https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021

Impacts of experimental conditions on soil saturated hydraulic conductivity in conventional and conservation tillage practices

Kaihua Liao[1,2*], Xiaoming Lai[1,2], Qing Zhu[1,2,3*]

[1]Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

[2]University of Chinese Academy of Sciences, Beijing 100049, China

[3]Jiangsu Collaborative Innovation Center of Regional Modern Agriculture & Environmental Protection, Huaiyin Normal University, Huaian 223001, China

---

[*] Corresponding author. Tel.: +86 25 86882139; fax: +86 25 57714759.
E-mail addresses: khliao@niglas.ac.cn (K. Liao); qzhu@niglas.ac.cn (Q. Zhu)

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 201 paired observations for soil K_{sat} from 59 published studies, and investigated factors influencing the effects of conversion to CS on K_{sat}. Results showed that the K_{sat} measured by hood infiltrometer, tension disc infiltrometer, and Guelph permeameter produced a similar pattern under CS practices, with non-significant ($p > 0.05$) increase of 6.6%, 3.6% and 4.9%, respectively. However, conversion to CS significantly ($p < 0.05$) increased K_{sat} by 32.0% for ring infiltrometer, while it decreased K_{sat} by 3.2% for constant/falling head ($p > 0.05$). Soil layer, CS type and soil texture had no significant ($p > 0.05$) effects on the influence of conversion to CS on the K_{sat}, but the K_{sat} under CS showed a greater increase for a longer conversion period (time since conversion). In addition, mean annual temperature (MAT) was found to be an important driver controlling the response of K_{sat} to tillage conversion at the large scale. 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). In addition, 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).

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., 2019). 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., 2019). 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, texture 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). 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. (2019) 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, 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 59 studies.

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 June 30, 2020. 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 107 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 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, 59 published studies conducted around the world were selected from 107 published articles (Fig. 1). The locations of these studies and their site information are presented in Tables S1 and S2.

Of the 59 studies, 7 did not provide K_{sat} values. These 7 studies only provided the steady-state infiltration rate, which was assumed to be the K_{sat} by convention in this study (Yolcubal et al., 2004; Kirkham, 2014) (Table S2). A total of 5 measurement techniques for infiltration rate and K_{sat} were involved in these 59 studies, including hood infiltrometer, tension disc infiltrometer, ring infiltrometer, Guelph permeameter used in field, and constant/falling head applied on undisturbed soil cores. The first three 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

https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021

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 three 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 often predicted as 0.1 times the mean in previous studies (Li et al., 2019). Considering the relatively strong spatial variability of soil K_{sat}, we set the SD value as 0.4 in this study. In addition to K_{sat}, the measurement technique of K_{sat}, soil depth, texture, CS practices, conversion period (time since the conversion), 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):

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

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 (including measurement technique, soil layer, texture and CS type) 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 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) and conversion period (1-5 yr, 6-10 yr, 11-15 yr, 16-20 yr, 21-30 yr and > 30 yr). 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

https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021

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 *i*th 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.

Linear 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 saturated hydraulic conductivity under CS with MAP, MAT and elevation.

3 Results

The mean effect sizes of K_{sat} under CS were 0.064 (95% CI: -0.519 to 0.681), 0.035 (95% CI: -0.078 to 0.144), 0.278 (95% CI: 0.084 to 0.508), 0.048 (95% CI: -0.156 to 0.253) and -0.033 (95% CI: -0.201 to 0.138) for hood infiltrometer, tension disc infiltrometer, ring infiltrometer, Guelph permeameter and constant/falling head, respectively (Fig. 2a). The K_{sat} measured by hood infiltrometer, tension disc infiltrometer, and Guelph permeameter showed a similar pattern, with non-significant ($p > 0.05$) increase of 6.6%, 3.6% and 4.9%, respectively. However, conversion from

CT to CS significantly ($p < 0.05$) increased K_{sat} by 32.0% for ring infiltrometer used in field, while it decreased K_{sat} by 3.2% for constant/falling head ($p > 0.05$).

