Effects of environmental factors on the influence of tillage conversion on saturated soil hydraulic conductivity obtained with different methodologies: A global meta-analysis

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Submitted to: ***Soil***

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Abstract. The saturated hydraulic conductivity (K_{sat}) is a key soil hydraulic property governing agricultural production. However, the influence of conversion from conventional tillage (CT) to conservation tillage (CS) (including no tillage (NT) and reduced tillage (RT)) on K_{sat} of soils is not well understood and still debated. In this study, we applied a global meta-analysis method to synthesize 227 paired observations for soil K_{sat} from 69 published studies, and investigated factors influencing the effects of conversion to CS on K_{sat}. Results showed that soil layer, conservation tillage type, soil texture type and cropping system management did not have significant effects on the influence of conversion to CS on K_{sat}. When the K_{sat} was measured by rainfall simulator, conversion to CS significantly ($p < 0.05$) increased the surface and subsurface soil K_{sat} by 41.7% and 36.9%, respectively. In addition, the subsurface K_{sat} also tended to increase under CS practices when the K_{sat} was measured by tension disc infiltrometer. However, when the K_{sat} was measured by hood infiltrometer, ring infiltrometer, constant/falling head and Guelph permeameter, conversion to CS had no significant effects on the K_{sat}. It is observed that when the conversion period was less than 15 yr, the K_{sat} under CS showed a greater increase for a longer conversion period. Climatic and topographic factors including the mean annual temperature (MAT) and the mean annual precipitation (MAP) were statistically related to the responses of K_{sat} to tillage conversion at the global scale. Quadratic polynomials can describe the relationships between them. These findings suggested that quantifying the effects of tillage conversion on soil K_{sat} needed to consider

experimental conditions, especially the measurement technique and conversion period.

1 Introduction

The saturated hydraulic conductivity (K_{sat}), which reflects soil permeability when the soil is saturated, is critical for calculating water flux in soil profile and designing irrigation and drainage systems (Bormann and Klaassen, 2008). It is also an essential soil parameter in agro-ecological, hydrological and biogeochemical models across different scales. The K_{sat} changes greatly in space and time due to factors such as texture, organic matter content, bulk density, porosity, vegetation types or tillage practices (Schaap et al., 1998; Zhu et al., 2014; Liao et al., 2018; Schlüter et al., 2020). Infiltration experiments are often applied to measure infiltration rate of soils in field by different techniques, such as hood infiltrometer (Schwärzel and Punzel, 2007), tension disc infiltrometer (Perroux and White, 1988) and single- or double-ring infiltrometer (Bouwer, 1986). Permeameters are also adopted to measure K_{sat}, such as Guelph permeameter (Reynolds and Elrick, 1985) used in field and constant/falling head permeameter applied on intact (undisturbed) or repacked soil cores (Klute and Dirksen, 1986). In addition, rainfall simulators have been applied to simulate rainfall events for the infiltration runs (Gupta et al., 1994).

Tillage is one of the main causes of spatio-temporal variability in K_{sat}. Conventional tillage (CT), mainly refers to as heavy tillage practices down to 25–30 cm soil depths, is a widely adopted management practice which could significantly affect soil aggregation and hydraulic properties (Pittelkow et al., 2014; Li et al., 2019a). Conservation tillage (CS) is often defined as no-tillage (NT) or reduced tillage (RT) with/without residue retention. NT is confined to soil disturbance associated with crop seeding or planting, while in RT a cultivator or disc harrow is used to loosen the soil superficially (Licht and Al-Kaisi, 2005). The CS practices directly affect soil physical properties by increasing residue retention and decreasing soil disturbance (Turmel et al., 2015). The conversion from CT to CS has been demonstrated to improve physical environment of the soil (Li et al., 2019a). In a wheat/soybean–corn rotation field in the Argentinian Pampas, Sasal et al. (2006) found that aggregates of silty cultivated soils were 30% more stable in CS than under CT due to 21% increase in organic matter. Based on long-term wheat-fallow tillage experiments, Blanco-Canqui et al. (2009) observed that the near-surface soil maximum bulk density of the CT was higher than that of the NT soil by about 6% at Akron, Hays, and Tribune in the central Great Plains. However, it is still controversial whether the change from CT to CS can increase K_{sat}. Several studies (Jarecki and Lal, 2005; Abid and Lal, 2009; Nouri et al., 2018) have reported systematic improvements in the K_{sat} under CS practices, which may be attributed to the decomposition of aggregates, the formation of surface seal by the raindrop impact, the increase of compactness and the decrease of average pore-size distribution of topsoil under CT. In contrast, pores in CS soil may be well connected and protected from raindrop impact and other disturbances by residual mulch (Blanco-Canqui and Lal, 2007; Shukla et al., 2003). However, other studies have shown that K_{sat} under CS is not higher than that under CT (Anikwe and Ubochi, 2007; Abu and Abubakar, 2013; Busari, 2017). Tillage conversion may also lead to different degrees of changes in the factors (e.g., soil structure, organic matter content and bulk density) influencing K_{sat} (Cameira et al., 2003). There, the response of K_{sat} to tillage was complex and not well understood. In addition to CS practices, there are many other agricultural practices that may increase K_{sat}, such as compost addition, straw returning and biochar returning (Olson et al., 2013; Xiao et al., 2020). However, addressing these agricultural practices is beyond the scope of this study.

