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

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Keywords

Soil hydraulic conductivity, infiltration, Earth System Model, land use change, porosity

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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.

Introduction

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

Figure 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(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^3m^{-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).

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 <<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 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 less than 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.

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 0.30-0.93 m^{3}m^{-3} and soil organic carbon (SOC) between 1-25 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}.

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.

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 (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. 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 toward 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 summarised in Fig 4. A value of 1 indicates no difference in RR between two land uses, whereas values less than 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 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 2-3 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 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.

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). Figure 6 A&B compared the G/W RR with the soils' sand and clay content, again no discernible pattern was observable. Figure 6 C&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). Figure 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 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.

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 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(Van Looy et al., 2017). Whilst 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.(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. (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 (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.

Data availability statement

The data presented in this study were compiled from literature references that are all provided in the supplemental data.

The authors declare that all other data supporting the findings of this study are available within the article and its Supplementary Information files, or are available from the corresponding author upon reasonable request.

Acknowledgments

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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

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 grey rows are prior to outlier removal and the black rows are after. 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

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 Fig3 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

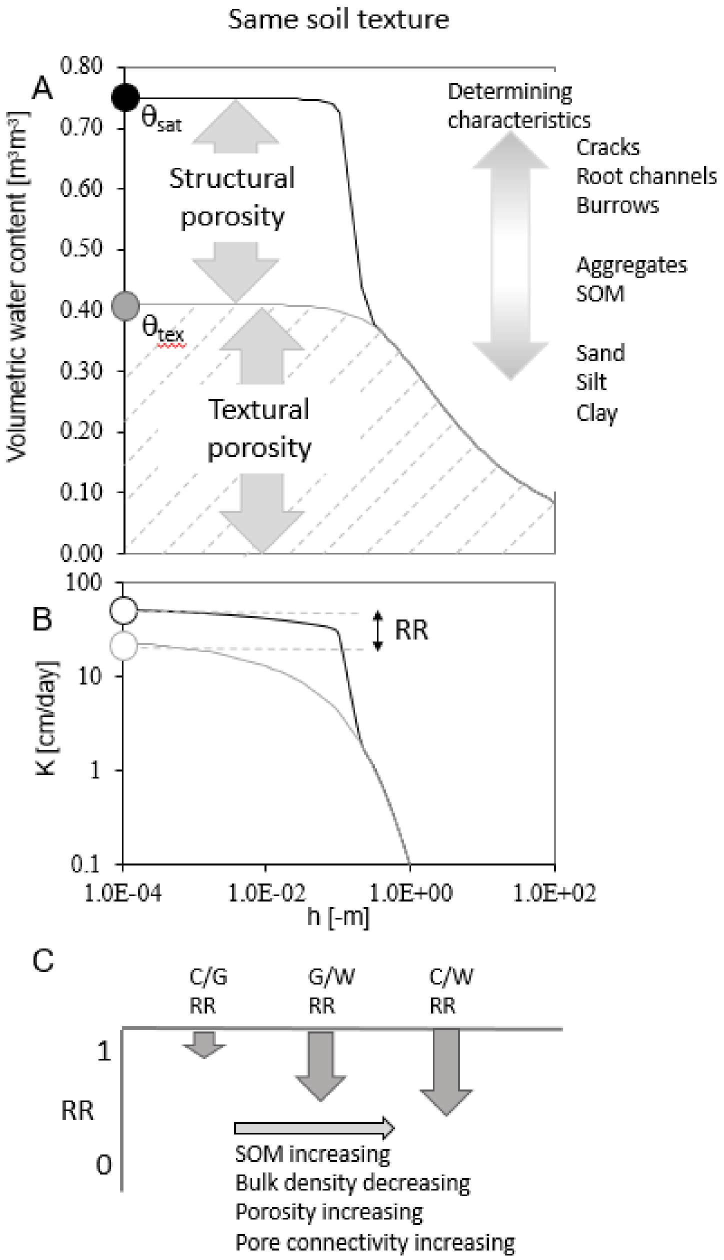


Figure 1. A, water retention curve with suction, h (-m) along the x-axis for A&B, showing the textural and structural hydraulic regions with the dominant characteristics that determine the properties of each region listed on the right. B, the corresponding hydraulic conductivity (K) with the grey line 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 less than 1 that the denominator is greater).

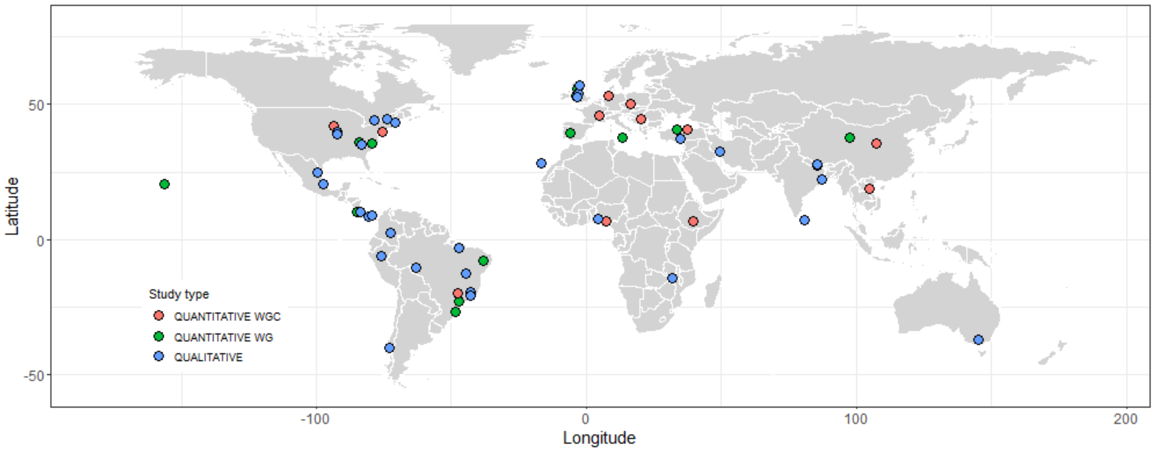


Fig. 2 Locations of the 58 study sites where published hydraulic conductivity and infiltration data allowed the calculation of response ratios (RR). The red dots show sites where information was available for woodland, grassland and cropland; green dots are where only woodland and grassland data were 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.

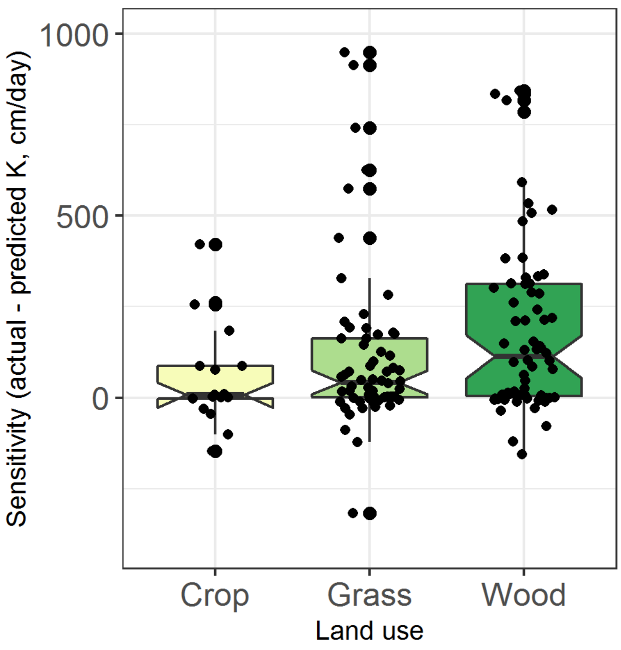


Fig 3. Sensitivity plot showing the actual (measured) K minus the predicted K using PTF and soil texture information. The data show that the median K for cropland is close to zero indicating unbiased correspondence between the measured and predicted K. Measured and predicted K increasingly diverge for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

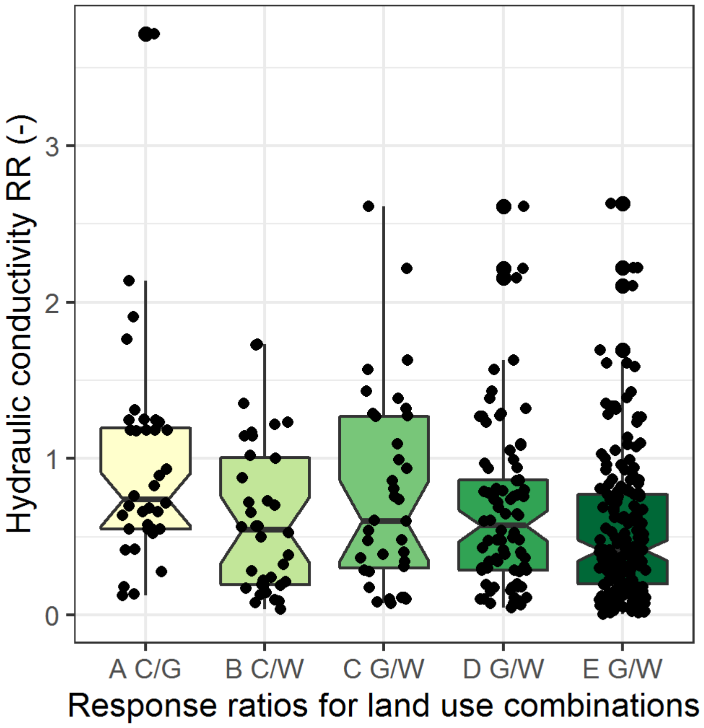
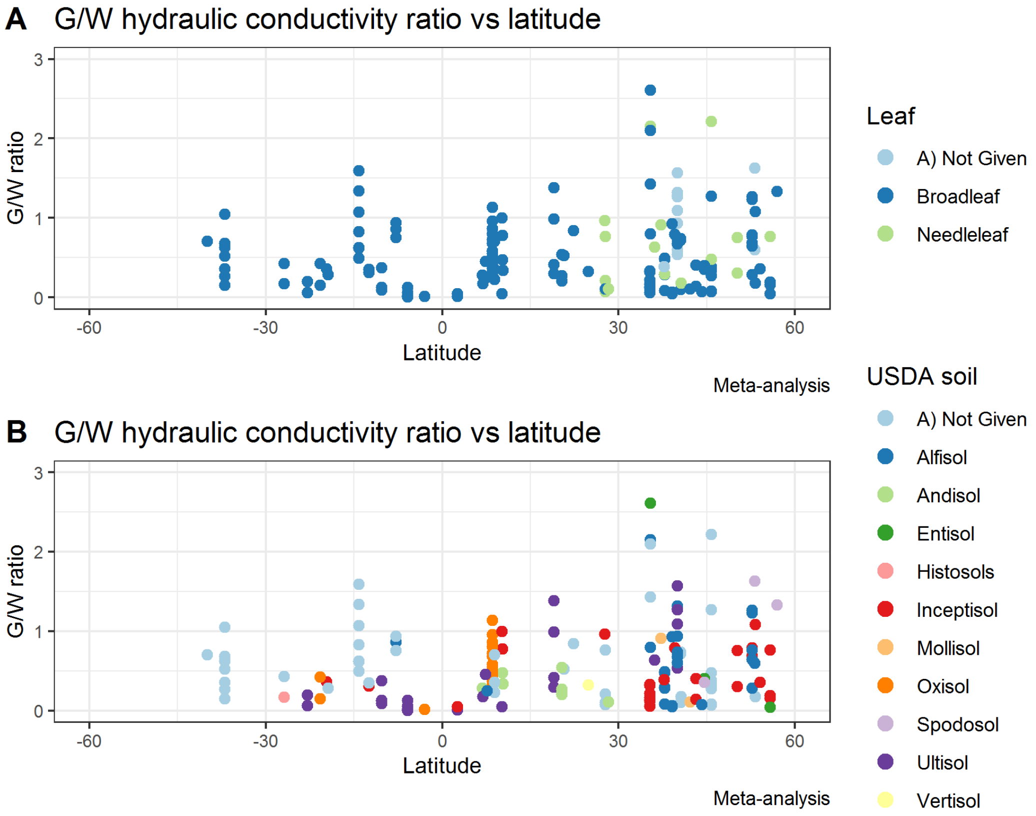


Fig. 4 Hydraulic conductivity response ratios (RR) as a function of the different land use comparisons as published. Medians of RR less than 1 indicate that the hydraulic conductivity (K) of the denominator is higher than the numerator. A, B and C are the main data set for C/G/W. D is the larger data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



A G/W hydraulic conductivity ratio vs latitude

B G/W hydraulic conductivity ratio vs latitude

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.

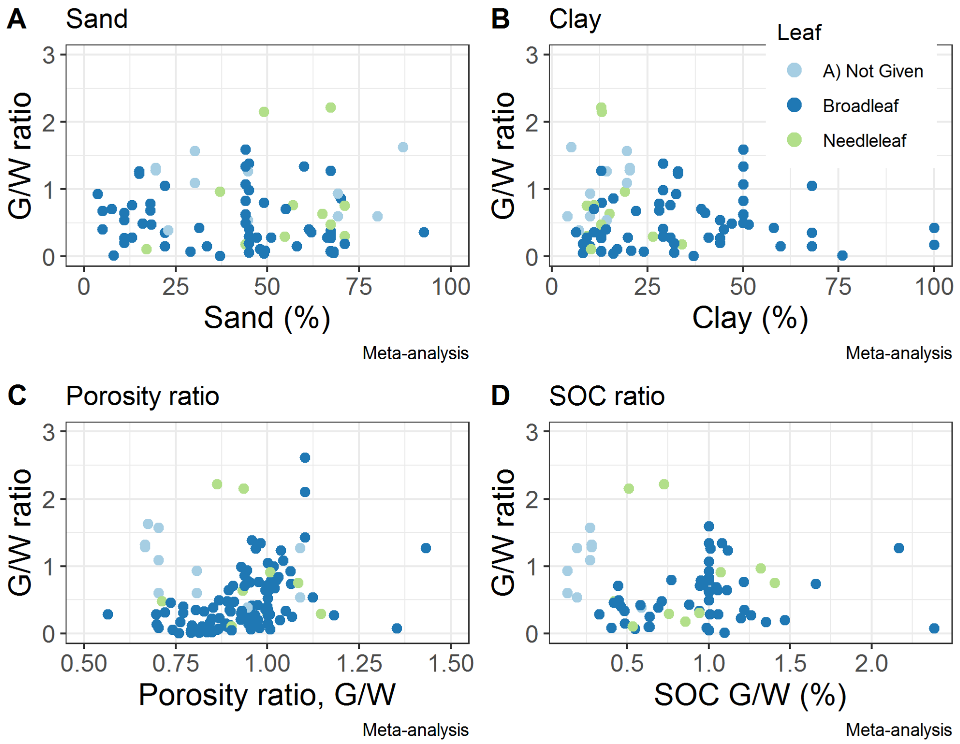


Fig. 6 Response ratios (RR) for G/W as a function of soil texture (A and B), where values lower than 1 indicate higher values of K in woodlands. RR for G/W with difference ratios for porosity and SOC on the x-axis. A difference ratio of 1 on the x-axis indicating no difference, whereas values below 1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