Surface and subsurface K_{sat} showed a similar pattern under CS, with non-significant ($p > 0.05$) increase of 6.8% and 6.1%, respectively (Fig. 2b). The reverse response of K_{sat} to both CS practices was observed. Conversion to NT increased K_{sat} by 3.4% ($p > 0.05$), whereas conversion to RT decreased K_{sat} by 6.5% ($p > 0.05$) (Fig. 2c). For coarse-, medium- and fine-textured soils, changes in tillage practices increased K_{sat} by 3.0%, 1.2% and 6.4% ($p > 0.05$), respectively. In addition, the mean effect sizes of K_{sat} under CS were -0.177 (95% CI: -0.331 to -0.031), 0.144 (95% CI: 0.010 to 0.278), 0.231 (95% CI: 0.046 to 0.444), 0.096 (95% CI: -0.690 to 0.739), 0.199 (95% CI: -0.237 to 0.617) and 0.427 (95% CI: 0.036 to 0.857) for 1-5 yr, 6-10 yr, 11-15 yr, 16-20 yr, 21-30 yr and > 30 yr after conversion, respectively.

The ln(R) of K_{sat} decreased significantly with MAT ($p < 0.001$; Fig. 3a), whereas no significant correlation was found between the ln(R) of K_{sat} and MAP and elevation ($p = 0.123$ and $p = 0.262$, respectively; Fig. 3bc).

4 Discussion

The change of K_{sat} caused by the conversion from CT to CS varied between the different measurement techniques employed (Fig. 2a). 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). Many previous studies found that K_{sat} measured with hood infiltrometer was substantially higher than that measured with tension disc infiltrometer (Matula et al., 2015; Schlüter et al., 2020). It is because

https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021

the hood infiltrometer measurements were conducted directly on field-moist soil, while fine particles of the contact material may cause clogging of pores when using tension disc infiltrometer (Schwärzel and Punzel, 2007). This study found that the increase of K_{sat} measured by hood and tension disc infiltrometer methods was similar when CT was changed to CS. Considering the CI of the effect sizes of K_{sat} was wide for the hood (Fig. 2a), more data are needed to verify this conclusion in the future.

The increase of K_{sat} measured by single- or double-ring infiltrometer was substantially larger than the other two types of infiltrometer. This is consistent with the study by Buczko et al. (2006), who also found that the K_{sat} measured with the ring infiltrometer were higher than the corresponding values measured with the tension infiltrometer. These differences may be caused by subcritical soil water repellency (i.e., contact angles of the soil-water-air interface below 90^o), and other factors, such as air entrapment and differences in water saturation. Another reason could be that the ring infiltrometer had a deeper water infiltration depth and bigger infiltration area. Overall, conversion to CS generally increased K_{sat} measured by the three infiltrometers. This is probably due to the aggregate destruction and formation of surface seals in the CT soil (Fodor et al., 2011). In addition, CT corresponded to lower organic matter of the soil and aggregate stability (Azooz and Arshad, 1996). Conversely, the K_{sat} measured by constant/falling head permeameter generally decreased under CS. The reason may be that the soil volume measured by this method is small, and the macropore channel may be cut off during the sampling process, thus reducing the K_{sat}. In addition, the constant/falling head method using intact core samples had a strong variability, which can affect the measurement results (Soracco et al., 2010). Moreover, the lack of vacuum when saturating the soil core sample prior to constant/falling head measurements could cause air entrapment, which greatly reduces the hydraulic conductivity (Faybishenko, 1995; Steenhauer et al., 2011). The above results suggested to us that the measurement technique had an important influence on the response of K_{sat} to tillage conversion. Recently, Schlüter et al. (2020) also found that the increase in K_{sat} caused by a higher abundance of large biopores under NT was only detected with hood infiltrometer measurements in the field and reversed in tension disc infiltrometer measurements on undisturbed soil cores.

Our results showed that the conversion period substantially affected the K_{sat}. It is noted that conversion from CT to CS significantly ($p < 0.05$) decreased K_{sat} for 1-5 yr. The possible reason is that soil compaction set in with the conversion to CS, which 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). In addition, the decreased soil disturbance with long-term CS practices can improve soil organic carbon accumulation over time, which also leaded to better water infiltration (Six et al., 2000; Li et al., 2019).