The effects of tillage on K_{sat} may partly depend on measurement techniques (Morbidelli et al., 2017). The K_{sat} measured by different measurement techniques may differ by an order of magnitude, which is mainly due to the following reasons: (1) the geometry of water application to the soil is different; (2) the strategies to prevent surface sealing and pore plugging are different; (3) the soil wetted (or saturated) volume is different; and (4) for laboratory procedures, the sample size and sampling method may alter the soil core conditions (Fodor et al., 2011; Schlüter et al., 2020). The uncertainty of measurement techniques can mask the influence of the conversion from CT to CS on K_{sat}. Soil layer, texture and CS type may also influence the tillage effect on K_{sat} (Alletto et al., 2010). For example, Yu et al. (2015) observed that tillage of cropland created temporarily well-structured topsoil but compacted subsoil as indicated by low subsoil K_{sat}. Soil texture is one of the main factors controlling soil infiltration and hydraulic conductivity. Coarse textured soils lose moisture much more easily than fine textured soils because of the weaker capillary forces in the large pore spaces. CS has direct and indirect effects on soil structure. Generally, soil compaction begins with the conversion to CS, which may lead to a decrease in air capacity and increase bulk density and permeability resistance of surface soil (Abdollahi and

Munkholm, 2017). In addition, climatic and topographic factors were also found to be related to K_{sat}. For instance, Jarvis et al. (2013) proposed that climatic factors can affect K_{sat} through the effects of soil moisture on soil biota and plant growth and thus the abundance of root and faunal biopores; Yang et al. (2018) found that elevation and soil properties dominated K_{sat} spatial distribution in the Loess Plateau of China. Previous studies have related the response of K_{sat} to tillage and environmental conditions (Strudley et al., 2008; Bodner et al., 2013). However, there has not yet been a global synthetic analysis specifically focusing on how environmental conditions could affect the tillage effect on K_{sat}. Recently, Li et al. (2019a) applied a global meta-analysis to investigate the direction and magnitude of changes in K_{sat} in response to CS practices. They found that CS practices improved K_{sat} in croplands compared with CT. However, the generalizable patterns and regulating factors of tillage effects on K_{sat} remain unclear at the global scale. Therefore, it is necessary to synthesize all available data to reveal global-scale response of K_{sat} and to identify the main regulating factors for its response under CS practices.

The objective of this study was to detect the influences of different experimental conditions (i.e., measurement technique, soil layer, texture, CS type, conversion period, cropping system management, mean annual precipitation or MAP, mean annual temperature or MAT and elevation) on the effects of conversion from CT to CS on the K_{sat} based on a global meta-analysis of 65 studies. We specifically hypothesized that conversion to CS can increase the soil K_{sat} measured by ring infiltrometer and rainfall simulator.

2 Materials and methods

2.1 Source of data and selection criteria

Peer-reviewed journal articles and dissertations related to K_{sat} under CT and CS were searched using Web of Science and China National Knowledge Infrastructure (CNKI, http://www.cnki.net) through 22 January 2022. The keywords used for the literature search were related to: "saturated hydraulic conductivity", "steady-state infiltration rate", "conventional tillage", "conservation tillage", and "till". Using these keywords, a total of 128 papers were searched. To minimize bias, our criteria were as follows: (1) the selected articles included paired observations comparing CT and CS based on field experiments; (2) specific CS practices included RT and NT; (3) other agronomic measures, such as residue retention and film mulching, must be similar between paired controls (CT) and treatments (CS) during the selection process; (4) means, standard deviations (SD) (or standard errors (SE)) and sample sizes were directly provided or could be calculated from the studies; (5) if one article contained K_{sat} in multiple years, only the latest results were applied since the observations should be independent in the meta-analysis (Hedges et al., 1999); (6) for ring infiltrometer, the diameter of a single ring, or the diameter of the inner ring of a double ring, should be greater than 50 cm in this study, although inner and outer ring diameters of about 30 and 60 cm have been widely applied to measure the soil infiltration process (e.g., Ronayne et al., 2012; Zhang et al., 2017). A recent study (Li et al., 2019b) have demonstrated that the ring infiltrometer with an inner diameter of 40 cm is not enough to completely overcome the scale effect; (7) for Guelph permeameter, only the one-head technique was considered for meta-analysis. Previous studies (Reynolds and Elrick, 1985; Jabro and Evans, 2006) have shown that for a significant percentage of times, the two-head method produced unreliable results when using Guelph permeameter. In total, 69 published studies conducted around the world were selected from 128 published articles (Fig. 1). The locations of these studies and their site information are presented in Tables S1 and S2.

