR combinations
7) RR G/W Outliers removed	**0.5676** [0.4907; 0.6565] (1/0.57 = 1.75) Expt n = 437; Control n = 405	51.6% [30.4%; 66.3%]	0.62	19 studies 40 RR combinations
8) RR G/W	NA	NA	0.41	58 studies 182 RR combinations

value, indicating that K in woodlands is ~2.2 times greater than in croplands. Comparing K between cropland and grassland, the effect size of 0.77 and its reciprocal suggests that K is only 1.3 times greater in grassland than cropland. Lastly, differences in K between grassland and woodland (n = 13, outliers removed) was 0.63 and its reciprocal of 1.59 times higher K in woodland than grassland.

Unfortunately, most studies do not indicate if the grassland was grazed or ungrazed, or mention the intensity of grazing. However, it was observed that studies indicating native grassland tended to have RR of 1, supporting the assertions in Table 1. Moreover, this also supports the contention that compaction in grasslands with grazing is one of the drivers of the effect size between G and W, and that the effect might be expected to be less if more native grasslands were observed. The effect sizes support the analysis with the medians (Fig. 4) and confirm the order, that K in Woodland > Grassland > Cropland for the aggregated land use data. The data for the grassland and woodland indicates that more than doubling the size of the data set had only a marginal impact on the effect size increasing from 1.59 to 1.75 for G/W (Table 1), suggesting that the effect size values obtained for the smaller set of studies (n = 13) that included results for all three land uses, are representative results.

3.2. Hydraulic response ratios and ancillary data

Hydraulic RR were correlated with a range of ancillary data to look for any potential relationships. No distinct patterns were observed for the G/W RR with latitude (Fig. 5A), or soil type (Fig. 5B; The pale blue points indicate there was data but it did not specify leaf type or soil type). Fig. 6A & B compared the G/W RR with the soils' sand and clay content, again no discernible pattern was observable. Fig. 6C & D compared the G/W RR with the porosity (C) and soil organic carbon, SOC (D) ratios respectively. A porosity or SOC ratio of 1 indicates both woodland and grassland have the same porosity or SOC content. Values below 1 indicate woodland has higher values (porosity or SOC), while values above 1 indicate grassland has higher values. The data for porosity (Fig. 6C) indicates in general that woodland has higher porosities and that this is consistent with higher K values (lower RR). The same pattern is not as distinct with SOC (Fig. 6D) as there are substantial numbers of data with SOC G/W higher than 1. While data suggest that woodlands often have higher porosity, this is not necessarily dependent on having higher SOC content, perhaps suggesting other factors such as root morphology and structure in the woodlands, or compaction in grasslands, may be at play (Chandler et al., 2018).

Further exploring the relationship of the RR for G/W with porosity, an attempt was made to extract additional information that helped isolate factors that could be contributing to the differences (Fig. 7). Fig. 7 is the same as Fig. 6C, but with studies where grazing intensity could be identified. By extracting this qualitative grazing intensity information from the articles, it was possible to pick out sites that specifically mentioned that there was no grazing (green), or that the site was heavily grazed (red dots), which is a useful indicator of compaction in grasslands. We found that RR identified as outliers were associated with heavy cattle grazing in one study (Mbagwu, 1997). In addition, Fig. 7 contains a black line that is a PTF modelled response for K that would be expected based on keeping soil texture constant and altering only the porosity. The Rosetta1 program was used to predict K with parameters (60 % sand, 20 % silt and 20 % clay) and the bulk density varied between (0.90–1.86 g cm^{-3}; porosity 0.66–0.30). The reference bulk density was 1.3 g cm^{-3} with response ratios calculated based on K at the equivalent porosity. The interpretation of the data around the line is that the RR values can simply be accounted for by the change in K expected as the bulk density (porosity) changes. Most of the green data points, where grazing wasn't present follow this curve, indicating that changes to RR are due to the difference in bulk density between the grassland and woodland. However, this also indicates that the red dots, indicating heavy grazing, cannot be accounted for by changes in porosity alone. This is interpreted as the heavy grazing altering other factors such as pore connectivity or soil sealing resulting in lower K in the grasslands than would be expected for the given porosity. This insight is important suggesting that in soils not subject to compaction changes in bulk density or porosity, which may be due to SOM or rooting, can account for changes