The response of K_{sat} was negatively correlated with MAT, indicating that this variable had potential controls on the K_{sat} responses to tillage conversion. The

https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021

possible reason is that mean annual temperature mainly indirectly control K_{sat} responses via other variables (e.g., biological processes and effective porosity). 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 generally positive effects on K_{sat}. However, these effects were related to experimental conditions, especially the measurement technique, conversion period and MAT. The increase of K_{sat} measured by single- or double-ring infiltrometer was substantially larger than the other techniques. In addition, the K_{sat} under CS showed a greater increase for a longer conversion period. Moreover, the lower the MAT, the more obvious the improvement effect of tillage conversion on K_{sat}. Our findings should be useful for understanding the underlying mechanisms driving the change of 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 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 two anonymous referees.

References

Abid, M., and Lal, R.: Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration, Soil Till. Res., 103, 364–372, https://doi.org/10.1016/j.still.2008.11.004, 2009.

Abdollahi, L., and Munkholm, L. J.: Eleven years' effect of conservation practices for temperate sandy loams: II. Soil pore characteristics, Soil Sci. Soc. Am. J., 81(2), 392–403, https://doi.org/10.2136/sssaj2016.07.0221, 2017.

Abu, S. T., and Abubakar, I. U.: Evaluating the effects of tillage techniques on soil hydro-physical properties in Guinea Savanna of Nigeria, Soil Till. Res., 126, 159–168, https://doi.org/10.1016/j.still.2012.09.003, 2013.

Abu-Zreig, M.: Measurement of saturated hydraulic conductivity with various techniques, 2001 ASAE Annual Meeting, http://dx.doi.org/10.13031/2013.7400, 2001.

Alletto, L., Coquet, Y., and Roger-Estrade, J.: Two-dimensional spatial variation of soil physical properties in two tillage systems, Soil Use Manage., 26, 432–444, https://doi.org/10.1111/j.1475-2743.2010.00295.x, 2010.

Anikwe, M. A. N., and Ubochi, J. N.: Short-term changes in soil properties under tillage systems and their effect on sweet potato (*Ipomea batatas L.*) growth and yield in an Ultisol in south-eastern Nigeria, Aust. J. Soil Res., 45, 351–358, https://doi.org/10.1071/SR07035, 2007.

Azooz, R. H., and Arshad, M. A.: Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems, Can. J. Soil Sci., 76, 143–152, https://doi.org/10.4141/cjss96-021, 1996.

Blanco-Canqui, H., and Lal, R.: Soil and crop response to harvesting corn residues for biofuel production, Geoderma, 141, 355–362, https://doi.org/10.1016/j.geoderma.2007.06.012, 2007.

Blanco-Canqui, H., Stone, L. R., Schlegel, A. J., Lyon., D. J., Vigil, M. F., Mikha, M. M., Stahlman, P. W., and Rice, C. W.: No-till induced increase in organic carbon reduces maximum bulk density of soils, Soil Sci. Soc. Am. J., 73, 1871–1879, https://doi.org/10.2136/sssaj2008.0353, 2009.

Blanco-Canqui, H., and Ruis, S. J.: No-tillage and soil physical environment, Geoderma, 326, 164–200, https://doi.org/10.1016/j.geoderma.2018.03.011, 2018.

Borenstein, M., Hedges, L. V., Higgins, J. P., and Rothstein, H. R.: A basic introduction to fixed-effect and random-effects models for meta-analysis, Res. Synth. Methods, 1, 97–111, https://doi.org/10.1002/jrsm.12, 2010.

Bormann, H., and Klaassen, K.: Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils, Geoderma, 145, 295–302, https://doi.org/10.1016/j.geoderma.2008.03.017, 2008.

Bouwer, H.: Intake rate: Cylinder infiltrometer, 825–844. In: Klute, A. (ed.) Methods of soil analysis, Part 1. 2nd ed. Agron. Monogr, 9. ASA and SSSA, Madison, WI, 1986.

