



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

3 Kaihua Liao^{1,2*}, Xiaoming Lai^{1,2}, Qing Zhu^{1,2,3*}

4 ¹Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography

5 and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

6 ²University of Chinese Academy of Sciences, Beijing 100049, China

7 ³Jiangsu Collaborative Innovation Center of Regional Modern Agriculture &

8 Environmental Protection, Huaiyin Normal University, Huaian 223001, China

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



11 **Abstract.** The saturated hydraulic conductivity (K_{sat}) is a key soil hydraulic property
12 governing agricultural production. However, the influence of conversion from
13 conventional tillage (CT) to conservation tillage (CS) (including no tillage (NT) and
14 reduced tillage (RT)) on K_{sat} of soils is not well understood and still debated. In this
15 study, we applied a global meta-analysis method to synthesize 201 paired
16 observations for soil K_{sat} from 59 published studies, and investigated factors
17 influencing the effects of conversion to CS on K_{sat} . Results showed that the K_{sat}
18 measured by hood infiltrometer, tension disc infiltrometer, and Guelph permeameter
19 produced a similar pattern under CS practices, with non-significant ($p > 0.05$)
20 increase of 6.6%, 3.6% and 4.9%, respectively. However, conversion to CS
21 significantly ($p < 0.05$) increased K_{sat} by 32.0% for ring infiltrometer, while it
22 decreased K_{sat} by 3.2% for constant/falling head ($p > 0.05$). Soil layer, CS type and
23 soil texture had no significant ($p > 0.05$) effects on the influence of conversion to CS
24 on the K_{sat} , but the K_{sat} under CS showed a greater increase for a longer conversion
25 period (time since conversion). In addition, **mean annual temperature (MAT)** was
26 found to be an important driver controlling the response of K_{sat} to tillage conversion at
27 the large scale. These findings suggested that quantifying the effects of tillage
28 conversion on soil K_{sat} needed to consider experimental conditions, especially the
29 measurement technique and conversion period.



30 **1 Introduction**

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

45 Tillage is one of the main causes of spatio-temporal variability in K_{sat} .
46 Conventional tillage (CT), mainly refers to as heavy tillage practices down to 25–30
47 cm soil depths, is a widely adopted management practice which could significantly
48 affect soil aggregation and hydraulic properties (Pittelkow et al., 2014; Li et al., 2019).
49 Conservation tillage (CS) is often defined as no-tillage (NT) or reduced tillage (RT)
50 with/without residue retention. NT is confined to soil disturbance associated with crop
51 seeding or planting, while in RT a cultivator or disc harrow is used to loosen the soil



52 superficially (Licht and Al-Kaisi, 2005). The CS practices directly affect soil physical
53 properties by increasing residue retention and decreasing soil disturbance (Turmel et
54 al., 2015). The conversion from CT to CS has been demonstrated to improve physical
55 environment of the soil (Li et al., 2019). In a wheat/soybean–corn rotation field in the
56 Argentinian Pampas, Sasal et al. (2006) found that aggregates of silty cultivated soils
57 were 30% more stable in CS than under CT due to 21% increase in organic matter.
58 Based on long-term wheat-fallow tillage experiments, Blanco-Canqui et al. (2009)
59 observed that the near-surface soil maximum bulk density of the CT was higher than
60 that of the NT soil by about 6% at Akron, Hays, and Tribune in the central Great
61 Plains. However, it is still controversial whether the change from CT to CS can
62 increase K_{sat} . Several studies (Jarecki and Lal, 2005; Abid and Lal, 2009; Nouri et al.,
63 2018) have reported systematic improvements in the K_{sat} under CS practices, which
64 may be attributed to the decomposition of aggregates, the formation of surface seal by
65 the raindrop impact, the increase of compactness and the decrease of average
66 pore-size distribution of topsoil under CT. In contrast, pores in CS soil may be well
67 connected and protected from raindrop impact and other disturbances by residual
68 mulch (Blanco-Canqui and Lal, 2007; Shukla et al., 2003). However, other studies
69 have shown that K_{sat} under CS is not higher than that under CT (Anikwe and Ubochi,
70 2007; Abu and Abubakar, 2013; Busari, 2017). Tillage conversion may also lead to
71 different degrees of changes in the factors (e.g., soil structure, texture and bulk
72 density) influencing K_{sat} (Cameira et al., 2003). There, the response of K_{sat} to tillage
73 was complex and not well understood. In addition to CS practices, there are many



74 other agricultural practices that may increase K_{sat} , such as compost addition, straw
75 returning and biochar returning (Olson et al., 2013; Xiao et al., 2020). However,
76 addressing these agricultural practices is beyond the scope of this study.