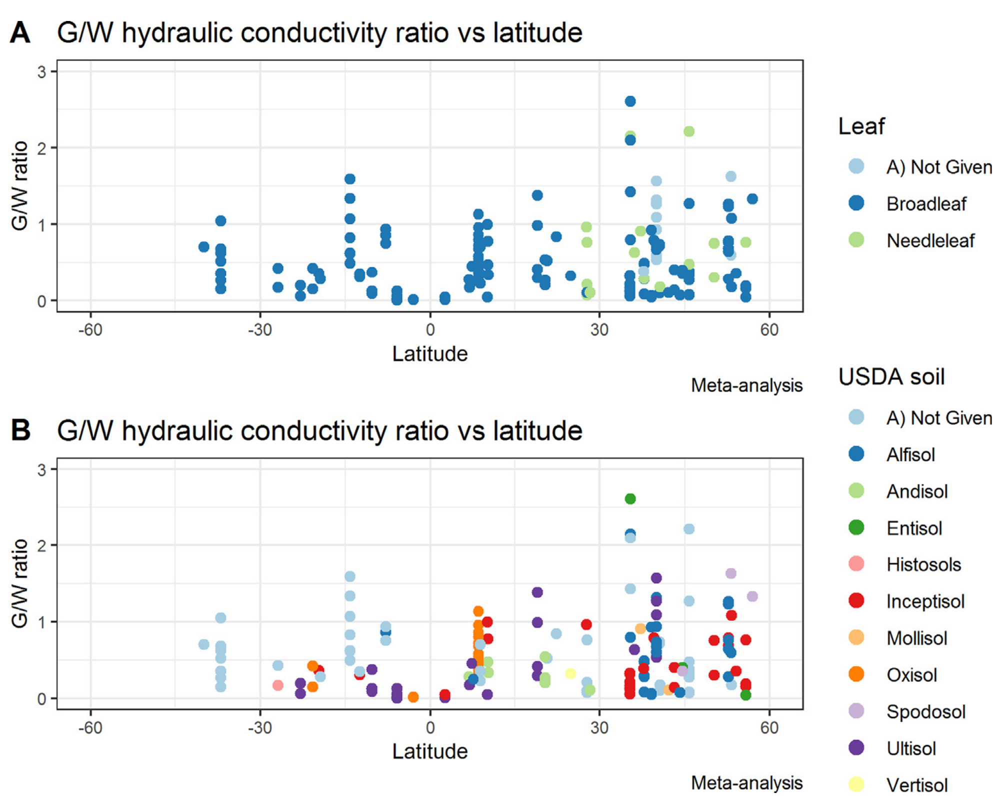

Fig. 5. Response ratios (RR) for G/W as a function of latitude. A is coloured by woodland leaf type while B is coloured by soil type. The pale blue colour indicates data but with no leaf or soil type given.

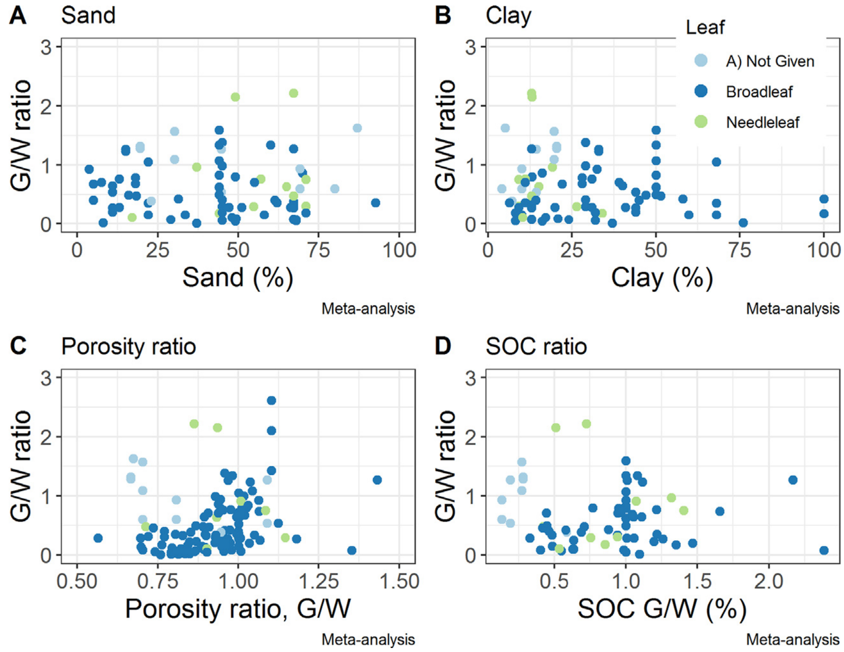

Fig. 6. Response ratios (RR) for G/W as a function of soil texture (A and B), where values lower than 1 indicate higher values of K in woodlands. RR for G/W with difference ratios for porosity and SOC on the x-axis. A difference ratio of 1 on the x-axis indicating no difference, whereas values below 1 indicate higher values in woodland and those above 1 higher values in grassland.