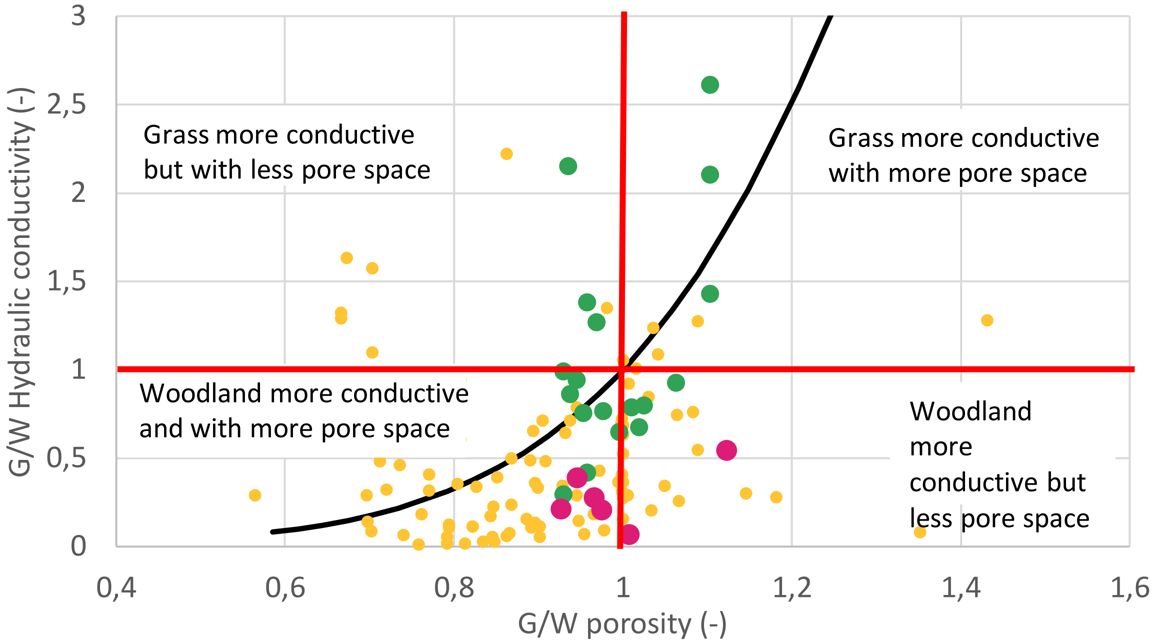


Fig. 7 The K response ratio (RR) for G/W vs the difference in porosity RR (Fig 6C). Where the red lines meet there is no difference between the woodland and grassland samples. The colours represent: green, native or no grazing; red heavily grazed and orange everything else. The black line is the expected 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/).

References

Batjes NH. ISRIC-WISE Harmonized Global Soil Profile Dataset. ISRIC-World Soil Information, Wageningen 2008.

Best M, Pryor M, Clark D, Rooney G, Essery R, Ménard C, et al. The Joint UK Land Environment Simulator (JULES), model description–Part 1: energy and water fluxes. Geoscientific Model Development 2011; 4: 677-699.

Blyth E, Gash J, Lloyd A, Pryor M, Weedon GP, Shuttleworth J. Evaluating the JULES land surface model energy fluxes using FLUXNET data. Journal of Hydrometeorology 2010; 11: 509-519.

Bonetti S, Wei Z, Or D. A framework for quantifying hydrologic effects of soil structure across scales. Communications Earth & Environment 2021; 2: 1-10.

Borrelli P, Alewell C, Alvarez P, Anache JAA, Baartman J, Ballabio C, et al. Soil erosion modelling: A global review and statistical analysis. Science of the total environment 2021; 780: 146494.

Borrelli P, Robinson DA, Fleischer LR, Lugato E, Ballabio C, Alewell C, et al. An assessment of the global impact of 21st century land use change on soil erosion. Nature communications 2017; 8: 2013.

Chandler K, Stevens C, Binley A, Keith A. Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. Geoderma 2018; 310: 120-127.

Clark D, Mercado L, Sitch S, Jones C, Gedney N, Best M, et al. The Joint UK Land Environment Simulator (JULES), model description–Part 2: carbon fluxes and vegetation dynamics. Geoscientific Model Development 2011; 4: 701-722.

Fatichi S, Or D, Walko R, Vereecken H, Young MH, Ghezzehei TA, et al. Soil structure is an important omission in Earth System Models. Nature communications 2020; 11: 1-11.

Green TR, Ahuja LR, Benjamin JG. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 2003; 116: 3-27.

Gupta S, Hengl T, Lehmann P, Bonetti S, Or D. SoilKsatDB: global database of soil saturated hydraulic conductivity measurements for geoscience applications. Earth System Science Data 2021; 13: 1593-1612.

Hedges LV, Gurevitch J, Curtis PS. The meta-analysis of response ratios in experimental ecology. Ecology 1999; 80: 1150-1156.

Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Statistics in medicine 2002; 21: 1539-1558.

Hirmas DR, Giménez D, Nemes A, Kerry R, Brunsell NA, Wilson CJ. Climate-induced changes in continental-scale soil macroporosity may intensify water cycle. Nature 2018; 561: 100.

Hu W, Shao M, Si B. Seasonal changes in surface bulk density and saturated hydraulic conductivity of natural landscapes. European Journal of Soil Science 2012; 63: 820-830.

Hu W, Shao M, Wang Q, Fan J, Horton R. Temporal changes of soil hydraulic properties under different land uses. Geoderma 2009; 149: 355-366.

Jarvis N, Koestel J, Messing I, Moeys J, Lindahl A. Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. Hydrology and Earth System Sciences 2013; 17: 5185-5195.

Johannes Dolman A, Gregory D. The parametrization of rainfall interception in GCMs. Quarterly Journal of the Royal Meteorological Society 1992; 118: 455-467.

Largeron C, Cloke H, Verhoef A, Martinez-de la Torre A, Mueller A. Impact of the Representation of the Infiltration on the River Flow during Intense Rainfall Events in JULES. ECMWF Technical Memorandum 2018.

Mbagwu J. Quasi-steady infiltration rates of highly permeable tropical moist savannah soils in relation to landuse and pore size distribution. Soil Technology 1997; 11: 185-195.

Or D, Keller T, Schlesinger WH. Natural and managed soil structure: On the fragile scaffolding for soil functioning. Soil and Tillage Research 2021; 208: 104912.

Rahmati M, Weihermüller L, Vanderborght J, Pachepsky YA, Mao L, Sadeghi SH, et al. Development and analysis of the Soil Water Infiltration Global database. Earth system science data 2018; 10: 1237-1263.

Reynolds B, Chamberlain P, Poskitt J, Woods C, Scott W, Rowe E, et al. Countryside Survey: National "Soil Change" 1978–2007 for Topsoils in Great Britain—acidity, carbon, and total nitrogen status. Vadose Zone Journal 2013; 12: 1-15.

Rietkerk M, Dekker SC, de Ruiter PC, van de Koppel J. Self-organized patchiness and catastrophic shifts in ecosystems. Science 2004; 305: 1926-1929.

Ritchie H, Roser M. "Land Use". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/land-use' [Online Resource]. 2013.

Robinson D, Thomas A, Reinsch S, Lebron I, Feeney C, Maskell L, et al. Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. Scientific reports 2022; 12: 1-13.

Schaap MG, Leij FJ, Van Genuchten MT. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of hydrology 2001; 251: 163-176.

Schenk HJ, Jackson RB. The global biogeography of roots. Ecological monographs 2002; 72: 311-328.

Schwarzer G, Carpenter JR, Rücker G. Meta-analysis with R. Vol 4784: Springer, 2015.

Thompson S, Harman C, Heine P, Katul G. Vegetation-infiltration relationships across climatic and soil type gradients. Journal of Geophysical Research: Biogeosciences 2010; 115.

Van den Hoof C, Hanert E, Vidale PL. Simulating dynamic crop growth with an adapted land surface model–JULES-SUCROS: Model development and validation. Agricultural and Forest Meteorology 2011; 151: 137-153.

Van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. Soil science society of America journal 1980; 44: 892-898.

Van Looy K, Bouma J, Herbst M, Koestel J, Minasny B, Mishra U, et al. Pedotransfer functions in Earth system science: challenges and perspectives. Reviews of Geophysics 2017; 55: 1199-1256.

Webb B. Investigating the impact of trees and hedgerows on landscape hydrology. Bangor University (United Kingdom), 2021.

Weynants M, Montanarella L, Toth G, Arnoldussen A, Anaya Romero M, Bilas G, et al. European HYdropedological Data Inventory (EU-HYDI). EUR Scientific and Technical Research Series 2013.

Wösten J. The HYPRES database of hydraulic properties of European soils. Advances in GeoEcology 2000: 135-143.

Yu M, Zhang L, Xu X, Feger KH, Wang Y, Liu W, et al. Impact of land-use changes on soil hydraulic properties of Calcaric Regosols on the Loess Plateau, NW China. Journal of Plant Nutrition and Soil Science 2015; 178: 486-498.

Zhang Y, Schaap MG. Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3). Journal of Hydrology 2017; 547: 39-53.

Zhang Y, Schaap MG. Estimation of saturated hydraulic conductivity with pedotransfer functions: A review. Journal of Hydrology 2019; 575: 1011-1030.

Supplementary information

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

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Methods

Prisma method

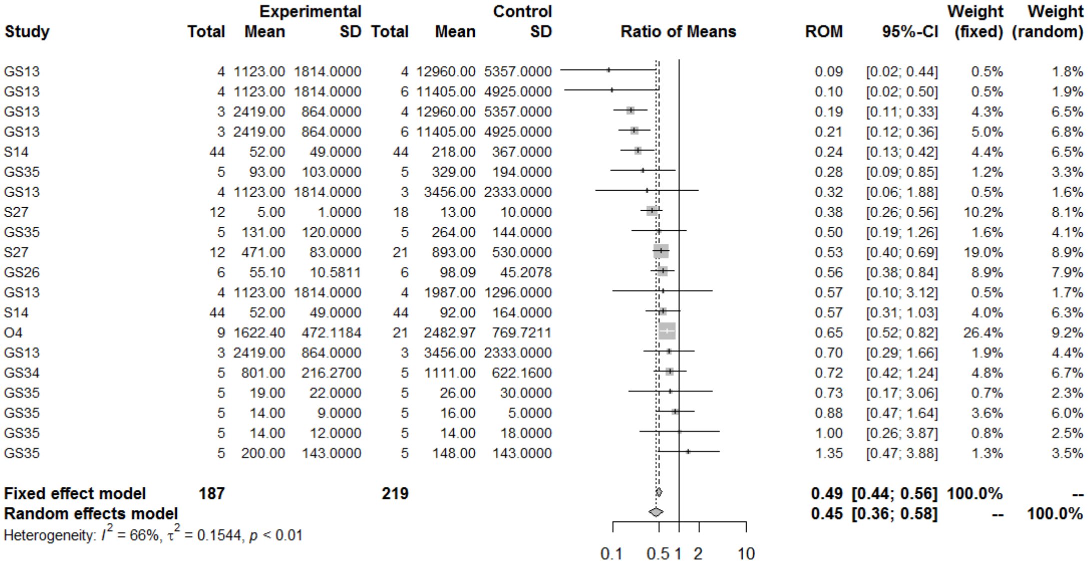
PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) methodology was used for this study with the relevant material and methods detailed further on.

Data preparation and meta-analysis

Searches were conducted in the literature using Google Scholar and Scopus (see supplemental information). Data was extracted from papers identified from the structured searches. The data were converted to common units and as much ancillary data was extracted as possible. Meta-analysis was undertaken using the Meta package in R[1] and following the procedures described in [2]. Data were visualised using a combination of Forest, Baujat, Funnel and GOSH plots. The Forest plots were used to visualise the data and determine the RR using a random effects model. Baujat plots and funnel plots were used to identify the influence of studies and data heterogeneity respectively. In addition, Graphic display of heterogeneity (GOSH) plots were used to explore the patterns of heterogeneity for the random effects model. Outliers were detected and removed using the function call find.outliers, which detects and removes outliers using the dmetar package described in[2]. Eggers' test of the intercept for bias was used to determine the presence of funnel plot asymmetry. Data were accepted for analysis when there was no asymmetry.

Cropland and Woodlands (C/W): In Table 1 (main text) rows 1 & 2 contain the data for the cropland and woodland (C/W), based on 13 studies that contained measurements for cropland, grassland and woodland. The results in pale grey represent all 13 studies, while on the row below the data set has had the outliers removed. The effect size increases marginally from 0.4337 to 0.4535, with the forest plot for the data with outliers removed presented in Fig S1a. The between-study heterogeneity variance reduced from $\tau^2 = 0.5432$ [0.3631; 1.2563] to $\tau^2 = 0.1544$ [0.0482; 0.6479], with an I^2 value that dropped from 91.4% [89.1%; 93.2%] to an $I^2 = 65.5\%$ [44.7%; 78.5%] after outlier removal. Plots are presented for the influence, Baujat plot (Fig S1b) and heterogeneity, funnel plot (Fig S1c). The Eggers' test confirming the absence of funnel plot asymmetry following the removal of the outliers. Further exploration of the effect size and heterogeneity was conducted using a GOSH[3] plot (Fig S1d) which shows relative homogeneity for the effect size and the absence of clustering. While the heterogeneity shows some spread and a cluster close to zero.

S1a Corresponding to Table 1 (main text) row 2. Meta-analysis for C/W response ratios after outliers removed shown using a forest plot.



	Experimental			Control					Weight	Weight
Study	Total	Mean	SD	Total	Mean	SD	ROM	95%-CI	(fixed)	(random)
GS13	4	1123.00	1814.0000	4	12960.00	5357.0000	0.09	[0.02; 0.44]	0.5%	1.8%
GS13	4	1123.00	1814.0000	6	11405.00	4925.0000	0.10	[0.02; 0.50]	0.5%	1.9%
GS13	3	2419.00	864.0000	4	12960.00	5357.0000	0.19	[0.11; 0.33]	4.3%	6.5%
GS13	3	2419.00	864.0000	6	11405.00	4925.0000	0.21	[0.12; 0.36]	5.0%	6.8%
S14	44	52.00	49.0000	44	218.00	367.0000	0.24	[0.13; 0.42]	4.4%	6.5%
GS35	5	93.00	103.0000	5	329.00	194.0000	0.28	[0.09; 0.85]	1.2%	3.3%
GS13	4	1123.00	1814.0000	3	3456.00	2333.0000	0.32	[0.06; 1.88]	0.5%	1.6%
S27	12	5.00	1.0000	18	13.00	10.0000	0.38	[0.26; 0.56]	10.2%	8.1%
GS35	5	131.00	120.0000	5	264.00	144.0000	0.50	[0.19; 1.26]	1.6%	4.1%
S27	12	471.00	83.0000	21	893.00	530.0000	0.53	[0.40; 0.69]	19.0%	8.9%
GS26	6	55.10	10.5811	6	98.09	45.2078	0.56	[0.38; 0.84]	8.9%	7.9%
GS13	4	1123.00	1814.0000	4	1987.00	1296.0000	0.57	[0.10; 3.12]	0.5%	1.7%
S14	44	52.00	49.0000	44	92.00	164.0000	0.57	[0.31; 1.03]	4.0%	6.3%
O4	9	1622.40	472.1184	21	2482.97	769.7211	0.65	[0.52; 0.82]	26.4%	9.2%
GS13	3	2419.00	864.0000	3	3456.00	2333.0000	0.70	[0.29; 1.66]	1.9%	4.4%
GS34	5	801.00	216.2700	5	1111.00	622.1600	0.72	[0.42; 1.24]	4.8%	6.7%
GS35	5	19.00	22.0000	5	26.00	30.0000	0.73	[0.17; 3.06]	0.7%	2.3%
GS35	5	14.00	9.0000	5	16.00	5.0000	0.88	[0.47; 1.64]	3.6%	6.0%
GS35	5	14.00	12.0000	5	14.00	18.0000	1.00	[0.26; 3.87]	0.8%	2.5%
GS35	5	200.00	143.0000	5	148.00	143.0000	1.35	[0.47; 3.88]	1.3%	3.5%
Fixed effect model	**187**			**219**			**0.49**	**[0.44; 0.56]**	**100.0%**	**--**
Random effects model							**0.45**	**[0.36; 0.58]**	**--**	**100.0%**

Heterogeneity: $I^2 = 66\%$, $\tau^2 = 0.1544$, $p < 0.01$

Fig S1b Corresponding to Table 1 (main text) row 2. Baujat plot and S1c funnel plot indicating the influence and data heterogeneity patterns for the C/W (n=7 studies, 20 RR). Eggers' test of the intercept for bias, intercept -0.756; 95% CI [-2.13 - 0.61]; t -1.081; p 0.2939785. Eggers' test does not indicate the presence of funnel plot asymmetry.