Buczko, U., Bens, O., and Hüttl, R. F.: Tillage effects on hydraulic properties and macroporosity in silty and sandy soils, Soil Sci. Soc. Am. J., 70, 1998–2007, https://doi.org/10.2136/sssaj2006.0046, 2006.

Busari, M. A.: Soil physical properties in relation to maize (*Zea mays*) yield after tillage and application of organic and inorganic fertilisers in Abeokuta, southwestern Nigeria, Soil Res., 55, 704–714, https://doi.org/10.1071/SR16162, 2017.

Cameira, M. R., Fernando, R. M., and Pereira, L. S.: Soil macropore dynamics affected by tillage and irrigation for a silty loam alluvial soil in southern Portugal, Soil Till. Res., 70, 131–140, https://doi.org/10.1016/S0167-1987(02)00154-X, 2003.

Daryanto, S., Wang, L., and Jacinthe, P. A.: Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review, Agr. Water Manage., 1, 18–33, https://doi.org/10.1016/j.agwat.2016.04.022, 2016.

Faybishenko, B. A.: Hydraulic behaviour of quasi-saturated soils in the presence of entrapped air: Laboratory experiments, Water Resour. Res., 31, 2421–2435, https://doi.org/10.1016/0148-9062(96)89946-3, 1995.

Fodor, N., Sándor, R., Orfanus, T., Lichner, L., and Rajkai, K.: Evaluation method dependency of measured saturated hydraulic conductivity, Geoderma, 165, 60–68, https://doi.org/10.1016/j.geoderma.2011.07.004, 2011.

Ghosh, B., Pekkat, S., and Yamsani, S.: Evaluation of infiltrometers and permeameters for measuring hydraulic conductivity, Adv. Civ. Eng., 8, 308–321, https://doi.org/10.1520/ACEM20180056, 2019.

Hedges, L. V., Gurevitch, J., and Curtis, P. S.: The meta-analysis of response ratios in experimental ecology, Ecology, 80, 1150–1156, 1999.

Huang, J., Jiang, D., Deng, Y., Ding, S., Cai, C., and Huang, Z.: Soil physicochemical properties and fertility evolution of permanent gully during ecological restoration in granite hilly region of South China, Forests, 12, 510, https://doi.org/10.3390/f12040510, 2021.

Jabro, J. D., and Evans, R. G.: Discrepancies between analytical solutions of two borehole permeameters for estimating field-saturated hydraulic conductivity, Appl. Eng. Agric., 22(4), 549–554, https://doi.org/10.13031/2013.21223, 2006.

Jarecki, M. K., and Lal, R.: Soil organic carbon sequestration rates in two long-term no-till experiments in Ohio, Soil Sci., 170, 280–291, 2005.

Kirkham, M. B.: Principles of Soil and Plant Water Relations - 2nd Edition, Elsevier, Amsterdam, the Netherlands, 2014.

Klute, A., and Dirksen, C.: Hydraulic conductivity and diffusivity: Laboratory methods. 687–734. In: Klute, A. (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, 1986.

Li, Y., Li, Z., Cui, S., Jagadamma, S., and Zhang, Q.: Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis, Soil Till. Res., 194, 104292, https://doi.org/10.1016/j.still.2019.06.009, 2019.

Liao, K., Lai, X., Zhou, Z., Zhu, Q., and Han, Q.: A simple and improved model for describing soil hydraulic properties from saturation to oven dryness, Vadose Zone J., 17, 180082, https://doi.org/10.2136/vzj2018.04.0082, 2018.

Licht, M. A., and Al-Kaisi, M.: Strip-tillage effect on seedbed soil temperature and other soil physical properties, Soil Till. Res., 80(1), 233–249, https://doi.org/10.1016/j.still.2004.03.017, 2005.

Luo, Y., Hui, D., and Zhang, D.: Elevated CO_2 stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis, Ecology, 87, 53–63, https://doi.org/10.1890/04-1724, 2006.