Of the 69 studies, 15 did not provide K_{sat} values, but steady-state infiltration rate values. The K_{sat} refers to flow through a saturated porous medium, and the infiltration rate represents the imbibition of water from free water above the soil to pore water beneath the soil surface. In this case there are interface issues such as surface tension, surface crust and seal effects, the influence of litter, mulch, and other factors. Nevertheless, the steady-state infiltration rate was assumed to be the K_{sat} by convention in this study (Yolcubal et al., 2004; Kirkham, 2014) (Table S2). A total of 6 measurement techniques for infiltration rate and K_{sat} were involved in these 65 studies, including hood infiltrometer, tension disc infiltrometer, ring infiltrometer, rainfall simulator, Guelph permeameter used in field, and constant/falling head applied on undisturbed soil cores. The first four techniques determined infiltration rate based on water entry into an unsaturated soil at the soil-atmosphere boundary, while the last two measured the flow of water from one point to another within the soil mass. The final infiltration rate measured by a single or double ring infiltrometer and by tension and hood infiltrometer methods at zero tension were often equated to K_{sat} of the soil. In the selected literature, the infiltration rate has been converted to K_{sat} for the first four techniques.

2.2 Data extraction and statistical analysis

For each study, the mean, the standard error (SE) or standard deviation (SD), and sample size values for treatment and control groups were extracted for K_{sat}. The units of K_{sat} for all studies were converted to cm d^{-1}. For studies that did not provide SD or SE, SD was predicted as 0.1 times the mean (Li et al., 2019a). In addition to K_{sat}, the measurement technique of K_{sat}, soil depth, texture, CS type, conversion period (time since the conversion), cropping system management, MAP, MAT and elevation were also recorded if they could be obtained. All data were extracted from words, tables or digitized from graphs with the software GetData v2.2.4 (http://www.getdata-graph-digitizer.com).

The METAWIN 2.1 software (Sinauer Associates Inc., Sunderland, MA, USA) (Rosenberg et al., 2000) was used to perform meta-analysis in this study. The natural logarithm of the response ratio (R) was used to estimate the effects of changes in tillage practices on K_{sat} (Hedges et al., 1999):

$$\ln(R) = \ln\left(\frac{\overline{X_s}}{\overline{X_t}}\right) = \ln(\overline{X_s}) - \ln(\overline{X_t}) \qquad (1)$$

where $\overline{X_s}$ and $\overline{X_t}$ are the mean value of K_{sat} under CS (treatment) and CT practices (control), respectively. The natural log was applied for meta-analysis since its bias is relatively small and its sampling distribution is approximately normal (Luo et al., 2006). In addition, the variance (VAR) of ln(R) was calculated as:

$$VAR = \frac{{S_s}^2}{n_s\overline{X_s}^2} + \frac{{S_t}^2}{n_t\overline{X_t}^2} \qquad (2)$$

where n_s and n_t are the sample sizes for the CS and CT practices, respectively; and

S_s and S_t are the SDs for CS and CT practices, respectively. To examine whether experimental conditions alter the response direction and magnitude of K_{sat}, observations were divided into subgroups according to the measurement techniques (hood infiltrometer, tension disc infiltrometer, Guelph permeameter, ring infiltrometer, rainfall simulator used in field and constant/falling head used on undisturbed soil cores), soil layer (surface (0-20 cm) and subsurface (> 20 cm depth)), CS practices (NT and RT), soil texture (fine-, medium-, and coarse-textured soil), conversion period (1-5 yr, 6-10 yr, 11-15 yr, 16-20 yr, 21-30 yr and > 30 yr) and cropping system management (single cropping and crop rotation). For differentiating among soil textural classes, we applied the United States Department of Agriculture (USDA) soil textural triangle, and considered clay, sandy clay, and silty clay soils as fine texture; silt, silt loam, silty clay loam, loam, sandy clay loam, and clay loam soils as medium texture; and sand, loamy sand, and sandy loam soils as coarse texture (Daryanto et al., 2016).

A random effects model with a grouping variable was used to compare responses among different subgroups. In this model, there are two sources of variance, including within-study variance (*VAR*) and between-study variance (τ^2), both of which were used to calculate the weighting factor $\omega = [1/(VAR+\tau^2)]$, with $\tau^2 = (Q\text{-}df)/C$, where Q is the observed weighted sum of squares, *df* are the degrees of freedom, and C is a normalization factor. The calculation equations of Q, *df* and C can be referred to Borenstein et al. (2010). The weighted ln(R) (ln(R^*)), which was used as the effect size, was then determined based on the ω. ln(R^*) is defined as

$\ln(R^*) = \sum_{i=1}^{m}[\omega_i \ln(R_i)] / \sum_{i=1}^{m} \omega_i$, where ω_i and $\ln(R_i)$ are ω and $\ln(R)$ of the ith observation, respectively. The $\ln(R^*)$ value indicated the magnitude of the treatment impact. Positive or negative $\ln(R^*)$ values represented an increase or decrease effect of the tillage treatment, respectively. Zero meant no difference between treatment (CS) and control (CT) group. Finally, resampling tests were incorporated into our meta-analysis using the bootstrap method (999 random replicates). The mean effect size ($\overline{\ln(R^*)}$, calculated from 999 iterations) and 95% bootstrap confidence intervals (CI) were generated. If the 95% CI values of $\ln(R^*)$ did not overlap zero, the effect of changes in tillage practices on K_{sat} were considered significant at $p < 0.05$. The percentage change between CS and CT was calculated as exp[$\overline{\ln(R^*)}$]-1.