77 The effects of tillage on K_{sat} may partly depend on measurement techniques
78 (Morbidelli et al., 2017). The K_{sat} measured by different measurement techniques may
79 differ by an order of magnitude, which is mainly due to the following reasons: (1) the
80 geometry of water application to the soil is different; (2) the strategies to prevent
81 surface sealing and pore plugging are different; (3) the soil wetted (or saturated)
82 volume is different; and (4) for laboratory procedures, the sample size and sampling
83 method may alter the soil core conditions (Fodor et al., 2011; Schlüter et al., 2020).
84 The uncertainty of measurement techniques can mask the influence of the conversion
85 from CT to CS on K_{sat} . Soil layer, texture and CS type may also influence the tillage
86 effect on K_{sat} (Alletto et al., 2010). For example, Yu et al. (2015) observed that tillage
87 of cropland created temporarily well-structured topsoil but compacted subsoil as
88 indicated by low subsoil K_{sat} . Soil texture is one of the main factors controlling soil
89 infiltration and hydraulic conductivity. Coarse textured soils lose moisture much more
90 easily than fine textured soils because of the weaker capillary forces in the large pore
91 spaces. CS has direct and indirect effects on soil structure. Generally, soil compaction
92 begins with the conversion to CS, which may lead to a decrease in air capacity and
93 increase bulk density and permeability resistance of surface soil (Abdollahi and
94 Munkholm, 2017). However, there has not yet been a global synthetic analysis
95 specifically focusing on how environmental conditions could affect the tillage effect



96 on K_{sat} . Recently, Li et al. (2019) applied a global meta-analysis to investigate the
97 direction and magnitude of changes in K_{sat} in response to CS practices. They found
98 that CS practices improved K_{sat} in croplands compared with CT. However, the
99 generalizable patterns and regulating factors of tillage effects on K_{sat} remain unclear at
100 the global scale. Therefore, it is necessary to synthesize all available data to reveal
101 global-scale response of K_{sat} and to identify the main regulating factors for its
102 response under CS practices.

103 The objective of this study was to detect the influences of different experimental
104 conditions (i.e., measurement technique, soil layer, texture, CS type, conversion
105 period, mean annual precipitation or MAP, mean annual temperature or MAT and
106 elevation) on the effects of conversion from CT to CS on the K_{sat} based on a global
107 meta-analysis of 59 studies.

108 **2 Materials and methods**

109 **2.1 Source of data and selection criteria**

110 Peer-reviewed journal articles and dissertations related to K_{sat} under CT and CS were
111 searched using Web of Science and China National Knowledge Infrastructure (CNKI,
112 <http://www.cnki.net>) through June 30, 2020. The keywords used for the literature
113 search were related to: “saturated hydraulic conductivity”, “steady-state infiltration
114 rate”, “conventional tillage”, “conservation tillage”, and “till”. Using these keywords,
115 a total of 107 papers were searched. To minimize bias, our criteria were as follows: (1)
116 the selected articles included paired observations comparing CT and CS based on
117 field experiments; (2) specific CS practices included RT and NT; (3) other agronomic



118 measures, such as residue retention and film mulching, must be similar between
119 paired controls (CT) and treatments (CS) during the selection process; (4) means,
120 standard deviations (SD) (or standard errors (SE)) and sample sizes were directly
121 provided or could be calculated from the studies; (5) if one article contained K_{sat} in
122 multiple years, only the latest results were applied since the observations should be
123 independent in the meta-analysis (Hedges et al., 1999); (6) for Guelph permeameter,
124 only the one-head technique was considered for meta-analysis. Previous studies
125 (Reynolds and Elrick, 1985; Jabro and Evans, 2006) have shown that for a significant
126 percentage of times, the two-head method produced unreliable results when using
127 Guelph permeameter. In total, 59 published studies conducted around the world were
128 selected from 107 published articles (Fig. 1). The locations of these studies and their
129 site information are presented in Tables S1 and S2.

130 Of the 59 studies, 7 did not provide K_{sat} values. These 7 studies only provided the
131 steady-state infiltration rate, which was assumed to be the K_{sat} by convention in this
132 study (Yolcubal et al., 2004; Kirkham, 2014) (Table S2). A total of 5 measurement
133 techniques for infiltration rate and K_{sat} were involved in these 59 studies, including
134 hood infiltrometer, tension disc infiltrometer, ring infiltrometer, Guelph permeameter
135 used in field, and constant/falling head applied on undisturbed soil cores. The first
136 three techniques determined infiltration rate based on water entry into an unsaturated
137 soil at the soil-atmosphere boundary, while the last two measured the flow of water
138 from one point to another within the soil mass. The final infiltration rate measured by
139 a single or double ring infiltrometer and by tension and hood infiltrometer methods at



140 zero tension were often equated to K_{sat} of the soil. In the selected literature, the
141 infiltration rate has been converted to K_{sat} for the first three techniques.