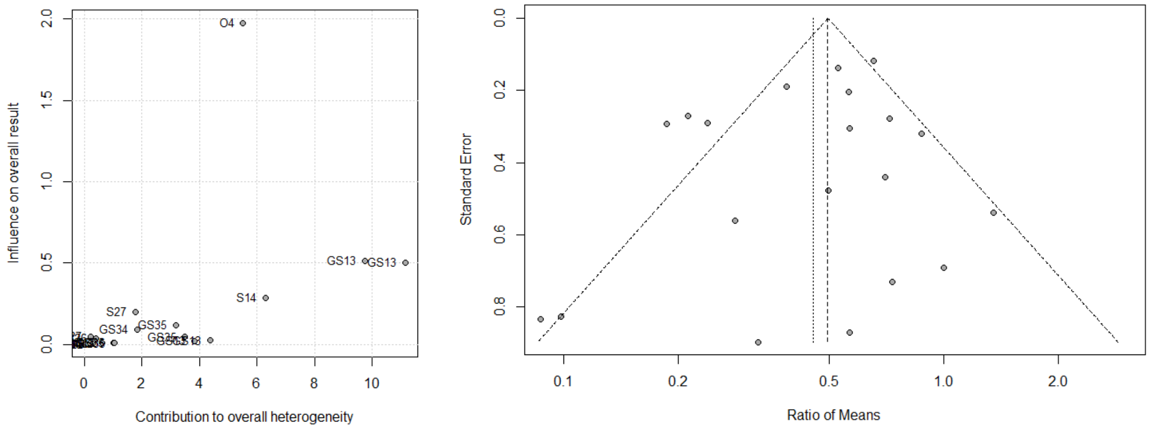
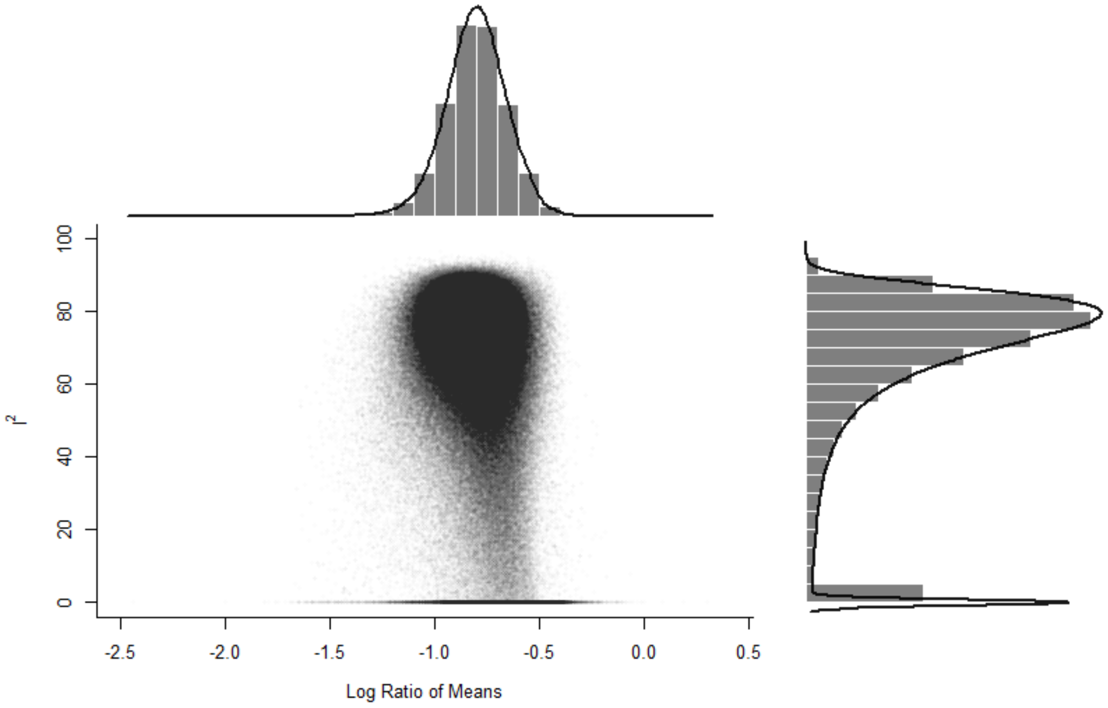
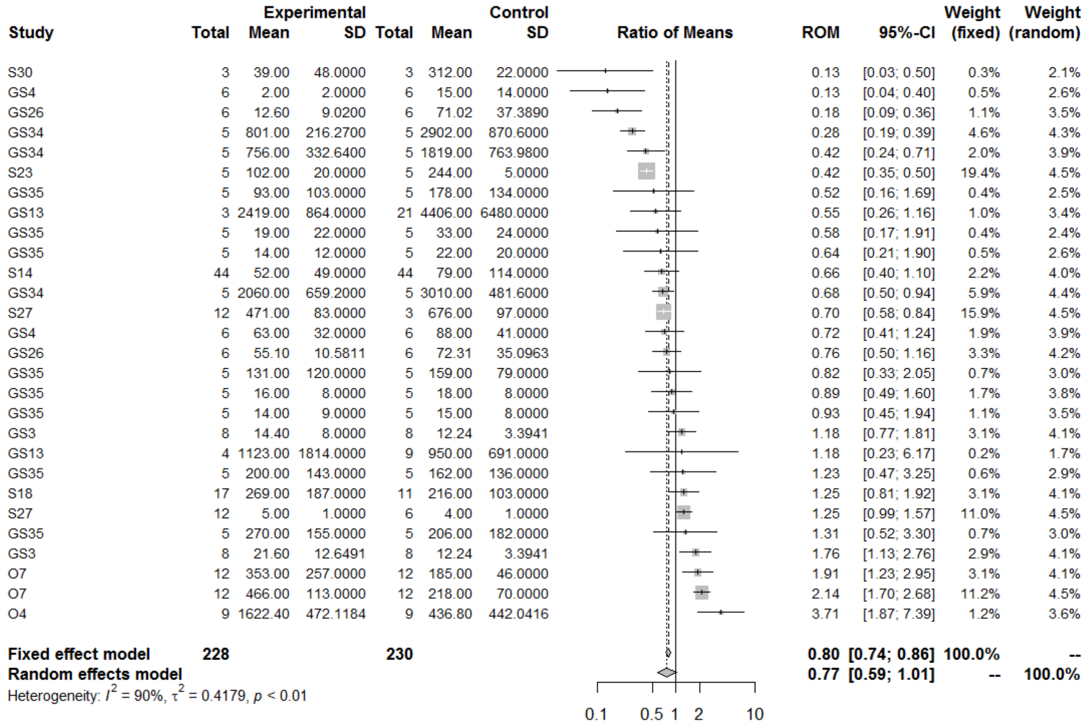


Figure S1d Corresponding to Table 1 (main text) row 2. Graphic display of heterogeneity (GOSH) plot to explore the patterns of heterogeneity for the random effects model Trikalinos 2012)



Cropland and Grassland (C/G): In Table 1 (main text) row 3 contains the data for the cropland and grassland (C/G), based on the same 13 studies, with no outliers detected. The effect size = 0.7696 [0.5860; 1.0107] and its reciprocal 1.3 indicated a small but significant increase in K in grassland compared to cropland. The forest plot for the data is presented in Fig S2a. The between-study heterogeneity variance was high $\tau^2 = 0.4179$ [0.2289; 0.9423], with an I^2 value of 90.2% [87.1%; 92.6%]. The corresponding Baujat plot for the influence is (Fig S2b) and the funnel plot for heterogeneity is (Fig S2c). The Eggers' test confirms the absence of funnel plot asymmetry. The GOSH plot (Fig S2d) shows relative homogeneity for the effect size and the absence of clusters, but the range is quite broad

S2a Corresponding to Table 1 (main text) row 3. Meta-analysis for C/G response ratios after outliers removed shown using a forest plot.



		Experimental				Control			Weight	Weight
Study	**Total**	**Mean**	**SD**	**Total**	**Mean**	**SD**	**ROM**	**95%-CI**	**(fixed)**	**(random)**
S30	3	39.00	48.0000	3	312.00	22.0000	0.13	[0.03; 0.50]	0.3%	2.1%
GS4	6	2.00	2.0000	6	15.00	14.0000	0.13	[0.04; 0.40]	0.5%	2.6%
GS26	6	12.60	9.0200	6	71.02	37.3890	0.18	[0.09; 0.36]	1.1%	3.5%
GS34	5	801.00	216.2700	5	2902.00	870.6000	0.28	[0.19; 0.39]	4.6%	4.3%
GS34	5	756.00	332.6400	5	1819.00	763.9800	0.42	[0.24; 0.71]	2.0%	3.9%
S23	5	102.00	20.0000	5	244.00	5.0000	0.42	[0.35; 0.50]	19.4%	4.5%
GS35	5	93.00	103.0000	5	178.00	134.0000	0.52	[0.16; 1.69]	0.4%	2.5%
GS13	3	2419.00	864.0000	21	4406.00	6480.0000	0.55	[0.26; 1.16]	1.0%	3.4%
GS35	5	19.00	22.0000	5	33.00	24.0000	0.58	[0.17; 1.91]	0.4%	2.4%
GS35	5	14.00	12.0000	5	22.00	20.0000	0.64	[0.21; 1.90]	0.5%	2.6%
S14	44	52.00	49.0000	44	79.00	114.0000	0.66	[0.40; 1.10]	2.2%	4.0%
GS34	5	2060.00	659.2000	5	3010.00	481.6000	0.68	[0.50; 0.94]	5.9%	4.4%
S27	12	471.00	83.0000	3	676.00	97.0000	0.70	[0.58; 0.84]	15.9%	4.5%
GS4	6	63.00	32.0000	6	88.00	41.0000	0.72	[0.41; 1.24]	1.9%	3.9%
GS26	6	55.10	10.5811	6	72.31	35.0963	0.76	[0.50; 1.16]	3.3%	4.2%
GS35	5	131.00	120.0000	5	159.00	79.0000	0.82	[0.33; 2.05]	0.7%	3.0%
GS35	5	16.00	8.0000	5	18.00	8.0000	0.89	[0.49; 1.60]	1.7%	3.8%
GS35	5	14.00	9.0000	5	15.00	8.0000	0.93	[0.45; 1.94]	1.1%	3.5%
GS3	8	14.40	8.0000	8	12.24	3.3941	1.18	[0.77; 1.81]	3.1%	4.1%
GS13	4	1123.00	1814.0000	9	950.00	691.0000	1.18	[0.23; 6.17]	0.2%	1.7%
GS35	5	200.00	143.0000	5	162.00	136.0000	1.23	[0.47; 3.25]	0.6%	2.9%
S18	17	269.00	187.0000	11	216.00	103.0000	1.25	[0.81; 1.92]	3.1%	4.1%
S27	12	5.00	1.0000	6	4.00	1.0000	1.25	[0.99; 1.57]	11.0%	4.5%
GS35	5	270.00	155.0000	5	206.00	182.0000	1.31	[0.52; 3.30]	0.7%	3.0%
GS3	8	21.60	12.6491	8	12.24	3.3941	1.76	[1.13; 2.76]	2.9%	4.1%
O7	12	353.00	257.0000	12	185.00	46.0000	1.91	[1.23; 2.95]	3.1%	4.1%
O7	12	466.00	113.0000	12	218.00	70.0000	2.14	[1.70; 2.68]	11.2%	4.5%
O4	9	1622.40	472.1184	9	436.80	442.0416	3.71	[1.87; 7.39]	1.2%	3.6%
Fixed effect model	**228**			**230**			**0.80**	**[0.74; 0.86]**	**100.0%**	**--**
Random effects model							**0.77**	**[0.59; 1.01]**	**--**	**100.0%**

Heterogeneity: $I^2 = 90\%$, $\tau^2 = 0.4179$, $p < 0.01$

Fig S2b Corresponding to Table 1 (main text) row 3. Baujat plot and S2c funnel plot indicating the influence and data heterogeneity patterns for the C/G RR (n=13 studies, RR = 28). Eggers' test of the intercept for bias, intercept -0.069; 95% CI [-2.28 – 2.15]; t -0.061; p 0.9520215. Eggers' test does not indicate the presence of funnel plot asymmetry.