Regression analyses were performed by SPSS software (version 13.0, SPSS Inc., Chicago, Illinois, USA) to evaluate the relationships between the $\ln(R)$ for soil K_{sat} under CS with MAP, MAT and elevation.

3 Results

The mean effect sizes of K_{sat} under CS conversion were 0.040 (95% CI: -0.108 to 0.156) and 0.110 (95% CI: -0.068 to 0.259) for surface and subsurface layers, respectively (Fig. 2). For surface soil K_{sat}, the mean effect sizes under CS conversion were 0.102 (95% CI: -0.422 to 0.415), -0.002 (95% CI: -0.087 to 0.069), 0.114 (95% CI: -0.213 to 0.412), -0.106 (95% CI: -0.402 to 0.159), 0.046 (95% CI: -0.187 to 0.269) and 0.348 (95% CI: 0.142 to 0.558) for hood infiltrometer, tension disc infiltrometer, ring infiltrometer, constant/falling head, Guelph permeameter and rainfall simulator, respectively (Fig. 3a). However, the mean effect sizes of subsurface

K_{sat} under CS conversion were 0.623 (95% CI: 0.164 to 0.997), 0.036 (95% CI: -0.161 to 0.231), 0.213 (95% CI: -0.028 to 0.486), and 0.314 (95% CI: 0.062 to 0.566) for tension disc infiltrometer, constant/falling head, Guelph permeameter and rainfall simulator, respectively (Fig. 3b).

The CS type, soil texture and cropping system management had no significant ($p >$ 0.05) influences on the effect of conversion to CS on K_{sat}, either in the surface layer or the subsurface layer (Fig. 3cdefij). In addition, the mean effect sizes of surface K_{sat} under CS were -0.057 (95% CI: -0.248 to 0.127), 0.239 (95% CI: 0.056 to 0.419), 0.168 (95% CI: 0.002 to 0.377), -0.097 (95% CI: -0.608 to 0.302), 0.106 (95% CI: -0.352 to 0.517) and 0.723 (95% CI: -0.130 to 1.699) for conversion periods of 1–5, 6–10, 11–15, 16–20, 21–30 and > 30 yr, respectively (Fig. 3g), while those of subsurface K_{sat} under CS conversion were 0.097 (95% CI: -0.120 to 0.354), 0.109 (95% CI: -0.102 to 0.306), 0.339 (95% CI: 0.138 to 0.550), -0.399 (95% CI: -1.802 to 1.387) and -0.009 (95% CI: -0.580 to 0.343) for conversion periods of 1–5, 6–10, 11–15, 16–20 and > 30 yr, respectively (Fig. 3h).

The relationships between the ln(R) of K_{sat} and MAT, MAP, and elevation can be fitted by quadratic polynomials, with the R^2 values ranging between 0.005 and 0.099 (Fig. 4).

4 Discussion

The change of K_{sat} caused by the conversion from CT to CS varied between the different measurement techniques employed (Fig. 3ab). Our findings implied that the measurement technique had an important influence on the determination of K_{sat}

(Reynolds et al., 2000; Rienzner and Gandolfi, 2014). When the K_{sat} was measured by rainfall simulator, conversion to CS significantly ($p < 0.05$) increased the surface and subsurface soil K_{sat} by 41.7% and 36.9%, respectively. This is consistent with the findings of previous studies. For instance, Singh et al. (1994) observed that rainfall can reduce surface roughness, especially the first rains after tillage due to breakdown and sloughing of soil clods upon wetting during rainstorms. Lampurlanés and Cantero-Martínez (2006) proposed that if a rainfall simulator had been used, greater infiltration rates would probably have been found on NT, because residues play a role similar to that of surface roughness, i.e., increasing the time for infiltration to take place. However, Gupta et al. (1997) found the lower K_{sat} values of soil measured by rainfall simulator in NT plots compared with those in CT plots, which was attributed to the fact that the NT practice allowed a consolidated layer to form. This was relatively impervious to the infiltrating water on the soil surface. The restricted downward movement of rain water produced lower K_{sat} under NT. Therefore, more data are needed to test the effect of conversion to CS on K_{sat} measured by rainfall simulator in the future. In addition, the subsurface K_{sat} measured by tension disc infiltrometer also tended to increase under CS practices. The possible reason is that the tension disc infiltrometer had a deep water infiltration depth and big infiltration area. Sasal et al. (2006) observed that using a tension disc infiltrometer, water entry into the soil profile under NT was mainly conditioned by pore orientation. However, when the K_{sat} was measured by hood infiltrometer, ring infiltrometer, constant/falling head and Guelph permeameter, conversion to CS had no significant effects on the surface and subsurface K_{sat}.

It is noted that since studies comparing tillage conversion effects on K_{sat} using different methodologies are from different places, maybe there are other reasons that explain the differences found. For example, the study of Lozano et al. (2016) from Argentinean pampas region did not include ring infiltrometer, hood infiltrometer and rainfall simulator, maybe in those soils the results are not only affected by the measurement technique, MAT and MAP, but also by the clay type or other factors. Some cold weather soils present freezing-thawing processes that are important for pore generation.