in K. However, compaction results in alteration to the pore connectivity resulting in lower values of K. This supports the previous assertion that in native grassland and woodland similar values of porosity and K emerge, in the absence of grazing. This is most likely driven by bulk density that is a function of SOM and rooting as previously proposed. The results also suggest that estimating K for grasslands may be more uncertain when grazing status is unknown.

3.3. Comparison with the literature

The results indicate that land use is an important factor influencing K, most likely with land use acting as a surrogate for both biological (root and faunal) and anthropogenic activities (compaction by machinery or grazing). This interpretation is supported by recent research that shows the importance of tree species and rooting on hydraulic function (Webb, 2021), something that PTFs do not explicitly account for. It is known that root architectures differ across plant types, species and biomes (Schenk and Jackson, 2002), and reflect different strategies for accessing nutrient and water resources while maintaining stability. Hence, intuitively one would expect the vegetation to modify the effective soil hydraulic characteristics. Moreover, we recognise that the link the plant growth and rooting means that there is likely a temporal dynamic to K that can be attributed to both management such as tillage (Green et al., 2003), root dynamics and land use more broadly (Hu et al., 2012; Hu et al., 2009). Indeed, it is an important ambition in soil physics research and linked modelling applications that the temporal variability of such properties is accounted

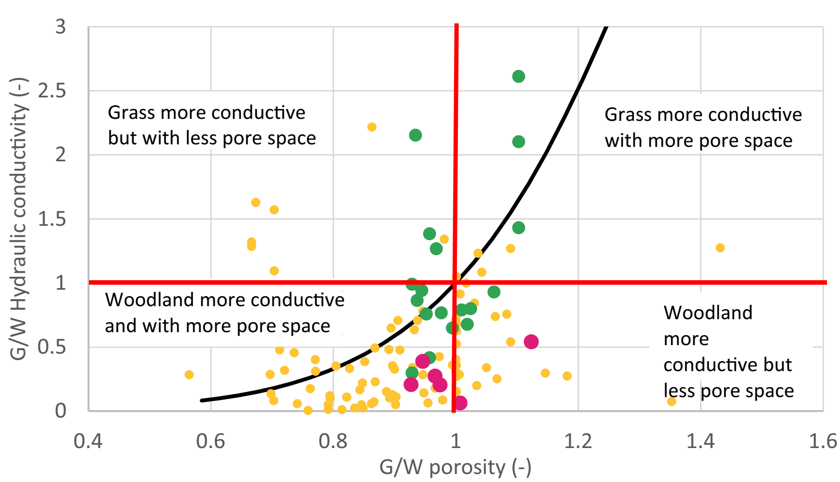

Fig. 7. The K response ratio (RR) for G/W vs the difference in porosity RR (Fig. 6C). Where the red lines meet there is no difference between the woodland and grassland samples. The colours represent: green, native or no grazing; red heavily grazed and orange everything else. The black line is the expected K (RR) for a generic soil (60 % sand, 20 % silt and 20 % clay) and the porosity difference determined from bulk density where a bulk density of 1.3 (porosity = 0.51) is set as the reference. Modelled with Rosetta (Skaggs, 2022: https://www.handbook60.org/rosetta/).

for. Given management and plant growth in particular impact this, this meta-analysis goes some way to illustrating the importance of at least the vegetation component. At present, the data are limited if at all available, and most (if not all) hydrological models are unable to account for seasonally variable soil hydraulic properties without the model being stopped and re-parameterized.