Matula, S., Miháliková, M., Lufinková, J., and Báťková, K.: The role of the initial soil water content in the determination of unsaturated soil hydraulic conductivity using a tension infiltrometer, Plant Soil Environ., 61(11), 515–521, https://doi.org/10.17221/527/2015-PSE, 2015.

Morbidelli, R., Saltalippi, C., Flammini, A., Cifrodelli, M., Picciafuoco, T., Corradini, C., and Govindaraju, R. S.: In situ measurements of soil saturated hydraulic conductivity: assessment of reliability through rainfall-runoff experiments, Hydrol. Process., 31, 3084–3094, https://doi.org/10.1002/hyp.11247, 2017.

Nouri, A., Lee, J., Yin, X., Tyler, D. D., Jagadamma, S., and Arelli, P.: Soil physical properties and soybean yield as influenced by long-term tillage systems and cover cropping in the Midsouth USA, Sustainability, 10, 4696, https://doi.org/10.3390/su10124696, 2018.

Olson, N. C., Gulliver, J. S., Nieber, J. L., and Kayhanian, M.: Remediation to improve infiltration into compact soils, J. Environ. Manage., 117, 85–95, https://doi.org/10.1016/j.jenvman.2012.10.057, 2013.

Perroux, K. M., and White, I.: Designs for disc permeameters, Soil Sci. Soc. Am. J., 52, 1205–1215, https://doi.org/10.2136/sssaj1988.03615995005200050001x, 1988.

Philip, J. R.: The theory of infiltration: 4. Sorptivity and algebraic infiltration equations, Soil Sci., 84, 257–264, 1957.

Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, K. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T., and van Kessel, C.: Productivity limits and potentials of the principles of conservation agriculture, Nature, 517, 365, https://doi.org/10.1038/nature13809, 2014.

Reynolds, W., and Elrick, D.: In situ measurement of field-saturated hydraulic conductivity, sorptivity, and the α-parameter using the Guelph permeameter, Soil Sci., 140(4), 292–302, 1985.

Reynolds, W. D., Bowman, B. T., Brunke, R. R., Drury, C. F., and Tan, C.S.:

Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity, Soil Sci. Soc. Am. J., 64, 478–484, https://doi.org/10.2136/sssaj2000.642478x, 2000.

Rienzner, M., and Gandolfi, C.: Investigation of spatial and temporal variability of saturated soil hydraulic conductivity at the field-scale, Soil Till. Res., 135, 28–40, https://doi.org/10.1016/j.still.2013.08.012, 2014.

Rosenberg, M., Adams, D., and Gurevitch, J.: MetaWin: Statistical Software for Meta-Analysis, Sinauer Associates, Sunderland, MA, USA, 2000.

Sasal, M. C., Andriulo, A. E., and Taboada, M. A.: Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas, Soil Till. Res., 87, 9–18, https://doi.org/10.1016/j.still.2005.02.025, 2006.

Schaap, M. G., Leij, F. J., and van Genuchten, M. Th.: Neural network analysis for hierarchical prediction of soil water retention and saturated hydraulic conductivity, Soil Sci. Soc. Am. J., 62, 847–855, https://doi.org/10.2136/sssaj1998.03615995006200040001x., 1998.

Schlüter, S., Albrecht, L., Schwärzel, K., and Kreiselmeier, J.: Long-term effects of conventional tillage and no-tillage on saturated and near-saturated hydraulic conductivity – Can their prediction be improved by pore metrics obtained with X-ray CT? Geoderma, 361, 114082, https://doi.org/10.1016/j.geoderma.2019.114082, 2020.

Schwärzel, K., and Punzel, J.: Hood infiltrometer—a new type of tension infiltrometer, Soil Sci. Soc. Am. J., 71(5), 1438–1447, https://doi.org/10.2136/sssaj2006.0104, 2007.

Shukla, M. K., Lal, R., and Ebinger, M.: Tillage effects on physical and hydrological properties of a typic argiaquoll in Central Ohio, Soil Sci., 168, 802–811, 2003.

Six, J., Paustian, K., Elliott, E. T., and Combrink, C.: Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon, Soil Sci. Soc. Am. J. 64, 681–689, https://doi.org/10.2136/sssaj2000.642681x, 2000.