The CS type, soil texture and cropping system management had weak effects on the influence of tillage conversion on K_{sat}, suggesting that the single factor of CS, texture or cropping system type could not well explain the variations of K_{sat} under CS practices. However, our results showed that the conversion period substantially affected the influence of conversion to CS on K_{sat}. Tillage conversion tended to decrease surface K_{sat} for the conversion period of 1-5 yr. The possible reason is that soil compaction under CS can lead to a reduction in macroporosity and an increase in bulk density and microporosity. Many previous studies have demonstrated the negative relationship between bulk density and K_{sat} (e.g., Vereecken et al., 1989; Huang et al., 2021). In this case, initially bulk density increased, while K_{sat} decreased. However, after several years this reversed through a re-structuring of the soil by bioturbation (Schlüter et al., 2020). As can be seen from Fig. 3gh, the K_{sat} under CS showed a greater increase for a longer conversion period, when the conversion period was less than 15 yr. It is noted that when the conversion period exceeded 15 yr, the improvement of the K_{sat} under CS is not significant. The reason may be that the decreased soil disturbance with long-term CS practices can increase soil bulk density over time, which can lead to lower water infiltration rate (Six et al., 2000; Li et al., 2019a).

The response of surface K_{sat} was generally negatively correlated with MAT and MAP (Fig. 4ab). This indicated that climatic factors had potential controls on the response of K_{sat} to tillage conversion. The possible reason is that climatic factors mainly indirectly control K_{sat} responses via other variables (e.g., soil moisture, biological processes and effective porosity) (Jarvis et al., 2013). In addition, the correlations between the response of K_{sat} and elevation were very weak (Fig. 4c). Based on these results, we argue that in the cold and temperate regions, the improvement of K_{sat} by tillage conversion will be greater than that in the tropical regions. Although this study provided a global meta-analysis of the responses of K_{sat} to changes in tillage practices under different experimental conditions, the magnitude of these responses might be uncertain. For example, a relatively small number of observations were obtained with the hood infiltrometer, which would affect the results of meta-analysis. Nevertheless, this study emphasized the importance of experimental conditions in judging the change of tillage practices for enhancing soil permeability.

5 Conclusions

Our global meta-analysis indicated that conversion from CT to CS had no significant effects on surface and subsurface K_{sat}. However, these effects were related to experimental conditions, especially the measurement technique, conversion period and climatic factors. The increase of K_{sat} measured by rainfall simulator was substantially larger than the other techniques. In addition, the K_{sat} under CS showed a greater increase for a longer conversion period, when the conversion period was less than 15 yr. Moreover, the lower the MAT or MAP, the more obvious the improvement effect of tillage conversion on surface K_{sat}. Our findings should be useful for understanding the underlying mechanisms driving the change of soil K_{sat} with CS practices.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

Author contributions. KL designed this study, KL, JF and XL performed the meta-analysis, KL and QZ obtained funding, and KL wrote the paper with contributions from QZ.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We thank two anonymous reviewers and editor for their efforts on this paper. Support for this research was provided by the National Natural Science Foundation of China and by Chinese Academy of Sciences.

Financial support. This study was financially supported by the National Natural Science Foundation of China (42125103 and 42171077), and the Youth Innovation Promotion Association, Chinese Academy of Sciences (2020317).

Review statement. This paper was reviewed by editor and two anonymous referees.

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List of Figures:

Figure 1: The geographical coverage of the 69 studies used in the meta-analysis.