142 **2.2 Data extraction and statistical analysis**

143 For each study, the mean, the standard error (SE) or standard deviation (SD), and
144 sample size values for treatment and control groups were extracted for K_{sat} . The units
145 of K_{sat} for all studies were converted to cm d^{-1} . For studies that did not provide SD or
146 SE, SD was often predicted as 0.1 times the mean in previous studies (Li et al., 2019).
147 Considering the relatively strong spatial variability of soil K_{sat} , we set the SD value as
148 0.4 in this study. In addition to K_{sat} , the measurement technique of K_{sat} , soil depth,
149 texture, CS practices, conversion period (time since the conversion), MAP, MAT and
150 elevation were also recorded if they could be obtained. All data were extracted from
151 words, tables or digitized from graphs with the software GetData v2.2.4
152 (<http://www.getdata-graph-digitizer.com>).

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

$$157 \ln(R) = \ln\left(\frac{\bar{X}_s}{\bar{X}_t}\right) = \ln(\bar{X}_s) - \ln(\bar{X}_t) \quad (1)$$

158 where \bar{X}_s and \bar{X}_t are the mean value of K_{sat} under CS (treatment) and CT practices
159 (control), respectively. The natural log was applied for meta-analysis since its bias is
160 relatively small and its sampling distribution is approximately normal (Luo et al.,
161 2006). In addition, the variance (VAR) of $\ln(R)$ was calculated as:



$$162 \quad VAR = \frac{S_s^2}{n_s \bar{X}_s^2} + \frac{S_t^2}{n_t \bar{X}_t^2} \quad (2)$$

163 where n_s and n_t are the sample sizes for the CS and CT practices, respectively; and
164 S_s and S_t are the SDs for CS and CT practices, respectively. To examine whether
165 experimental conditions (including measurement technique, soil layer, texture and CS
166 type) alter the response direction and magnitude of K_{sat} , observations were divided
167 into subgroups according to the measurement techniques (hood infiltrometer, tension
168 disc infiltrometer, Guelph permeameter, ring infiltrometer used in field and
169 constant/falling head used on undisturbed soil cores), soil layer (surface (0-20 cm)
170 and subsurface (> 20 cm depth)), CS practices (NT and RT), soil texture (fine-,
171 medium-, and coarse-textured soil) and conversion period (1-5 yr, 6-10 yr, 11-15 yr,
172 16-20 yr, 21-30 yr and > 30 yr). For differentiating among soil textural classes, we
173 applied the United States Department of Agriculture (USDA) soil textural triangle,
174 and considered clay, sandy clay, and silty clay soils as fine texture; silt, silt loam, silty
175 clay loam, loam, sandy clay loam, and clay loam soils as medium texture; and sand,
176 loamy sand, and sandy loam soils as coarse texture (Daryanto et al., 2016).

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



184 size, was then determined based on the ω . $\ln(R^*)$ is defined as
185 $\ln(R^*) = \frac{\sum_{i=1}^m [\omega_i \ln(R_i)]}{\sum_{i=1}^m \omega_i}$, where ω_i and $\ln(R_i)$ are ω and $\ln(R)$ of the i th
186 observation, respectively. The $\ln(R^*)$ value indicated the magnitude of the treatment
187 impact. Positive or negative $\ln(R^*)$ values represented an increase or decrease effect of
188 the tillage treatment, respectively. Zero meant no difference between treatment (CS)
189 and control (CT) group. Finally, resampling tests were incorporated into our
190 meta-analysis using the bootstrap method (999 random replicates). The mean effect
191 size ($\overline{\ln(R^*)}$, calculated from 999 iterations) and 95% bootstrap confidence intervals
192 (CI) were generated. If the 95% CI values of $\ln(R^*)$ did not overlap zero, the effect of
193 changes in tillage practices on K_{sat} were considered significant at $p < 0.05$. The
194 percentage change between CS and CT was calculated as $\exp[\overline{\ln(R^*)}] - 1$.

195 Linear regression analyses were performed by SPSS software (version 13.0,
196 SPSS Inc., Chicago, Illinois, USA) to evaluate the relationships between the $\ln(R)$ for
197 soil saturated hydraulic conductivity under CS with MAP, MAT and elevation.