Soracco, C. G., Lozano, L. A., Sarli, G. O., Gelati, P. R., and Filgueira, R. R.: Anisotropy of saturated hydraulic conductivity in a soil under conservation and no-till treatments, Soil Till. Res., 109, 18–22, https://doi.org/10.1016/j.still.2010.03.013, 2010.

Steenhauer, K., Pokrajac, D., O'Donoghue, T., and Kikkert, G. A.: Subsurface processes generated by bore-driven swash on coarse-grained beaches, J. Geophys. Res. Oceans, 116, https://doi.org/10.1029/2010JC006789, 2011.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., and Govaerts, B.: Crop residue management and soil health: a systems analysis, Agric. Syst., 134, 6–16, https://doi.org/10.1016/j.agsy.2014.05.009, 2015.

Vereecken, H., Maes, J., and Darius, P.: Estimating the soil moisture retention characteristics from texture, bulk density and carbon content, Soil Sci., 148, 389–403, 1989.

Xiao, L., Yuan, G., Feng, L., Bi, D., Wei, J., Shen, G., and Liu, Z.: Coupled effects of biochar use and farming practice on physical properties of a salt-affected soil with wheat–maize rotation, J. Soil. Sediment., 20, 3053–3061, https://doi.org/10.1007/s11368-020-02616-0, 2020.

Yolcubal, I., Brusseau, M. L., Artiola, J. F., Wierenga, P., and Wilson, L. G.: 12-Environmental physical properties and processes. In: Artiola, J. F., Pepper, I. L., Brusseau, M. L. (eds.) Environmental Monitoring and Characterization, 207–239, 2004.

Yu, M., Zhang, L., Xu, X., Feger, K., Wang, Y., Liu, W., and Schwärzel, K.: Impact of land-use changes on soil hydraulic properties of Calcaric Regosols on the Loess Plateau, NW China, J. Plant Nutr. Soil Sci., 178, 486–498, https://doi.org/10.1002/jpln.201400090, 2015.

Zhu, Q., Nie, X., Zhou, X., Liao, K., and Li, H.: Soil moisture response to rainfall at different topographic positions along a mixed land-use hillslope, Catena, 119, 61–70, https://doi.org/10.1016/j.catena.2014.03.010, 2014.

List of Figures:

Figure 1: The geographical coverage of the 59 studies used in the meta-analysis.

Figure 2: Factors influencing the effect sizes of the soil saturated hydraulic conductivity under conservation tillage (CS) from a global meta-analysis of 59 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: 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.