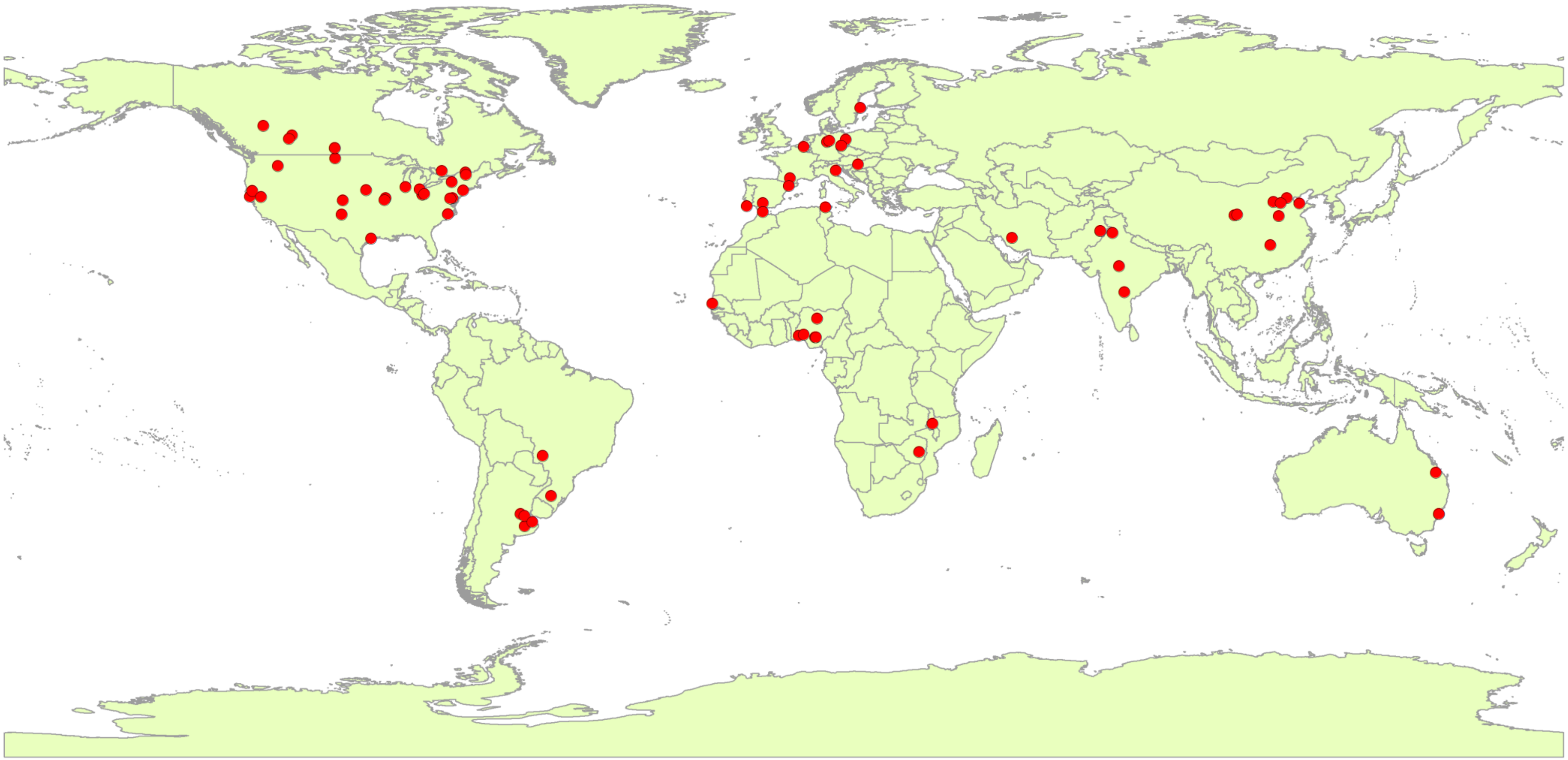


Figure 2: Influence of soil layer on the effect sizes of the soil saturated hydraulic conductivity under conservation tillage (CS) from a global meta-analysis of 69 studies. The error bars indicate effect sizes and 95% bootstrap confidence intervals (CI). The effect of CS was statistically significant if the 95% CI did not bracket zero. The sample size for each variable is shown next to the bar.