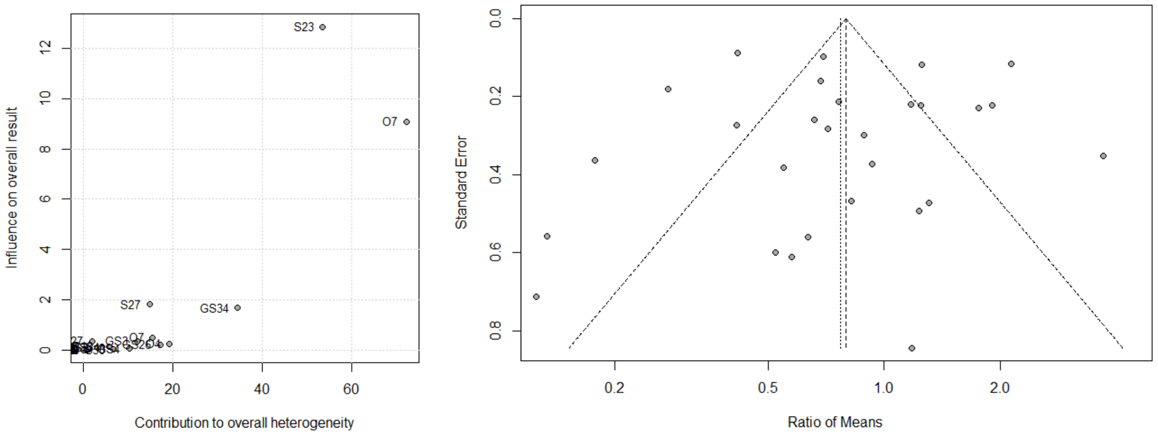
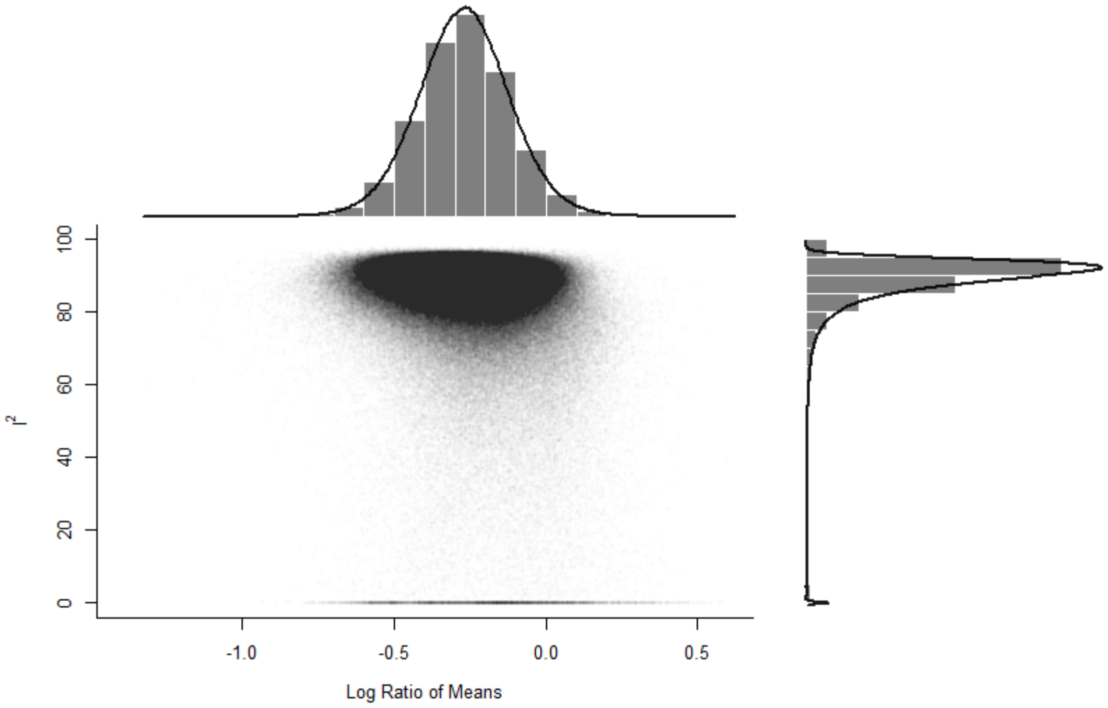
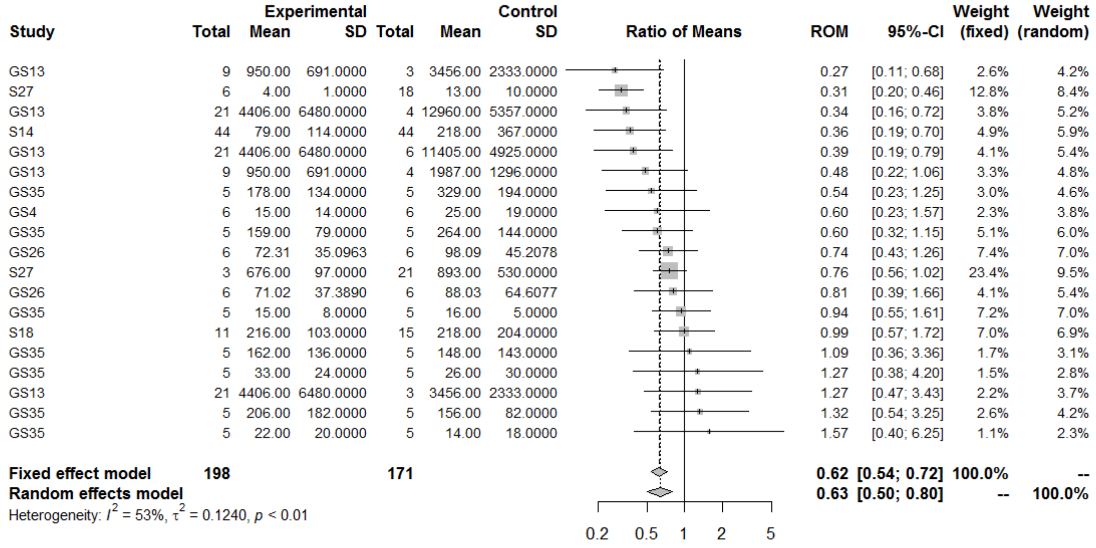


Figure S2d Corresponding to Table 1 (main text) row 3. GOSH plot for random effects



Grassland and Woodlands (G/W): In Table 1 (main text) rows 4-8 contain data for the grassland and woodland (G/W), results for the 13 studies (C/G/W) are in rows 4 and 5 (outliers removed), while the results from the larger data set of 30 studies are in rows 6 and, with the outliers removed, 7; row 8 contains the median of data for all 58 studies and 182 RR. The effect size for the 13 studies increased from 0.5415 to 0.6327 after the outliers were removed, with the forest plot for the data with outliers removed presented are in Fig S4a. The between-study heterogeneity variance reduced from $\tau^2 = 0.6471$ [0.3341; 1.8995] to $\tau^2 = 0.1478$ [0.0419; 0.5657], with an I^2 value that dropped from 96.8% [96.2%; 97.3%] to an $I^2 = 52.9\%$ [20.6%; 72.0%]. Plots for the influence, Baujat plot (Fig S4b) and heterogeneity, funnel plot (Fig S4c) are presented in the supplemental data; the Eggers' test confirming the absence of funnel plot asymmetry following the removal of the outliers. The GOSH plot (Fig S3d) again indicates homogeneity for the effect size and the absence of clusters, while the heterogeneity is quite broad with a small spike at low values.

S3a Corresponding to Table 1 (main text) row 5. Meta-analysis for G/W response ratios after outliers removed shown using a forest plot.



Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	ROM	95%-CI	Weight (fixed)	Weight (random)
GS13	9	950.00	691.0000	3	3456.00	2333.0000	0.27	[0.11; 0.68]	2.6%	4.2%
S27	6	4.00	1.0000	18	13.00	10.0000	0.31	[0.20; 0.46]	12.8%	8.4%
GS13	21	4406.00	6480.0000	4	12960.00	5357.0000	0.34	[0.16; 0.72]	3.8%	5.2%
S14	44	79.00	114.0000	44	218.00	367.0000	0.36	[0.19; 0.70]	4.9%	5.9%
GS13	21	4406.00	6480.0000	6	11405.00	4925.0000	0.39	[0.19; 0.79]	4.1%	5.4%
GS13	9	950.00	691.0000	4	1987.00	1296.0000	0.48	[0.22; 1.06]	3.3%	4.8%
GS35	5	178.00	134.0000	5	329.00	194.0000	0.54	[0.23; 1.25]	3.0%	4.6%
GS4	6	15.00	14.0000	6	25.00	19.0000	0.60	[0.23; 1.57]	2.3%	3.8%
GS35	5	159.00	79.0000	5	264.00	144.0000	0.60	[0.32; 1.15]	5.1%	6.0%
GS26	6	72.31	35.0963	6	98.09	45.2078	0.74	[0.43; 1.26]	7.4%	7.0%
S27	3	676.00	97.0000	21	893.00	530.0000	0.76	[0.56; 1.02]	23.4%	9.5%
GS26	6	71.02	37.3890	6	88.03	64.6077	0.81	[0.39; 1.66]	4.1%	5.4%
GS35	5	15.00	8.0000	5	16.00	5.0000	0.94	[0.55; 1.61]	7.2%	7.0%
S18	11	216.00	103.0000	15	218.00	204.0000	0.99	[0.57; 1.72]	7.0%	6.9%
GS35	5	162.00	136.0000	5	148.00	143.0000	1.09	[0.36; 3.36]	1.7%	3.1%
GS35	5	33.00	24.0000	5	26.00	30.0000	1.27	[0.38; 4.20]	1.5%	2.8%
GS13	21	4406.00	6480.0000	3	3456.00	2333.0000	1.27	[0.47; 3.43]	2.2%	3.7%
GS35	5	206.00	182.0000	5	156.00	82.0000	1.32	[0.54; 3.25]	2.6%	4.2%
GS35	5	22.00	20.0000	5	14.00	18.0000	1.57	[0.40; 6.25]	1.1%	2.3%
Fixed effect model	**198**			**171**			**0.62**	**[0.54; 0.72]**	**100.0%**	**--**
Random effects model							**0.63**	**[0.50; 0.80]**	**--**	**100.0%**

Heterogeneity: $I^2 = 53\%$, $\tau^2 = 0.1240$, $p < 0.01$

Fig S3b Corresponding to Table 1 (main text) row 5. Baujat plot and S3c funnel plot indicating the influence and data heterogeneity patterns for the G/W RR (n=7 studies, RR=19). Eggers' test of the intercept for bias, intercept 0.51; 95% CI [-1.23 - 2.25]; t 0.573; p 0.5744352. Eggers' test does not indicate the presence of funnel plot asymmetry.

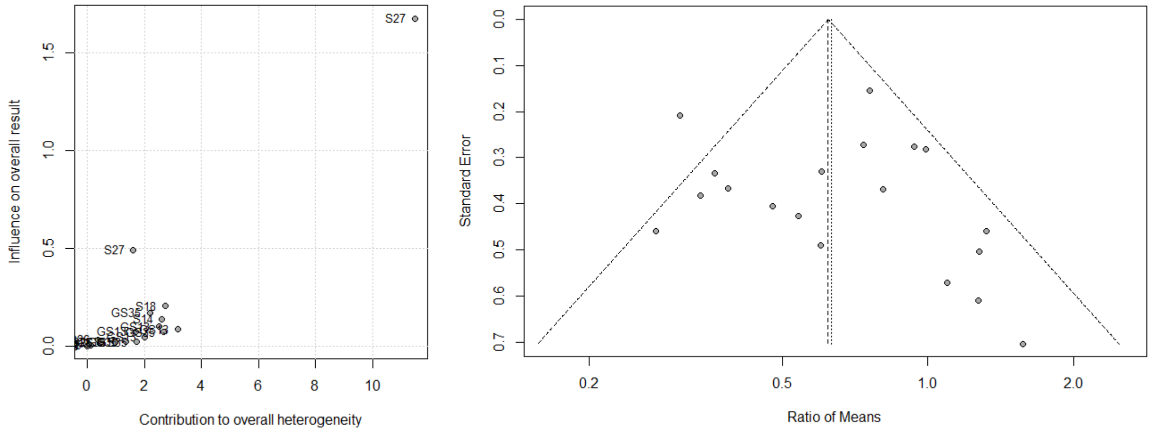
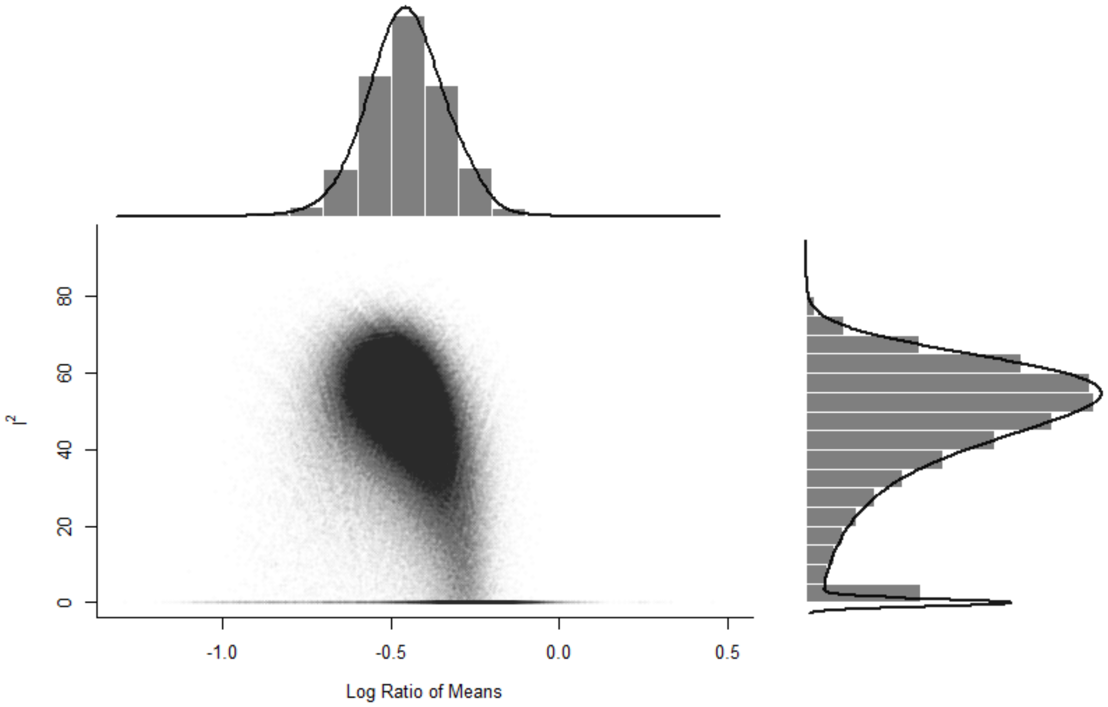
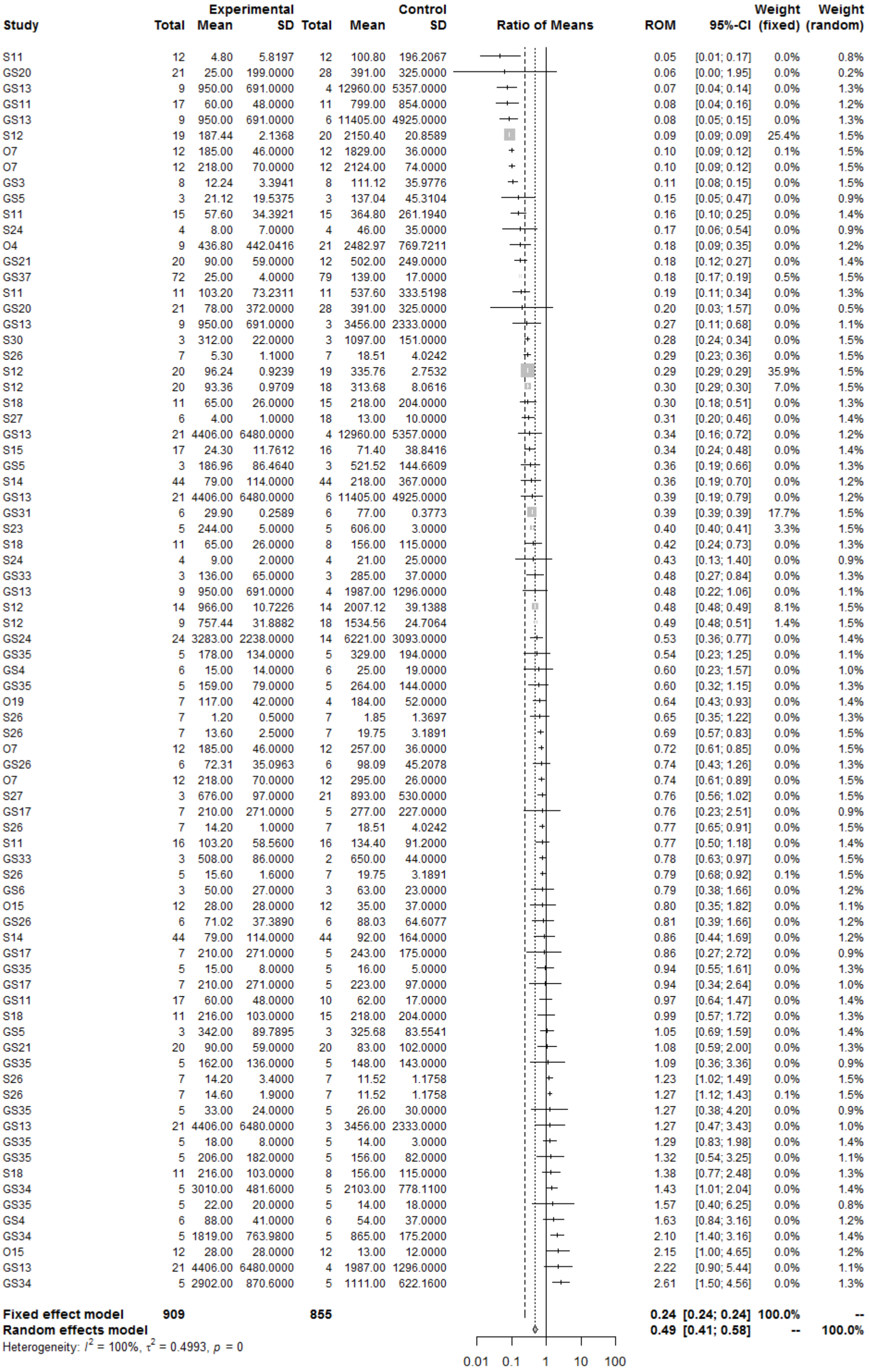


Figure S3d Corresponding to Table 1 (main text) row 5. GOSH plot for random effects



A forest plot for 30 studies (RR = 79) with G/W data prior to outlier removal is presented in Fig S4a and has an effect size of 0.4898 before the removal of outliers.