Figure 1

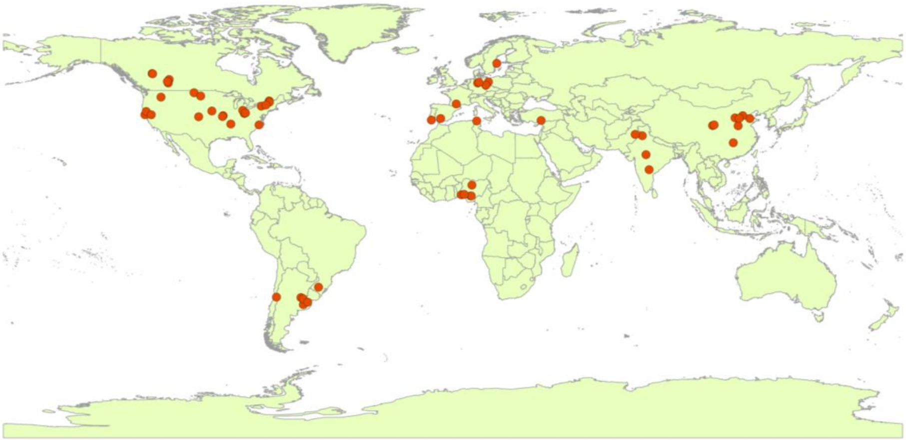
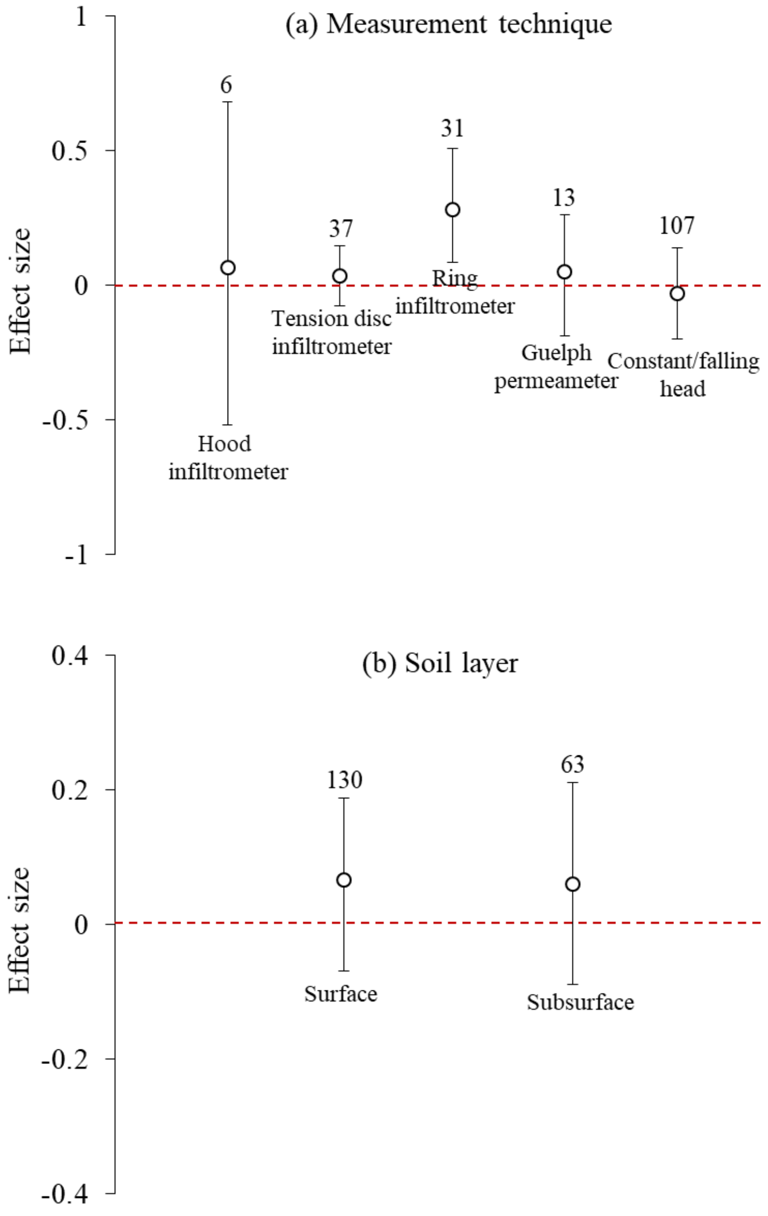
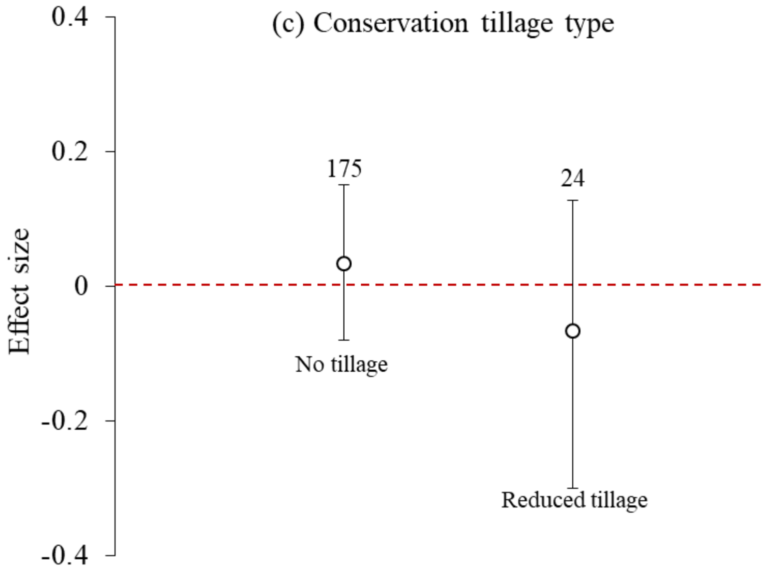
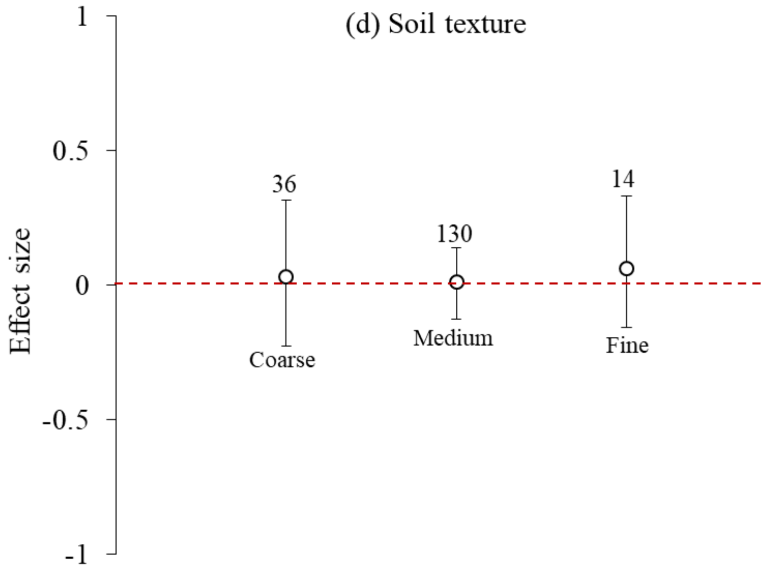