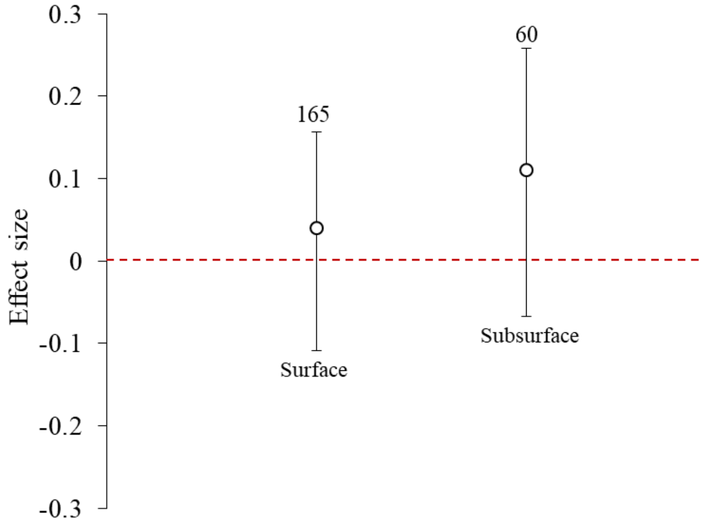
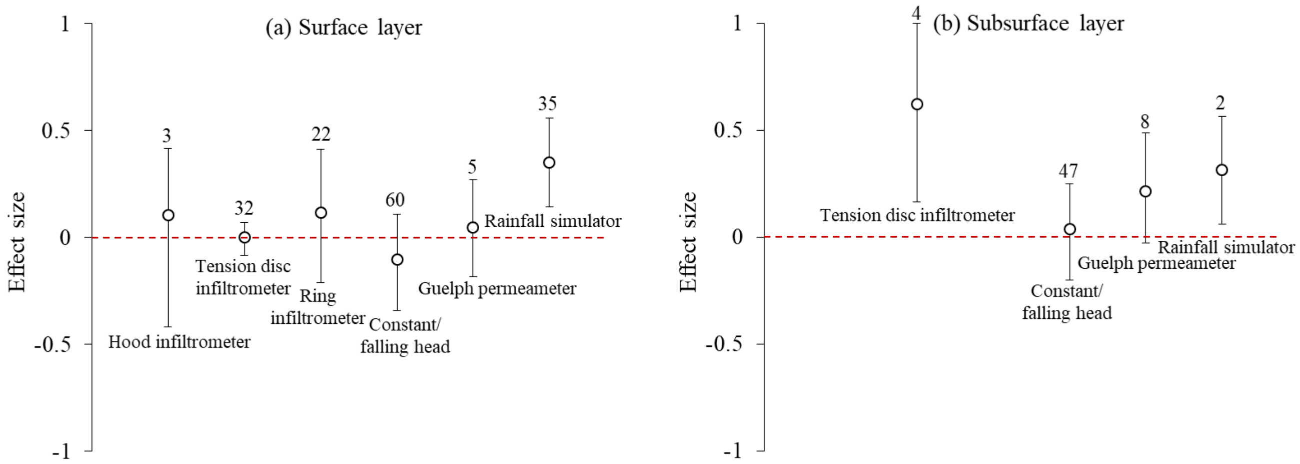
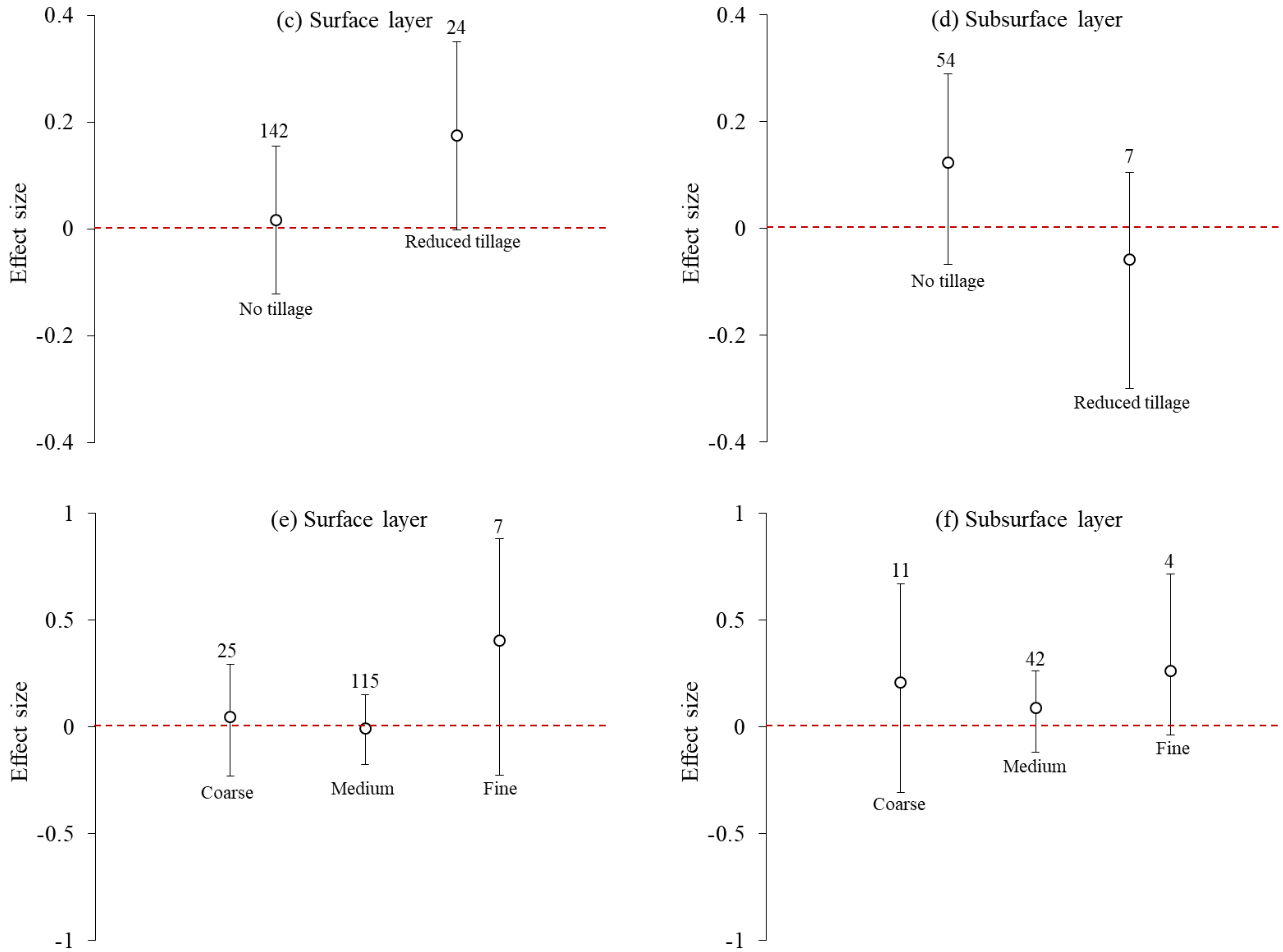
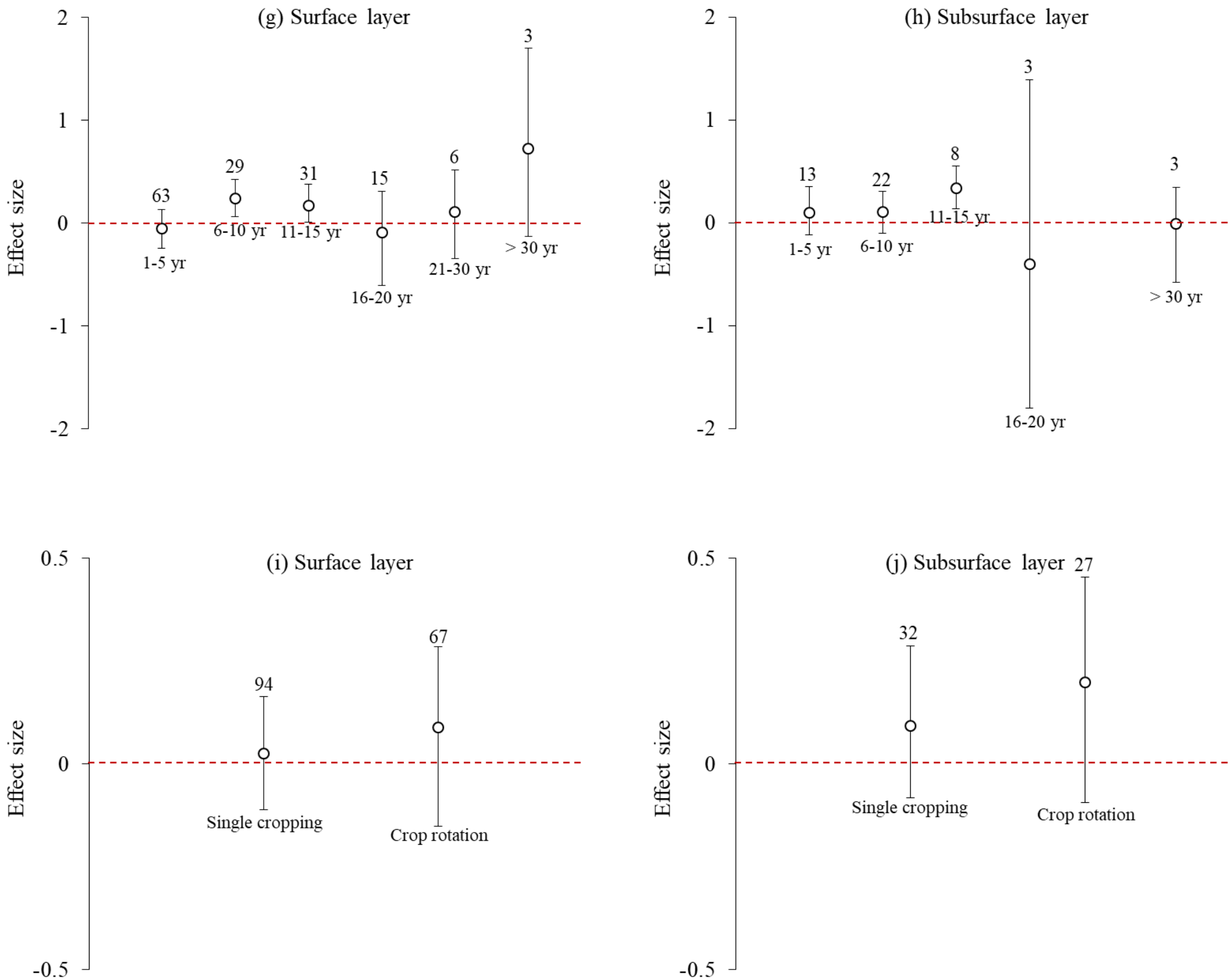