The soil science community has historically focused on covering spatial variability of K by repeated measurements (and reported mean values based on replicates), which has a comparable or often even greater degree of variability than the temporal change. This has its imprint on data availability in both national and the most broadly used international databases in soil physics and hydrology research (e.g. UNSODA, HYPRES, EU-HYDI, GRIZZLY, WISE or NRCS-NSSC). These databases severely underrepresent soils under grasslands, but especially woodlands, and they are yet to facilitate credible, generalizable research on temporal evolution/variability of K despite the subject's recognized importance. For a recent acknowledgement of the unresolved problem of temporal variability in global soil hydrology see Van Looy et al. (2017). While acknowledging these issues, the validity of our findings is under the assumption that temporal variability is embedded in the statistical distribution of sampling (times) under each of the examined land uses, and minimised by focusing on the growing season. This global meta-analysis supports the findings, limited for drylands, of the importance of biotic factors in determining soil hydraulic properties (Thompson et al., 2010) and lends support to the work in (Bonetti et al., 2021) developing a framework to incorporate such processes in hydrological process models. In arid systems the enhancement of infiltration capacity due to vegetation is well documented (Thompson et al., 2010); Thompson et al. (2010) showed that infiltration increased with biomass in arid ecosystems. Furthermore, modification of hydraulic properties by vegetation plays an important role in both the water balance and the spatial structure of vegetation, often resulting in pattern formation due to feedbacks (Rietkerk et al., 2004). Compaction caused by machinery or animals is challenging to measure spatially, but as shown, even a simple assessment of grazing intensity such as low, medium or high, could prove useful in interpreting and understanding hydraulic processes and developing adjustment factors for modelling exercises.

Land use transitions and their direction are likely to be important in determining the level of structural porosity and hydraulic function. It is known for example that SOC plays an important role in determining soil bulk density or porosity (Reynolds et al., 2013; Robinson et al., 2022). Moreover, compilations of results showing the change of SOC through time after a transition from cropland to grassland or grassland to cropland indicate that the degradation and loss of SOC transitioning from cropland to grassland is much quicker than regeneration (Or et al., 2021). Given that the total pore space is related to the SOC it is more than likely that the direction of the transition will impact K and RR. Studies found in this work, such as (Yu et al., 2015) support this potentially slow regeneration path, where they found that K didn't increase under plantation woodland, with the soil having remained compacted from the time of planting. This shows that care must be taken, to avoid unintended consequences, and maximise soil regeneration when it comes to afforestation or agro-forestry used to mitigate climate change or increase functional agro-biodiversity (FAB).

The results indicate complex interactions with land use that result in a quantifiable increase in K from C < G < W. The results in this work are also consistent with (Jarvis et al., 2013); using multiple linear regression techniques they found that the saturated hydraulic conductivity, Ks, in topsoil (<0.3 m depth) was only weakly related to texture, but depended more on bulk density (porosity), SOM, and land use and management factors. The regression analysis, not based on paired sites, indicated that intensive agriculture reduced topsoil Ks by, on average, a factor of ca. 2 to 3 compared to perennial agriculture, natural vegetation and forests; the results are in firm agreement with the findings presented in this work.

The results in this work, using co-located K measurements on the same soil type, under different land uses, puts this finding on a more robust footing, with tangible effect sizes that might be used as K adjustment parameters for vegetation type in biophysical models and ESMs. Both this, and the study of Jarvis et al. (2013) indicate that it is the disturbance by tillage, and its associated effects on soil, that leads to K being dominated by textural porosity. It implies that one of the degradation effects of cropping is the loss of structural porosity and reversion of hydraulic characteristics to those predominantly related to soil texture. Our understanding of soil hydraulic properties across biomes is skewed by a paucity of measurements in pristine or native ecosystems and much better data for croplands (Rahmati et al., 2018). However, even for cultivated soils Green et al. (2003) argued that the greatest challenge for the future was to improve the process-based prediction of hydraulic properties using a systems approach to include tightly coupled process interactions in space and time.

The results presented here indicate that while there is a spread about the median prediction using PTFs, this spread is much greater for grassland and woodland soils and needs to be understood. Further research is needed, but it may well be that relatively undisturbed soils in grassland and woodland converge on an emergent state with similar structural characteristics and hydraulic function at maturity. The results suggest how further research could be improved in the following ways:

- Experimentalists should always report means with uncertainty and the number of replicates for inclusion in the meta-analysis methodology.
- Experiments incorporating a measurable degree of compaction may shed light on the structural impact that grazing or land use has on K, over and above changes to porosity.
- Rooting metrics are rarely presented in hydraulic studies, and determining how root traits impact K would be valuable in linking K prediction to vegetation when soil texture is held constant.
- Determining the extent to which K depends on SOM, roots and the interplay with different plant species and their diversity would provide new insight.
- Incorporating temporal dynamics into K due to management and roots will require the above. Potential may exist for linking K dynamics to root trait libraries.
- Studies which include a broader set of land uses would be helpful, the number of studies with reliable data for three land uses was limited in the literature. Data for shrubs would be a useful addition.
- Determining a surrogate measure for bulk density or porosity, related to land use, would be helpful to determine this parameter for PTF input and improved prediction.