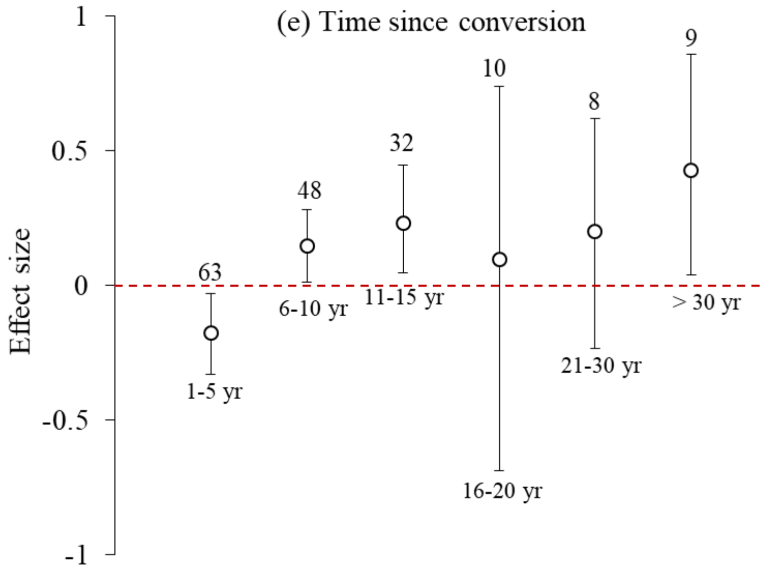
Figure 2


(a) Measurement technique
Effect size
1
0.5
0
-0.5
-1
6
37
31
13
107
Hood infiltrometer
Tension disc infiltrometer
Ring infiltrometer
Guelph permeameter
Constant/falling head
(b) Soil layer
Effect size
0.4
0.2
0
-0.2
-0.4
130
63
Surface
Subsurface

https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021


(c) Conservation tillage type


(d) Soil texture


(e) Time since conversion
Effect size
1
0.5
0
-0.5
-1
63
1-5 yr
48
6-10 yr
32
11-15 yr
10
16-20 yr
8
21-30 yr
9
> 30 yr

https://doi.org/10.5194/soil-2021-118
Preprint. Discussion started: 18 November 2021

Figure 3