Figure 3: Factors influencing the effect sizes of the surface and subsurface saturated hydraulic conductivity under conservation tillage (CS) from a global meta-analysis of 69 studies, including (a, b) measurement technique, (c, d) conservation tillage type, (e, f) soil texture type, (g, h) time since conversion, and (i, j) cropping system management. The error bars indicate effect sizes and 95% bootstrap confidence intervals (CI). The effect of CS was statistically significant if the 95% CI did not bracket zero. The sample size for each variable is shown next to the bar.





(c) Surface layer
(d) Subsurface layer
(e) Surface layer
(f) Subsurface layer
Effect size
0.4
0.2
0
-0.2
-0.4
1
0.5
-0.5
-1
142
24
54
7
No tillage
Reduced tillage
25
115
11
42
4
Coarse
Medium
Fine



(g) Surface layer
Effect size
2
1
0
-1
-2
63
29
31
15
6
3
1-5 yr
6-10 yr
11-15 yr
16-20 yr
21-30 yr
> 30 yr
(h) Subsurface layer
13
22
8
3
3
16-20 yr
(i) Surface layer
0.5
-0.5
94
67
Single cropping
Crop rotation
(j) Subsurface layer
32
27

Figure 4: Relationships between the natural logarithm of the response ratio (ln(R)) for soil saturated hydraulic conductivity under conservation tillage with (a) mean annual temperature (MAT), (b) mean annual precipitation (MAP) and (c) elevation.