S4a Corresponding to Table 1 (main text) row 6. Meta-analysis for G/W response ratios for all papers with grassland and woodland data (n=30 studies 79 RR).

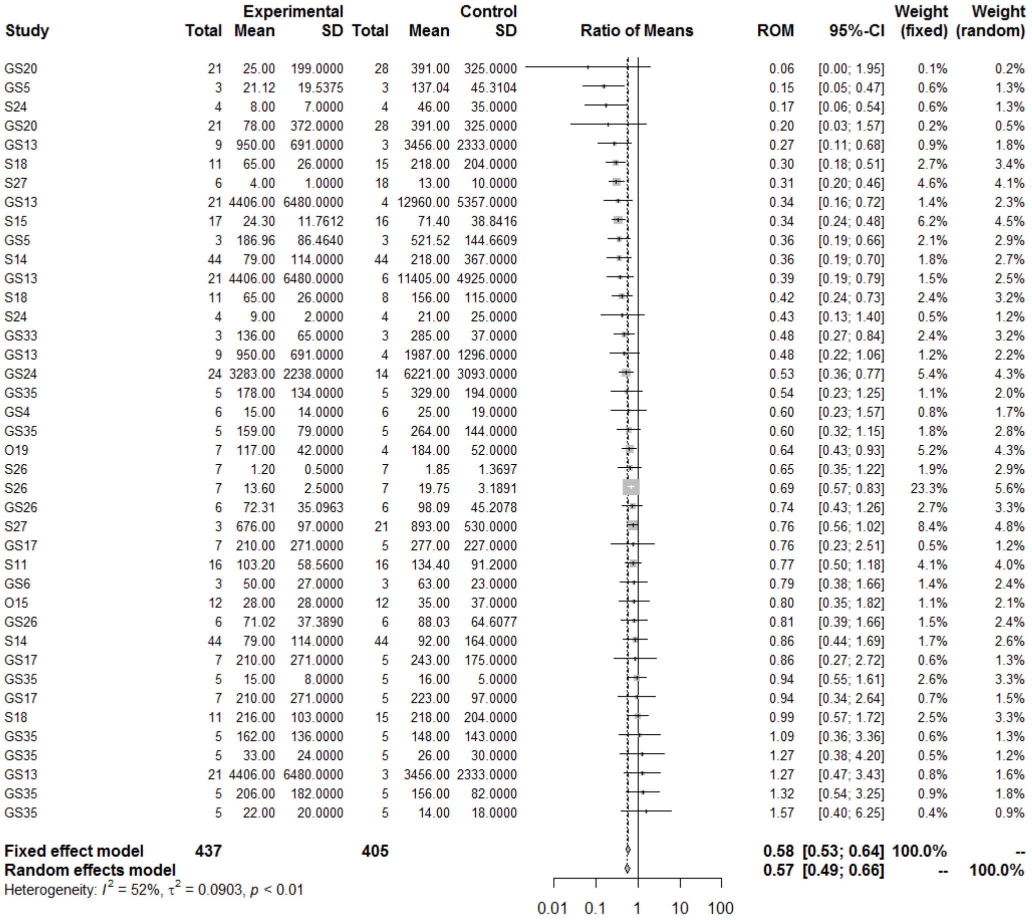


		Experimental			Control					Weight	Weight
Study	**Total**	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Ratio of Means**	**ROM**	**95%-CI**	**(fixed)**	**(random)**
S11	12	4.80	5.8197	12	100.80	196.2067		0.05	[0.01; 0.17]	0.0%	0.8%
GS20	21	25.00	199.0000	28	391.00	325.0000		0.06	[0.00; 1.95]	0.0%	0.2%
GS13	9	950.00	691.0000	4	12960.00	5357.0000		0.07	[0.04; 0.14]	0.0%	1.3%
GS11	17	60.00	48.0000	11	799.00	854.0000		0.08	[0.04; 0.16]	0.0%	1.2%
GS13	9	950.00	691.0000	6	11405.00	4925.0000		0.08	[0.05; 0.15]	0.0%	1.3%
S12	19	187.44	2.1368	20	2150.40	20.8589		0.09	[0.09; 0.09]	25.4%	1.5%
O7	12	185.00	46.0000	12	1829.00	36.0000		0.10	[0.09; 0.12]	0.1%	1.5%
O7	12	218.00	70.0000	12	2124.00	74.0000		0.10	[0.09; 0.12]	0.0%	1.5%
GS3	8	12.24	3.3941	8	111.12	35.9776		0.11	[0.08; 0.15]	0.0%	1.5%
GS5	3	21.12	19.5375	3	137.04	45.3104		0.15	[0.05; 0.47]	0.0%	0.9%
S11	15	57.60	34.3921	15	364.80	261.1940		0.16	[0.10; 0.25]	0.0%	1.4%
S24	4	8.00	7.0000	4	46.00	35.0000		0.17	[0.06; 0.54]	0.0%	0.9%
O4	9	436.80	442.0416	21	2482.97	769.7211		0.18	[0.09; 0.35]	0.0%	1.2%
GS21	20	90.00	59.0000	12	502.00	249.0000		0.18	[0.12; 0.27]	0.0%	1.4%
GS37	72	25.00	4.0000	79	139.00	17.0000		0.18	[0.17; 0.19]	0.5%	1.5%
S11	11	103.20	73.2311	11	537.60	333.5198		0.19	[0.11; 0.34]	0.0%	1.3%
GS20	21	78.00	372.0000	28	391.00	325.0000		0.20	[0.03; 1.57]	0.0%	0.5%
GS13	9	950.00	691.0000	3	3456.00	2333.0000		0.27	[0.11; 0.68]	0.0%	1.1%
S30	3	312.00	22.0000	3	1097.00	151.0000		0.28	[0.24; 0.34]	0.0%	1.5%
S26	7	5.30	1.1000	7	18.51	4.0242		0.29	[0.23; 0.36]	0.0%	1.5%
S12	20	96.24	0.9239	19	335.76	2.7532		0.29	[0.29; 0.29]	35.9%	1.5%
S12	20	93.36	0.9709	18	313.68	8.0616		0.30	[0.29; 0.30]	7.0%	1.5%
S18	11	65.00	26.0000	15	218.00	204.0000		0.30	[0.18; 0.51]	0.0%	1.3%
S27	6	4.00	1.0000	18	13.00	10.0000		0.31	[0.20; 0.46]	0.0%	1.4%
GS13	21	4406.00	6480.0000	4	12960.00	5357.0000		0.34	[0.16; 0.72]	0.0%	1.2%
S15	17	24.30	11.7612	16	71.40	38.8416		0.34	[0.24; 0.48]	0.0%	1.4%
GS5	3	186.96	86.4640	3	521.52	144.6609		0.36	[0.19; 0.66]	0.0%	1.3%
S14	44	79.00	114.0000	44	218.00	367.0000		0.36	[0.19; 0.70]	0.0%	1.2%
GS13	21	4406.00	6480.0000	6	11405.00	4925.0000		0.39	[0.19; 0.79]	0.0%	1.2%
GS31	6	29.90	0.2589	6	77.00	0.3773		0.39	[0.39; 0.39]	17.7%	1.5%
S23	5	244.00	5.0000	5	606.00	3.0000		0.40	[0.40; 0.41]	3.3%	1.5%
S18	11	65.00	26.0000	8	156.00	115.0000		0.42	[0.24; 0.73]	0.0%	1.3%
S24	4	9.00	2.0000	4	21.00	25.0000		0.43	[0.13; 1.40]	0.0%	0.9%
GS33	3	136.00	65.0000	3	285.00	37.0000		0.48	[0.27; 0.84]	0.0%	1.3%
GS13	9	950.00	691.0000	4	1987.00	1296.0000		0.48	[0.22; 1.06]	0.0%	1.1%
S12	14	966.00	10.7226	14	2007.12	39.1388		0.48	[0.48; 0.49]	8.1%	1.5%
S12	9	757.44	31.8882	18	1534.56	24.7064		0.49	[0.48; 0.51]	1.4%	1.5%
GS24	24	3283.00	2238.0000	14	6221.00	3093.0000		0.53	[0.36; 0.77]	0.0%	1.4%
GS35	5	178.00	134.0000	5	329.00	194.0000		0.54	[0.23; 1.25]	0.0%	1.1%
GS4	6	15.00	14.0000	6	25.00	19.0000		0.60	[0.23; 1.57]	0.0%	1.0%
GS35	5	159.00	79.0000	5	264.00	144.0000		0.60	[0.32; 1.15]	0.0%	1.3%
O19	7	117.00	42.0000	4	184.00	52.0000		0.64	[0.43; 0.93]	0.0%	1.4%
S26	7	1.20	0.5000	7	1.85	1.3697		0.65	[0.35; 1.22]	0.0%	1.3%
S26	7	13.60	2.5000	7	19.75	3.1891		0.69	[0.57; 0.83]	0.0%	1.5%
O7	12	185.00	46.0000	12	257.00	36.0000		0.72	[0.61; 0.85]	0.0%	1.5%
GS26	6	72.31	35.0963	6	98.09	45.2078		0.74	[0.43; 1.26]	0.0%	1.3%
O7	12	218.00	70.0000	12	295.00	26.0000		0.74	[0.61; 0.89]	0.0%	1.5%
S27	3	676.00	97.0000	21	893.00	530.0000		0.76	[0.56; 1.02]	0.0%	1.5%
GS17	7	210.00	271.0000	5	277.00	227.0000		0.76	[0.23; 2.51]	0.0%	0.9%
S26	7	14.20	1.0000	7	18.51	4.0242		0.77	[0.65; 0.91]	0.0%	1.5%
S11	16	103.20	58.5600	16	134.40	91.2000		0.77	[0.50; 1.18]	0.0%	1.4%
GS33	3	508.00	86.0000	2	650.00	44.0000		0.78	[0.63; 0.97]	0.0%	1.5%
S26	5	15.60	1.6000	7	19.75	3.1891		0.79	[0.68; 0.92]	0.1%	1.5%
GS6	3	50.00	27.0000	3	63.00	23.0000		0.79	[0.38; 1.66]	0.0%	1.2%
O15	12	28.00	28.0000	12	35.00	37.0000		0.80	[0.35; 1.82]	0.0%	1.1%
GS26	6	71.02	37.3890	6	88.03	64.6077		0.81	[0.39; 1.66]	0.0%	1.2%
S14	44	79.00	114.0000	44	92.00	164.0000		0.86	[0.44; 1.69]	0.0%	1.2%
GS17	7	210.00	271.0000	5	243.00	175.0000		0.86	[0.27; 2.72]	0.0%	0.9%
GS35	5	15.00	8.0000	5	16.00	5.0000		0.94	[0.55; 1.61]	0.0%	1.3%
GS17	7	210.00	271.0000	5	223.00	97.0000		0.94	[0.34; 2.64]	0.0%	1.0%
GS11	17	60.00	48.0000	10	62.00	17.0000		0.97	[0.64; 1.47]	0.0%	1.4%
S18	11	216.00	103.0000	15	218.00	204.0000		0.99	[0.57; 1.72]	0.0%	1.3%
GS5	3	342.00	89.7895	3	325.68	83.5541		1.05	[0.69; 1.59]	0.0%	1.4%
GS21	20	90.00	59.0000	20	83.00	102.0000		1.08	[0.59; 2.00]	0.0%	1.3%
GS35	5	162.00	136.0000	5	148.00	143.0000		1.09	[0.36; 3.36]	0.0%	0.9%
S26	7	14.20	3.4000	7	11.52	1.1758		1.23	[1.02; 1.49]	0.0%	1.5%
S26	7	14.60	1.9000	7	11.52	1.1758		1.27	[1.12; 1.43]	0.1%	1.5%
GS35	5	33.00	24.0000	5	26.00	30.0000		1.27	[0.38; 4.20]	0.0%	0.9%
GS13	21	4406.00	6480.0000	3	3456.00	2333.0000		1.27	[0.47; 3.43]	0.0%	1.0%
GS35	5	18.00	8.0000	5	14.00	3.0000		1.29	[0.83; 1.98]	0.0%	1.4%
GS35	5	206.00	182.0000	5	156.00	82.0000		1.32	[0.54; 3.25]	0.0%	1.1%
S18	11	216.00	103.0000	8	156.00	115.0000		1.38	[0.77; 2.48]	0.0%	1.3%
GS34	5	3010.00	481.6000	5	2103.00	778.1100		1.43	[1.01; 2.04]	0.0%	1.4%
GS35	5	22.00	20.0000	5	14.00	18.0000		1.57	[0.40; 6.25]	0.0%	0.8%
GS4	6	88.00	41.0000	6	54.00	37.0000		1.63	[0.84; 3.16]	0.0%	1.2%
GS34	5	1819.00	763.9800	5	865.00	175.2000		2.10	[1.40; 3.16]	0.0%	1.4%
O15	12	28.00	28.0000	12	13.00	12.0000		2.15	[1.00; 4.65]	0.0%	1.2%
GS13	21	4406.00	6480.0000	4	1987.00	1296.0000		2.22	[0.90; 5.44]	0.0%	1.1%
GS34	5	2902.00	870.6000	5	1111.00	622.1600		2.61	[1.50; 4.56]	0.0%	1.3%
Fixed effect model	**909**			**855**				**0.24**	**[0.24; 0.24]**	**100.0%**	**--**
Random effects model								**0.49**	**[0.41; 0.58]**	**--**	**100.0%**

Heterogeneity: $I^2 = 100\%$, $\tau^2 = 0.4993$, $p = 0$

19 studies were left following outlier removal (Fig S5a) . The reciprocal value for the mean random effect size for the larger study group (n=19, RR =40) table 1 row 7 (1/0.5676) was 1.75; in contrast to the smaller study group Table 1 row 5 (1/0.6327) which was similar at 1.59. These both indicate that K in woodland is somewhere close to one and three quarter times higher than in grassland.