The approach adopted in this work means that evidence based adjustment factors for ESMs for predicting K under different land uses are provided. Land surface modellers are aware that infiltration behaviour is affected by land use, despite a paucity of empirical evidence in the literature. Of the handful of ESMs, the Joint UK Land Environment Simulator

Table 3
Comparison of lookup values for the maximum infiltration rate (Imax = β Ks) used in JULES, with the response ratios determined in this work. Based on the results in Fig. 3 for PTF predictions for croplands, we place cultivated, or bare soil with a value of 1.00.

5 Plant functional types in JULES	β value to determine Imax, upper bound	Surface infiltration response ratio this work, corresponding to cropland = 1.00
•Broadleaf trees	4.00	2.21 (1.73–2.81)
•Needleleaf trees	4.00	2.21 (1.73–2.81)
•Temperate grass	2.00	1.30 (0.99–1.71)
•Tropical grass	2.00	1.30 (0.99–1.71)
•Shrub	2.00	Not determined in this work
4 Non vegetated surfaces		
•Urban	0.10	NA
•Inland water	NA	NA
•Bare soil	0.50	1.00
•Ice	NA	NA

(JULES) (Best et al., 2011; Blyth et al., 2010; Clark et al., 2011) tries to account for land use altering infiltration by introducing empirical correction factors to the hydraulic properties to constrain infiltration with a maximum value (Imax) (Table 3). In the standard version of JULES the maximum infiltration is given by Imax = β Ks, where Ks is determined from a Brooks and Corey or van Genuchten PTF and β is an infiltration enhancement factor (Best et al., 2011; Largeron et al., 2018) which varies from 4 for broadleaf and needle leaf trees, to 0.5 for bare soil and with grasslands in-between at 2. It is unclear how these enhancement factors were derived, but most likely from calibration in different biomes or catchments similar to rainfall interception (Johannes Dolman and Gregory, 1992). Comparison with the meta-analysis results suggests these are appropriate as a general upper bound for woodland and grassland but too low with respect to cropland or bare soil. The findings here for example indicate that a standard PTF from Rosetta (Schaap et al., 2001) predicts K in cropland without major bias (Fig. 3). Grassland, was 1.3 times greater, while woodland was 2.2 times greater. Determining more appropriate values and bounds for β and the implementation of infiltration in models like JULES, will be important for improving the hydraulic representation of processes within ESMs, perhaps more importantly, like us, the JULES modellers recognise that β is an adjustable parameter that likely has a distribution depending on land use and management (Largeron et al., 2018; Van den Hoof et al., 2011).

While substantial areas of the globe are under agricultural management, there is clearly a need to obtain empirical evidence for soil K values in more pristine ecosystems. This will determine whether soils converge to an emergent structural condition with associated porosity and K on the same soil type but under different land uses. Both this study and others (Jarvis et al., 2013) point to this being the case and it needs to be understood and incorporated into land surface models to improve hydrological and climate modelling. Finding a surrogate measure for bulk density or porosity is key and land use might at least provide some estimation. Correction factors are proposed based on cultivated soils, for which PTFs are better established, it is then intuitive to consider native or pristine systems as requiring adjustment for the presence of structural porosity, appreciating that these higher values may be reduced through degradation, either by change of land use, management or compaction. By documenting K for an emergent state in native woodland or grassland a much better understanding of the processes and factors that lead to a reduction in K due to different forms of degradation may be obtained. Moreover, this may lead to a much better representation of the impact of anthropogenic activities on soil hydraulic function and global hydrological cycling in response to both land use and climate change.

CRediT authorship contribution statement

DAR was responsible for the conceptualization and writing of the original draft, SR, AN, AR, AK were responsible for data checking – review & editing. LB and AN helped with the editing. DAR, SR and AN were responsible for the funding acquisition.

Data availability

This is a meta-analysis, all data is freely available in the literature and cited in the article

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.158506.

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