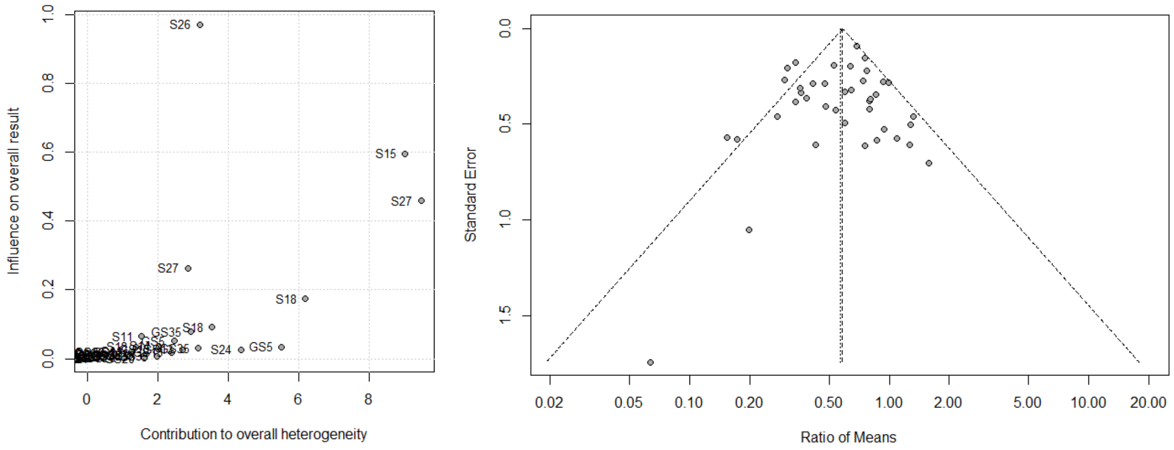
S5a Corresponding to Table 1 (main text) row 7. Meta-analysis for G/W response ratios for all papers with grassland and woodland data after the outliers were removed (n=19 studies).



	Experimental			Control						Weight	Weight
Study	**Total**	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Ratio of Means**	**ROM**	**95%-CI**	**(fixed)**	**(random)**
GS20	21	25.00	199.0000	28	391.00	325.0000		0.06	[0.00; 1.95]	0.1%	0.2%
GS5	3	21.12	19.5375	3	137.04	45.3104		0.15	[0.05; 0.47]	0.6%	1.3%
S24	4	8.00	7.0000	4	46.00	35.0000		0.17	[0.06; 0.54]	0.6%	1.3%
GS20	21	78.00	372.0000	28	391.00	325.0000		0.20	[0.03; 1.57]	0.2%	0.5%
GS13	9	950.00	691.0000	3	3456.00	2333.0000		0.27	[0.11; 0.68]	0.9%	1.8%
S18	11	65.00	26.0000	15	218.00	204.0000		0.30	[0.18; 0.51]	2.7%	3.4%
S27	6	4.00	1.0000	18	13.00	10.0000		0.31	[0.20; 0.46]	4.6%	4.1%
GS13	21	4406.00	6480.0000	4	12960.00	5357.0000		0.34	[0.16; 0.72]	1.4%	2.3%
S15	17	24.30	11.7612	16	71.40	38.8416		0.34	[0.24; 0.48]	6.2%	4.5%
GS5	3	186.96	86.4640	3	521.52	144.6609		0.36	[0.19; 0.66]	2.1%	2.9%
S14	44	79.00	114.0000	44	218.00	367.0000		0.36	[0.19; 0.70]	1.8%	2.7%
GS13	21	4406.00	6480.0000	6	11405.00	4925.0000		0.39	[0.19; 0.79]	1.5%	2.5%
S18	11	65.00	26.0000	8	156.00	115.0000		0.42	[0.24; 0.73]	2.4%	3.2%
S24	4	9.00	2.0000	4	21.00	25.0000		0.43	[0.13; 1.40]	0.5%	1.2%
GS33	3	136.00	65.0000	3	285.00	37.0000		0.48	[0.27; 0.84]	2.4%	3.2%
GS13	9	950.00	691.0000	4	1987.00	1296.0000		0.48	[0.22; 1.06]	1.2%	2.2%
GS24	24	3283.00	2238.0000	14	6221.00	3093.0000		0.53	[0.36; 0.77]	5.4%	4.3%
GS35	5	178.00	134.0000	5	329.00	194.0000		0.54	[0.23; 1.25]	1.1%	2.0%
GS4	6	15.00	14.0000	6	25.00	19.0000		0.60	[0.23; 1.57]	0.8%	1.7%
GS35	5	159.00	79.0000	5	264.00	144.0000		0.60	[0.32; 1.15]	1.8%	2.8%
O19	7	117.00	42.0000	4	184.00	52.0000		0.64	[0.43; 0.93]	5.2%	4.3%
S26	7	1.20	0.5000	7	1.85	1.3697		0.65	[0.35; 1.22]	1.9%	2.9%
S26	7	13.60	2.5000	7	19.75	3.1891		0.69	[0.57; 0.83]	23.3%	5.6%
GS26	6	72.31	35.0963	6	98.09	45.2078		0.74	[0.43; 1.26]	2.7%	3.3%
S27	3	676.00	97.0000	21	893.00	530.0000		0.76	[0.56; 1.02]	8.4%	4.8%
GS17	7	210.00	271.0000	5	277.00	227.0000		0.76	[0.23; 2.51]	0.5%	1.2%
S11	16	103.20	58.5600	16	134.40	91.2000		0.77	[0.50; 1.18]	4.1%	4.0%
GS6	3	50.00	27.0000	3	63.00	23.0000		0.79	[0.38; 1.66]	1.4%	2.4%
O15	12	28.00	28.0000	12	35.00	37.0000		0.80	[0.35; 1.82]	1.1%	2.1%
GS26	6	71.02	37.3890	6	88.03	64.6077		0.81	[0.39; 1.66]	1.5%	2.4%
S14	44	79.00	114.0000	44	92.00	164.0000		0.86	[0.44; 1.69]	1.7%	2.6%
GS17	7	210.00	271.0000	5	243.00	175.0000		0.86	[0.27; 2.72]	0.6%	1.3%
GS35	5	15.00	8.0000	5	16.00	5.0000		0.94	[0.55; 1.61]	2.6%	3.3%
GS17	7	210.00	271.0000	5	223.00	97.0000		0.94	[0.34; 2.64]	0.7%	1.5%
S18	11	216.00	103.0000	15	218.00	204.0000		0.99	[0.57; 1.72]	2.5%	3.3%
GS35	5	162.00	136.0000	5	148.00	143.0000		1.09	[0.36; 3.36]	0.6%	1.3%
GS35	5	33.00	24.0000	5	26.00	30.0000		1.27	[0.38; 4.20]	0.5%	1.2%
GS13	21	4406.00	6480.0000	3	3456.00	2333.0000		1.27	[0.47; 3.43]	0.8%	1.6%
GS35	5	206.00	182.0000	5	156.00	82.0000		1.32	[0.54; 3.25]	0.9%	1.8%
GS35	5	22.00	20.0000	5	14.00	18.0000		1.57	[0.40; 6.25]	0.4%	0.9%
Fixed effect model	**437**			**405**				**0.58**	**[0.53; 0.64]**	**100.0%**	**--**
Random effects model								**0.57**	**[0.49; 0.66]**	**--**	**100.0%**

Heterogeneity: $I^2 = 52\%$, $\tau^2 = 0.0903$, $p < 0.01$

S4b Corresponding to Table 1 (main text) row 7. Baujat plot and S4c funnel plot for the main data set after the outliers were removed G/W RR (n=19 studies, RR=40). Eggers' test of the intercept, intercept -0.327; 95% CI [-1.22 - 0.56]; t -0.722; p 0.4749672. Eggers' test does not indicate the presence of funnel plot asymmetry.



PRISMA 2009 checklist

Section/ topic	#	Checklist item
TITLE		
Title	1	Identify the report as a systematic review, meta-analysis, or both: Global meta-analysis of soil hydraulic properties on given soils under differing land use
ABSTRACT		
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number. See details in main text.
INTRODUCTION		
Rationale	3	Describe the rationale for the review in the context of what is already known. See details in main text
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS). The aim is to determine to what extent the land use or habitat, coarsely separated into woodland, grassland, and cultivated land (WGC) affects the hydraulic conductivity such that response ratios for hydraulic conductivity differ for different land uses given the same soil type. Hypothesis: Overarching hypothesis: H0: 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: H1: 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. The effect of land use management is expected to decrease progressing from cropland > grassland > woodland, hence seeing K increase with, cropland < grassland < woodland, accordingly. The objective of this work is to determine any effect size associated with the hydraulic conductivity response ratio so that it can be used in the development of land surface and ecosystem models to adjust hydraulic parameters such as hydraulic conductivity under different land uses on the same soil type. Test response ratios for cropland / grassland; cropland / woodland and grassland / woodland

METHODS		
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number. (NA)
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale. • All languages • Articles, reports, PhD's • Masters thesis excluded
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched. • Google Scholar • Scopus • Colleagues
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated. Records First pass Selected Google Scholar 900 214 37 08/09/2020 allintitle: Soil |topsoil ("hydraulic *"|"infiltration"| "hydrological *"|"physical * properties") ("land *"|forestation |forest|trees|woodland|grass|grassland|grazing|rangeland|pasture|arable|agricultural | crops | cropping) Scopus 906 50 8 15/09/2020 "soil hydraulic conductivity" AND tree* OR forest OR wood* AND grass* OR pasture TITLE-ABS-KEY ("soil hydraulic conductivity" AND tree* OR forest OR wood* AND grass* OR pasture) Scopus 1 0 0 17/09/2020 TITLE-ABS-KEY (infiltration AND "land use" AND tree* or forest or wood* and grass* or pasture) Scopus 1332 78 10 17/09/2020 TITLE-ABS-KEY (infiltration AND soil AND "land use") Others (within articles etc) 14 e.g. Chandler Duplicates then removed

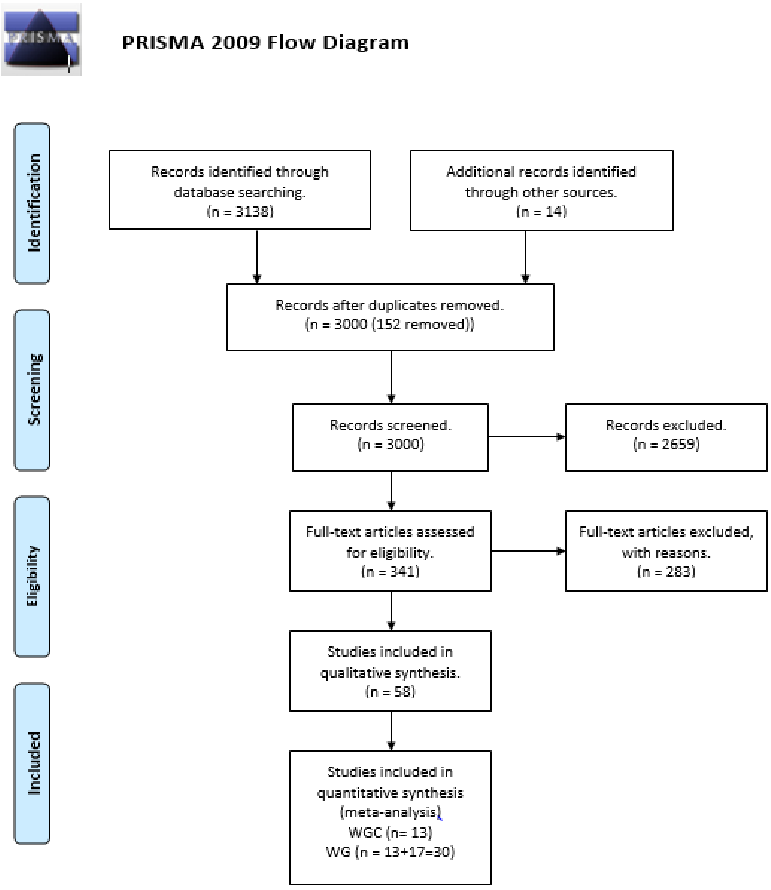
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis). *Qualitative woodland grassland dataset WG* 58 studies 182 RR All papers that contained at least RR values for G/W. • Qualitative data selection • Must have infiltration for trees and grass, primary target • Must be on the same soil type or in a similar soil texture range *Quantitative woodland and grassland dataset WG* 30 studies 79 RR Papers must have RR values for G/W and have the number of measurements and the error terms. • Meta analysis selection required: mean, standard deviation and number *Quantitative woodland, grassland and cropland dataset WGC* 13 studies 34 RR Papers must have RR values for G/W/C and have the number of measurements and the error terms. • Meta analysis selection required: mean, standard deviation and number
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators. • Three independent researchers selected and reviewed the publications • Web plot digitizer used to extract some qualitative data, e.g. medians
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made. • Hydraulic conductivity / infiltration rate • Soil type, soil texture, porosity, carbon, SOM • Location, mean T, Mean rainfall, • Woodland, grassland / pasture land, cultivated land
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis. The following sources of bias were considered: Sample selection bias: choosing where to measure infiltration, choosing more sites in cropland for example and less in woodland. Experimenter bias: where the scientists performing the research influence the results, e.g. selecting sites where the highest difference in infiltration is likely to maximise response ratio. Measurement bias: where errors occur in the data collection and the process of measuring. Hydraulic conductivity measured at tension or at saturation. Seemingly high infiltration rates, checked with authors.
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means). Response ratio (RR) – Hedges *g'*

		Hedges, L.V., Gurevitch, J. and Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology, 80(4), pp.1150-1156.[4]
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis. **Meta package in R** https://cran.r-project.org/web/packages/meta/meta.pdf Doing meta-analysis in R[2] https://bookdown.org/MathiasHarrer/Doing_Meta_Analysis_in_R/ metacont: Meta-analysis of means and standard deviations of two groups using Hedges *g'* Description: Calculation of random effects estimates for meta-analyses with data on means and standard deviation using sm=ROM. **Heterogeneity: Higgin's & Thompson's I^2** (Harrer et al, 2021)[2] I^2 (Higgins and Thompson 2002)[5] is the **percentage of variability** in the effect sizes which is not caused by sampling error. It is derived from Q: $I^2=\max[0,(Q-(K-1))/Q]$ I^2 is not sensitive to changes in the number of studies in the analyses. I^2 is therefore used extensively in medical and psychological research, especially since there is a **"rule of thumb"** to interpret it[5, 6]: I^2 = 25%: **low heterogeneity** I^2 = 50%: **moderate heterogeneity** I^2 = 75%: **substantial heterogeneity** References: Harrer, M., Cuijpers, P., Furukawa, T.A, & Ebert, D. D. (2019). Doing Meta-Analysis in R: A Hands-on Guide. https://bookdown.org/MathiasHarrer/Doing_Meta_Analysis_in_R/. Higgins, Julian PT, and Simon G Thompson. 2002. "Quantifying Heterogeneity in a Meta-Analysis." Statistics in Medicine 21 (11). Wiley Online Library: 1539–58 Higgins, Julian PT, Simon G Thompson, Jonathan J Deeks, and Douglas G Altman. 2003. "Measuring Inconsistency in Meta-Analyses." BMJ: British Medical Journal 327 (7414). BMJ Publishing Group: 557.

Section/topic	#	Checklist item
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies). The following sources of bias were considered: Sample selection bias: choosing where to measure infiltration, choosing more sites in cropland for example and less in woodland.

<table>
<tr><td></td><td></td><td>Experimenter bias: where the scientists performing the research influence the results, e.g. selecting sites where the highest difference in infiltration is likely to maximise response ratio.
Measurement bias: where errors occur in the data collection and the process of measuring. Hydraulic conductivity measured at tension or at saturation. Seemingly high infiltration rates, checked with authors.
Publication bias, within the meta analysis bias was detected using the meta package in R and identifying and excluding outliers. This was checked using funnel plots on the data and Eggers' test confirming the absence of funnel plot asymmetry.

We considered bias in terms of location, soil types studied, range of habitats and methodological. Hydraulic conductivity is measured in many different ways, to avoid this bias we used response ratios.</td></tr>
<tr><td>Additional analyses</td><td>16</td><td>Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.</td></tr>
<tr><td colspan="3">RESULTS</td></tr>
<tr><td>Study selection</td><td>17</td><td>Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.



From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *Preferred Reporting Items for Systematic Reviews and Meta-Analyses*: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit www.prisma-statement.org.</td></tr>
</table>

		The most common causes for rejection included, not having data on the same soil type or data on multiple land uses.
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.

List of citations chosen for the study, light grey colur indicates the reference contained data on CG & W.

Number & reference number	Code	Land use	Reference
1[7]	S12	GW	Agnese, C., Bagarello, V., Baiamonte, G. and Iovino, M., 2011. Comparing physical quality of forest and pasture soils in a Sicilian watershed. *Soil Science Society of America Journal*, *75*(5), pp.1958-1970.
2[8]	S11	GW	Archer, N.A.L., Bonell, M., Coles, N., MacDonald, A.M., Auton, C.A. and Stevenson, R., 2013. Soil characteristics and landcover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local flood management. *Journal of Hydrology*, *497*, pp.208-222.
3[9]	GS37	GW	Bayramin, I., Basaran, M., Erpul, G., Dolarslan, M. and Canga, M.R., 2009. Comparison of soil organic carbon content, hydraulic conductivity, and particle size fractions between a grassland and a nearby black pine plantation of 40 years in two surface depths. *Environmental geology*, *56*(8), pp.1563-1575.
4[10]	GS3	CGW	Bharati, L., Lee, K.H., Isenhart, T.M. and Schultz, R.C., 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. *Agroforestry systems*, *56*(3), pp.249-257.
5[11]	GS4	CGW	Bormann, H. and Klaassen, K., 2008. Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma*, *145*(3-4), pp.295-302.
6[12]	GS5	GW	Burch, G.J., Bath, R.K., Spate, A.P., Nicholls, A.O. and O'Loughlin, E.M., 1983. Soil water store, infiltration and runoff characteristics of forest and grassland catchments at Puckapunyal in central Victoria. In *Hydrology and Water Resources Symposium 1983: Preprints of Papers* (p. 293). Institution of Engineers, Australia.
7[13]	GS6	GW	Cerda, A., Schnabel, S., Ceballos, A. and Gomez-Amelia, D., 1998. Soil hydrological response under simulated rainfall in the Dehesa land system (Extremadura, SW Spain) under drought conditions. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group*, *23*(3), pp.195-209.
8[14]	S23	CGW	Gajić, B., 2013. Physical properties and organic matter of Fluvisols under forest, grassland, and 100 years of conventional tillage. *Geoderma*, *200*, pp.114-119.
9[15]	GS11	GW	Ghimire, C.P., Bonell, M., Bruijnzeel, L.A., Coles, N.A. and Lubczynski, M.W., 2013. Reforesting severely degraded grassland in the Lesser Himalaya of Nepal: Effects on soil hydraulic conductivity and overland flow production. *Journal*

			of Geophysical Research: Earth Surface, *118*(4), pp.2528-2545.
10[16]	O7	CGW	Gol, C., 2009. The effects of land use change on soil properties and organic carbon at Dagdami river catchment in Turkey. *Journal of Environmental Biology*, *30*(5), p.825.
11[17]	GS13	CGW	Gonzalez-Sosa, E., Braud, I., Dehotin, J., Lassabatère, L., Angulo-Jaramillo, R., Lagouy, M., Branger, F., Jacqueminet, C., Kermadi, S. and Michel, K., 2010. Impact of land use on the hydraulic properties of the topsoil in a small French catchment. *Hydrological processes*, *24*(17), pp.2382-2399.
12[18]	O19	GW	Harden, C.P. and Scruggs, P.D., 2003. Infiltration on mountain slopes: a comparison of three environments. Geomorphology, 55(1-4), pp.5-24.
13[19]	GS17	GW	Leite, P.A., de Souza, E.S., dos Santos, E.S., Gomes, R.J., Cantalice, J.R. and Wilcox, B.P., 2018. The influence of forest regrowth on soil hydraulic properties and erosion in a semiarid region of Brazil. *Ecohydrology*, *11*(3), p.e1910.
14[20]	S24	GW	Lopes, E., Marenzi, R.C. and Almeida, T.C.M.D., 2018. Comparison of soil use in the infiltration of rainwater: pasture and forest. *Revista Facultad Nacional de Agronomía Medellín*, *71*(3), pp.8593-8600.
15[21]	GS20	GW	Lozano-Baez, S.E., Cooper, M., Frosini de Barros Ferraz, S., Ribeiro Rodrigues, R., Castellini, M. and Di Prima, S., 2019. Recovery of soil hydraulic properties for assisted passive and active restoration: assessing historical land use and forest structure. *Water*, *11*(1), p.86.
16[22]	GS21	GW	Lunka, P. and Patil, S.D., 2016. Impact of tree planting configuration and grazing restriction on canopy interception and soil hydrological properties: implications for flood mitigation in silvopastoral systems. *Hydrological Processes*, *30*(6), pp.945-958.
17[23]	S26	GW	Marshall, M.R., Ballard, C.E., Frogbrook, Z.L., Solloway, I., McIntyre, N., Reynolds, B. and Wheater, H.S., 2014. The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. *Hydrological Processes*, *28*(4), pp.2617-2629.
18[24]	O4	CGW	Mbagwu, J.S.C., 1997. Quasi-steady infiltration rates of highly permeable tropical moist savannah soils in relation to landuse and pore size distribution. *Soil Technology*, *11*(2), pp.185-195.
19[25]	GS24	GW	Perkins, K.S., Nimmo, J.R. and Medeiros, A.C., 2012. Effects of native forest restoration on soil hydraulic properties, Auwahi, Maui, Hawaiian Islands. *Geophysical Research Letters*, *39*(5).
20[26]	S14	CGW	Pinto, L.C., Mello, C.R.D., Norton, L.D. and Curi, N., 2019. Land-use influence on the soil hydrology: An approach in upper Grande River basin, Southeast Brazil. *Ciência e Agrotecnologia*, *43*.
21[27]	S27	CGW	Podrazsky, V., Holubík, O., Vopravil, J., Khel, T., Moser, W.K. and Prknová, H., 2015. Effects of afforestation on soil structure formation in two climatic regions of the Czech Republic. *Journal of Forest Science. 61 (5): 225-234.*, *61*(5), pp.225-234.
22[28]	GS26	CGW	Sahin, H., Anderson, S.H. and Udawatta, R.P., 2016. Water infiltration and soil water content in claypan soils influenced by agroforestry and grass buffers compared to row crop management. *Agroforestry Systems*, *90*(5), pp.839-860.

23[29]	O15	GW	Thompson, S.E., Harman, C.J., Heine, P. and Katul, G.G., 2010. Vegetation-infiltration relationships across climatic and soil type gradients. *Journal of Geophysical Research: Biogeosciences*, *115*(G2).
24[30]	GS31	GW	Tian, J., Zhang, B., He, C. and Yang, L., 2017. Variability in soil hydraulic conductivity and soil hydrological response under different land covers in the mountainous area of the Heihe River Watershed, Northwest China. *Land Degradation & Development*, *28*(4), pp.1437-1449.
25[31]	S15	GW	Tobón, C., Bruijnzeel, L.A., Frumau, K.A. and Calvo-Alvarado, J.C., 2010. Changes in soil physical properties after conversion of tropical montane cloud forest to pasture in northern Costa Rica. *Tropical montane cloud forests: Science for conservation and management*, pp.502-515.
26[32]	GS33	GW	Weerts, G.J., 1991. Soil hydraulic conductivity on two tropical soil types under forest and a 25 year old pasture: field measurements and data application (Vol. 69). Bib. Orton IICA/CATIE.
27[33]	S30	CGW	Yimer, F., Messing, I., Ledin, S. and ABdelkadir, A., 2008. Effects of different land use types on infiltration capacity in a catchment in the highlands of Ethiopia. *Soil use and management*, *24*(4), pp.344-349.
28[34]	GS34	CGW	Yu, M., Zhang, L., Xu, X., Feger, K.H., Wang, Y., Liu, W. and Schwärzel, K., 2015. Impact of land-use changes on soil hydraulic properties of Calcaric Regosols on the Loess Plateau, NW China. *Journal of Plant Nutrition and Soil Science*, *178*(3), pp.486-498.
29[35]	GS35	CGW	Zhou, X., Lin, H.S. and White, E.A., 2008. Surface soil hydraulic properties in four soil series under different land uses and their temporal changes. *Catena*, *73*(2), pp.180-188.
30[36]	S18	CGW	Ziegler, A.D., Giambelluca, T.W., Tran, L.T., Vana, T.T., Nullet, M.A., Fox, J., Vien, T.D., Pinthong, J., Maxwell, J.F. and Evett, S., 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. *Journal of Hydrology*, *287*(1-4), pp.124-146.
Papers below used for qualitative analysis only using response ratios			
31[37]	O2	GW	Alegre, J.C. and Lara, P.D., 1991. Efecto de los animales en pastoreo sobre las propiedades físicas de suelos de la región tropical húmeda de Perú. *Pasturas Tropicales*, *13*(1), pp.18-23. **Reproduced in:** Alegre, J.C. and Cassel, D.K., 1996. Dynamics of soil physical properties under alternative systems to slash-and-burn. Agriculture, Ecosystems & Environment, 58(1), pp.39-48.
32[38]	S25	GW	Berry, Z.C., Jones, K.W., Aguilar, L.R.G., Congalton, R.G., Holwerda, F., Kolka, R., Looker, N., Ramirez, S.M.L., Manson, R., Mayer, A. and Muñoz-Villers, L., 2020. Evaluating ecosystem service trade-offs along a land-use intensification gradient in central Veracruz, Mexico. *Ecosystem Services*, *45*, p.101181. **Reproduced in:** López-Ramírez, S.M., Sáenz, L., Mayer, A., Muñoz-Villers, L.E., Asbjornsen, H., Berry, Z.C., Looker, N., Manson, R. and Aguilar, L.R.G., Land use change effects on catchment streamflow response in a humid tropical montane cloud

			forest region, central Veracruz, Mexico. *Hydrological Processes*.
33[39]	O9	GW	Celik, I., 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. *Soil and Tillage research*, *83*(2), pp.270-277.
34[40]	GS7	GW	Chandler, K.R., 2014. The Influence of Trees on Soil Hydraulic Properties: Species Effects and the Provision of Ecosystem Services.
35[41]	S19	GW	Chandler, K.R., Stevens, C.J., Binley, A. and Keith, A.M., 2018. Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. *Geoderma*, *310*, pp.120-127.
36[42]	O16	GW	Chirwa, T.S., Mafongoya, P.L. and Chintu, R., 2003. Mixed planted-fallows using coppicing and non-coppicing tree species for degraded Acrisols in eastern Zambia. *Agroforestry systems*, *59*(3), pp.243-251.
37[43]	GS8	GW	de Almeida, A.Q., Ribeiro, A., Rody, Y.P., da Silva, W.C.M. and Leite, F.P., 2014. Modeling of water infiltration in soil cultivated with eucalyptus and pasture. *Revista Caatinga*, *27*(1), pp.148-153.
38[44]	O14	GW	De Moraes, J.M., Schuler, A.E., Dunne, T., Figueiredo, R.D.O. and Victoria, R.L., 2006. Water storage and runoff processes in plinthic soils under forest and pasture in eastern Amazonia. *Hydrological Processes: An International Journal*, *20*(12), pp.2509-2526.
39[45]	GS9	GW	Dionizio, E.A. and Costa, M.H., 2019. Influence of land use and land cover on hydraulic and physical soil properties at the cerrado agricultural frontier. *Agriculture*, *9*(1), p.24.
40[46]	S22	GW	Dörner, J., Dec, D., Peng, X. and Horn, R., 2010. Effect of land use change on the dynamic behaviour of structural properties of an Andisol in southern Chile under saturated and unsaturated hydraulic conditions. *Geoderma*, *159*(1-2), pp.189-197.
41[47]	GS12	GW	GILMOURZ, D., BONELL, M. and CASSELLS, D., 1987. THE EFFECTS OF FORESTATION ON SOIL HYDRAULIC PROPERTIES IN THE MIDDLE HILLS OF NEPAL: A PRELEMINARY ASSESSMENT1. *Mountain Research and Development*, *7*(3), pp.239-249.
42[48]	S13	GW	Greenwood, W.J. and Buttle, J.M., 2014. Effects of reforestation on near-surface saturated hydraulic conductivity in a managed forest landscape, southern Ontario, Canada. *Ecohydrology*, *7*(1), pp.45-55.
43[49]	O8	GW	Hassler, S.K., Zimmermann, B., van Breugel, M., Hall, J.S. and Elsenbeer, H., 2011. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. *Forest Ecology and Management*, *261*(10), pp.1634-1642.
44[50]	GS14	GW	Idowu, O.J. and Oluwatosin, G.A., 2008. Hydraulic properties in relation to morphology of a tropical soil with hardened plinthite under three land use types. *Tropical and Subtropical Agroecosystems*, *8*(2), pp.145-155.
45[51]	GS15	GW	Islam, A., Mailapalli, D.R. and Behera, A., 2019. Comparison of saturated hydraulic conductivity methods for sandy loam soil with different land uses. *Water resources and environmental engineering I*, pp.99-117.

46[52]	O6	GW	Jiménez, C.C., Tejedor, M., Morillas, G. and Neris, J., 2006. Infiltration rate in andisols: Effect of changes in vegetation cover (Tenerife, Spain). *Journal of Soil and Water Conservation*, *61*(3), pp.153-158.
47[53]	GS16	GW	Kumar, S., Anderson, S.H., Bricknell, L.G., Udawatta, R.P. and Gantzer, C.J., 2008. Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. *journal of soil and water conservation*, *63*(4), pp.224-232.
48[54]	GS18	GW	Litt, G.F., Ogden, F.L., Mojica, A., Hendrickx, J.M., Kempema, E.W., Gardner, C.B., Bretfeld, M., Regina, J.A., Harrison, J.B.J., Cheng, Y. and Lyons, W.B., 2020. Land cover effects on soil infiltration capacity measured using plot scale rainfall simulation in steep tropical lowlands of Central Panama. *Hydrological Processes*, *34*(4), pp.878-897.
49[55]	GS19	GW	Lopes, V.S., Cardoso, I.M., Fernandes, O.R., Rocha, G.C., Simas, F.N.B., de Melo Moura, W., Santana, F.C., Veloso, G.V. and da Luz, J.M.R., 2020. The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil. *Soil and Tillage Research*, *198*, p.104538.
50[56]	O18	GW	Mapa, R.B., 1995. Effect of reforestation using Tectona grandis on infiltration and soil water retention. *Forest Ecology and Management*, *77*(1-3), pp.119-125.
51[57]	O3	GW	Martınez, L.J. and Zinck, J.A., 2004. Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. *Soil and Tillage Research*, *75*(1), pp.3-18.
52[58]	GS25	GW	Price, K., Jackson, C.R. and Parker, A.J., 2010. Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA. *Journal of hydrology*, *383*(3-4), pp.256-268.
53[59]	S28	GW	Safaei, M., Bashari, H., Mosaddeghi, M.R. and Jafari, R., 2019. Assessing the impacts of land use and land cover changes on soil functions using landscape function analysis and soil quality indicators in semi-arid natural ecosystems. *Catena*, *177*, pp.260-271.
54[60]	GS28	GW	Seobi, T., Anderson, S.H., Udawatta, R.P. and Gantzer, C.J., 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. *Soil Science Society of America Journal*, *69*(3), pp.893-901.
55[61]	O5	GW	Spaans, E.J., Baltissen, G.A.M., Bouma, J., Miedema, R., Lansu, A.L.E., Schoonderbeek, D. and Wielemaker, W.G., 1989. Changes in physical properties of young and old volcanic surface soils in Costa Rica after clearing of tropical rain forest. *Hydrological Processes*, *3*(4), pp.383-392.
56[62]	GS29	GW	Stewart, A., Coble, A., Contosta, A.R., Orefice, J.N., Smith, R.G. and Asbjornsen, H., 2019. Forest conversion to silvopasture and open pasture: effects on soil hydraulic properties. *Agroforestry Systems*, pp.1-11.
57[63]	S29	GW	Yáñez-Díaz, M.I., Cantú-Silva, I., González-Rodríguez, H. and Sánchez-Castillo, L., 2019. Effects of land use change and seasonal variation in the hydrophysical properties in Vertisols in northeastern Mexico. *Soil Use and Management*, *35*(3), pp.378-387.
58[64]	GS36	GW	Zimmermann, B., Elsenbeer, H. and De Moraes, J.M., 2006. The influence of land-use changes on soil hydraulic

		properties: implications for runoff generation. *Forest ecology and management*, *222*(1-3), pp.29-38.
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot. See Forest plots in supplementary
Synthesis of results	21	Present the main results of the review. If meta-analyses are done, include for each, confidence intervals and measures of consistency See Table 1 in main text
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15). See Funnel plots in supplementary.
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).
DISCUSSION		
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers). See main text
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias). See main text
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research. See main text
FUNDING		
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review. This paper is supported by the European Union's Interreg North-West Europe programme, part of the European Territorial Cooperation Programme and ERDF funding. The work was supported by grant agreement No. NWE 810, project FABulous Farmers (Functional Agro-Biodiversity in farming). In addition, UKCEH staff were supported by the Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCaPE programme delivering National Capability. The Research Council of Norway, Climasol, Project number: 325253.

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References

1. Balduzzi S, Rücker G, Schwarzer G. How to perform a meta-analysis with R: a practical tutorial. *Evidence-based mental health* **22**, 153-160 (2019).

2. Harrer M, Cuijpers P, Furukawa TA, Ebert DD. Doing meta-analysis with R: a hands-on guide. (2021).

3. Olkin I, Dahabreh IJ, Trikalinos TA. GOSH–a graphical display of study heterogeneity. *Research synthesis methods* **3**, 214-223 (2012).

4. Hedges LV, Gurevitch J, Curtis PS. The meta-analysis of response ratios in experimental ecology. *Ecology* **80**, 1150-1156 (1999).

5. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Statistics in medicine* **21**, 1539-1558 (2002).

6. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. *Bmj* **327**, 557-560 (2003).

7. Agnese C, Bagarello V, Baiamonte G, Iovino M. Comparing physical quality of forest and pasture soils in a Sicilian watershed. *Soil Science Society of America Journal* **75**, 1958-1970 (2011).

8. Archer N, Bonell M, Coles N, MacDonald A, Auton C, Stevenson R. Soil characteristics and landcover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local flood management. *Journal of hydrology* **497**, 208-222 (2013).

9. Bayramin I, Basaran M, Erpul G, Dolarslan M, Canga MR. Comparison of soil organic carbon content, hydraulic conductivity, and particle size fractions between a grassland and a nearby black pine plantation of 40 years in two surface depths. *Environmental geology* **56**, 1563-1575 (2009).

10. Bharati L, Lee K-H, Isenhart T, Schultz R. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. *Agroforestry systems* **56**, 249-257 (2002).

11. Bormann H, Klaassen K. Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma* **145**, 295-302 (2008).

12. Burch G, Bath R, Spate A, Nicholls A, O'Loughlin E. Soil water store, infiltration and runoff characteristics of forest and grassland catchments at Puckapunyal in central Victoria. (1983).

13. Cerda A, Schnabel S, Ceballos A, Gomez-Amelia D. Soil hydrological response under simulated rainfall in the Dehesa land system (Extremadura, SW Spain) under drought

conditions. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group* **23**, 195-209 (1998).

14. Gajić B. Physical properties and organic matter of Fluvisols under forest, grassland, and 100 years of conventional tillage. *Geoderma* **200**, 114-119 (2013).

15. Ghimire CP, Bonell M, Bruijnzeel LA, Coles NA, Lubczynski MW. Reforesting severely degraded grassland in the Lesser Himalaya of Nepal: Effects on soil hydraulic conductivity and overland flow production. *Journal of Geophysical Research: Earth Surface* **118**, 2528-2545 (2013).

16. Gol C. The effects of land use change on soil properties and organic carbon at Dagdami river catchment in Turkey. *Journal of Environmental Biology* **30**, 825 (2009).

17. Gonzalez-Sosa E*, et al.* Impact of land use on the hydraulic properties of the topsoil in a small French catchment. *Hydrological processes* **24**, 2382-2399 (2010).

18. Harden CP, Scruggs PD. Infiltration on mountain slopes: a comparison of three environments. *Geomorphology* **55**, 5-24 (2003).

19. Leite PA, de Souza ES, dos Santos ES, Gomes RJ, Cantalice JR, Wilcox BP. The influence of forest regrowth on soil hydraulic properties and erosion in a semiarid region of Brazil. *Ecohydrology* **11**, e1910 (2018).

20. Lopes E, Marenzi RC, Almeida TCMd. Comparison of soil use in the infiltration of rainwater: pasture and forest. *Revista Facultad Nacional de Agronomía Medellín* **71**, 8593-8600 (2018).

21. Lozano-Baez SE, Cooper M, Frosini de Barros Ferraz S, Ribeiro Rodrigues R, Castellini M, Di Prima S. Recovery of soil hydraulic properties for assisted passive and active restoration: assessing historical land use and forest structure. *Water* **11**, 86 (2019).

22. Lunka P, Patil SD. Impact of tree planting configuration and grazing restriction on canopy interception and soil hydrological properties: implications for flood mitigation in silvopastoral systems. *Hydrological Processes* **30**, 945-958 (2016).

23. Marshall M*, et al.* The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. *Hydrological Processes* **28**, 2617-2629 (2014).

24. Mbagwu J. Quasi-steady infiltration rates of highly permeable tropical moist savannah soils in relation to landuse and pore size distribution. *Soil Technology* **11**, 185-195 (1997).

25. Perkins KS, Nimmo JR, Medeiros AC. Effects of native forest restoration on soil hydraulic properties, Auwahi, Maui, Hawaiian Islands. *Geophysical Research Letters* **39**, (2012).

26. Pinto LC, Mello CRd, Norton LD, Curi N. Land-use influence on the soil hydrology: An approach in upper Grande River basin, Southeast Brazil. *Ciência e Agrotecnologia* **43**, (2019).

27. Podrazsky V, Holubík O, Vopravil J, Khel T, Moser W, Prknová H. Effects of afforestation on soil structure formation in two climatic regions of the Czech Republic. *Journal of Forest Science 61 (5): 225-234* **61**, 225-234 (2015).

28. Sahin H, Anderson S, Udawatta R. Water infiltration and soil water content in claypan soils influenced by agroforestry and grass buffers compared to row crop management. *Agroforestry systems* **90**, 839-860 (2016).

29. Thompson S, Harman C, Heine P, Katul G. Vegetation-infiltration relationships across climatic and soil type gradients. *Journal of Geophysical Research: Biogeosciences* **115**, (2010).

30. Tian J, Zhang B, He C, Yang L. Variability in soil hydraulic conductivity and soil hydrological response under different land covers in the mountainous area of the Heihe River Watershed, Northwest China. *Land degradation & development* **28**, 1437-1449 (2017).

31. Tobón C, Bruijnzeel L, Frumau KA, Calvo-Alvarado J. Changes in soil physical properties after conversion of tropical montane cloud forest to pasture in northern Costa Rica. *Tropical montane cloud forests: Science for conservation and management*, 502-515 (2010).

32. Weerts G. *Soil hydraulic conductivity on two tropical soil types under forest and a 25 year old pasture: field measurements and data application*. Bib. Orton IICA/CATIE (1991).

33. Yimer F, Messing I, Ledin S, ABdelkadir A. Effects of different land use types on infiltration capacity in a catchment in the highlands of Ethiopia. *Soil use and management* **24**, 344-349 (2008).

34. Yu M*, et al.* Impact of land-use changes on soil hydraulic properties of Calcaric Regosols on the Loess Plateau, NW China. *Journal of Plant Nutrition and Soil Science* **178**, 486-498 (2015).

35. Zhou X, Lin H, White E. Surface soil hydraulic properties in four soil series under different land uses and their temporal changes. *Catena* **73**, 180-188 (2008).

36. Ziegler AD*, et al.* Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. *Journal of Hydrology* **287**, 124-146 (2004).

37. Alegre JC, Cassel D. Dynamics of soil physical properties under alternative systems to slash-and-burn. *Agriculture, Ecosystems & Environment* **58**, 39-48 (1996).

38. Berry ZC*, et al.* Evaluating ecosystem service trade-offs along a land-use intensification gradient in central Veracruz, Mexico. *Ecosystem Services* **45**, 101181 (2020).

39. Celik I. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. *Soil and Tillage research* **83**, 270-277 (2005).

40. Chandler KR. *The influence of trees on soil hydraulic properties: species effects and the provision of ecosystem services*. Lancaster University (United Kingdom) (2014).

41. Chandler K, Stevens C, Binley A, Keith A. Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. *Geoderma* **310**, 120-127 (2018).

42. Chirwa T, Mafongoya P, Chintu R. Mixed planted-fallows using coppicing and non-coppicing tree species for degraded Acrisols in eastern Zambia. *Agroforestry systems* **59**, 243-251 (2003).

43. de Almeida AQ, Ribeiro A, Rody YP, da Silva WCM, Leite FP. Modeling of water infiltration in soil cultivated with eucalyptus and pasture. *Revista Caatinga* **27**, 148-153 (2014).

44. De Moraes JM, Schuler AE, Dunne T, Figueiredo RdO, Victoria RL. Water storage and runoff processes in plinthic soils under forest and pasture in eastern Amazonia. *Hydrological Processes: An International Journal* **20**, 2509-2526 (2006).

45. Dionizio EA, Costa MH. Influence of land use and land cover on hydraulic and physical soil properties at the cerrado agricultural frontier. *Agriculture* **9**, 24 (2019).

46. Dörner J, Dec D, Peng X, Horn R. Effect of land use change on the dynamic behaviour of structural properties of an Andisol in southern Chile under saturated and unsaturated hydraulic conditions. *Geoderma* **159**, 189-197 (2010).

47. Gilmourz D, Bonell M, Cassells D. The Effects of forestation on soil hydraulic properties in the middle hills of Nepal: A preliminary assessment 1. *Mountain Research and Development* **7**, 239-249 (1987).

48. Greenwood W, Buttle J. Effects of reforestation on near-surface saturated hydraulic conductivity in a managed forest landscape, southern Ontario, Canada. *Ecohydrology* **7**, 45-55 (2014).

49. Hassler SK, Zimmermann B, van Breugel M, Hall JS, Elsenbeer H. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. *For Ecol Manage* **261**, 1634-1642 (2011).

50. Idowu O, Oluwatosin G. Hydraulic properties in relation to morphology of a tropical soil with hardened plinthite under three land use types. *Tropical and Subtropical Agroecosystems* **8**, 145-155 (2008).

51. Islam A, Mailapalli D, Behera A. Comparison of saturated hydraulic conductivity methods for sandy loam soil with different land uses. In: *Water resources and environmental engineering I*). Springer (2019).

52. Jiménez C, Tejedor M, Morillas G, Neris J. Infiltration rate in andisols: Effect of changes in vegetation cover (Tenerife, Spain). *Journal of Soil and Water Conservation* **61**, 153-158 (2006).

53. Kumar S, Anderson SH, Bricknell LG, Udawatta RP, Gantzer CJ. Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. *journal of soil and water conservation* **63**, 224-232 (2008).

54. Litt GF*, et al.* Land cover effects on soil infiltration capacity measured using plot scale rainfall simulation in steep tropical lowlands of Central Panama. *Hydrological Processes* **34**, 878-897 (2020).

55. Lopes VS*, et al.* The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil. *Soil and Tillage Research* **198**, 104538 (2020).

56. Mapa RB. Effect of reforestation using Tectona grandis on infiltration and soil water retention. *For Ecol Manage* **77**, 119-125 (1995).

57. Martınez L, Zinck J. Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. *Soil and Tillage Research* **75**, 3-18 (2004).

58. Price K, Jackson CR, Parker AJ. Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA. *Journal of hydrology* **383**, 256-268 (2010).

59. Safaei M, Bashari H, Mosaddeghi MR, Jafari R. Assessing the impacts of land use and land cover changes on soil functions using landscape function analysis and soil quality indicators in semi-arid natural ecosystems. *Catena* **177**, 260-271 (2019).

60. Seobi T, Anderson S, Udawatta R, Gantzer C. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. *Soil Science Society of America Journal* **69**, 893-901 (2005).

61. Spaans EJ*, et al.* Changes in physical properties of young and old volcanic surface soils in Costa Rica after clearing of tropical rain forest. *Hydrological Processes* **3**, 383-392 (1989).

62. Stewart A, Coble A, Contosta AR, Orefice JN, Smith RG, Asbjornsen H. Forest conversion to silvopasture and open pasture: effects on soil hydraulic properties. *Agroforestry Systems* **94**, 869-879 (2020).

63. Yáñez-Díaz MI, Cantú-Silva I, González-Rodríguez H, Sánchez-Castillo L. Effects of land use change and seasonal variation in the hydrophysical properties in Vertisols in northeastern Mexico. *Soil Use and Management* **35**, 378-387 (2019).

64. Zimmermann B, Elsenbeer H, De Moraes JM. The influence of land-use changes on soil hydraulic properties: implications for runoff generation. *For Ecol Manage* **222**, 29-38 (2006).