198 **3 Results**

199 The mean effect sizes of K_{sat} under CS were 0.064 (95% CI: -0.519 to 0.681), 0.035
200 (95% CI: -0.078 to 0.144), 0.278 (95% CI: 0.084 to 0.508), 0.048 (95% CI: -0.156 to
201 0.253) and -0.033 (95% CI: -0.201 to 0.138) for hood infiltrometer, tension disc
202 infiltrometer, ring infiltrometer, Guelph permeameter and constant/falling head,
203 respectively (Fig. 2a). The K_{sat} measured by hood infiltrometer, tension disc
204 infiltrometer, and Guelph permeameter showed a similar pattern, with non-significant
205 ($p > 0.05$) increase of 6.6%, 3.6% and 4.9%, respectively. However, conversion from



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

208 Surface and subsurface K_{sat} showed a similar pattern under CS, with
209 non-significant ($p > 0.05$) increase of 6.8% and 6.1%, respectively (Fig. 2b). The
210 reverse response of K_{sat} to both CS practices was observed. Conversion to NT
211 increased K_{sat} by 3.4% ($p > 0.05$), whereas conversion to RT decreased K_{sat} by 6.5%
212 ($p > 0.05$) (Fig. 2c). For coarse-, medium- and fine-textured soils, changes in tillage
213 practices increased K_{sat} by 3.0%, 1.2% and 6.4% ($p > 0.05$), respectively. In addition,
214 the mean effect sizes of K_{sat} under CS were -0.177 (95% CI: -0.331 to -0.031), 0.144
215 (95% CI: 0.010 to 0.278), 0.231 (95% CI: 0.046 to 0.444), 0.096 (95% CI: -0.690 to
216 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,
217 6-10 yr, 11-15 yr, 16-20 yr, 21-30 yr and > 30 yr after conversion, respectively.

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

221 **4 Discussion**

222 The change of K_{sat} caused by the conversion from CT to CS varied between the
223 different measurement techniques employed (Fig. 2a). Our findings implied that the
224 measurement technique had an important influence on the determination of K_{sat}
225 (Reynolds et al., 2000; Rienzner and Gandolfi, 2014). Many previous studies found
226 that K_{sat} measured with hood infiltrometer was substantially higher than that measured
227 with tension disc infiltrometer (Matula et al., 2015; Schlüter et al., 2020). It is because



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

234 The increase of K_{sat} measured by single- or double-ring infiltrometer was
235 substantially larger than the other two types of infiltrometer. This is consistent with
236 the study by Buczko et al. (2006), who also found that the K_{sat} measured with the ring
237 infiltrometer were higher than the corresponding values measured with the tension
238 infiltrometer. These differences may be caused by subcritical soil water repellency
239 (i.e., contact angles of the soil-water-air interface below 90°), and other factors, such
240 as air entrapment and differences in water saturation. Another reason could be that the
241 ring infiltrometer had a deeper water infiltration depth and bigger infiltration area.
242 Overall, conversion to CS generally increased K_{sat} measured by the three
243 infiltrometers. This is probably due to the aggregate destruction and formation of
244 surface seals in the CT soil (Fodor et al., 2011). In addition, CT corresponded to lower
245 organic matter of the soil and aggregate stability (Azooz and Arshad, 1996).
246 Conversely, the K_{sat} measured by constant/falling head permeameter generally
247 decreased under CS. The reason may be that the soil volume measured by this method
248 is small, and the macropore channel may be cut off during the sampling process, thus
249 reducing the K_{sat} . In addition, the constant/falling head method using intact core



250 samples had a strong variability, which can affect the measurement results (Soracco et
251 al., 2010). Moreover, the lack of vacuum when saturating the soil core sample prior to
252 constant/falling head measurements could cause air entrapment, which greatly reduces
253 the hydraulic conductivity (Faybishenko, 1995; Steenhauer et al., 2011). The above
254 results suggested to us that the measurement technique had an important influence on
255 the response of K_{sat} to tillage conversion. Recently, Schlüter et al. (2020) also found
256 that the increase in K_{sat} caused by a higher abundance of large biopores under NT was
257 only detected with hood infiltrometer measurements in the field and reversed in
258 tension disc infiltrometer measurements on undisturbed soil cores.

259 Our results showed that the conversion period substantially affected the K_{sat} . It is
260 noted that conversion from CT to CS significantly ($p < 0.05$) decreased K_{sat} for 1-5 yr.
261 The possible reason is that soil compaction set in with the conversion to CS, which
262 can lead to a reduction in macroporosity and an increase in bulk density and
263 microporosity. Many previous studies have demonstrated the negative relationship
264 between bulk density and K_{sat} (e.g., Vereecken et al., 1989; Huang et al., 2021). In this
265 case, initially bulk density increased, while K_{sat} decreased. However, after several
266 years this reversed through a re-structuring of the soil by bioturbation (Schlüter et al.,
267 2020). In addition, the decreased soil disturbance with long-term CS practices can
268 improve soil organic carbon accumulation over time, which also led to better
269 water infiltration (Six et al., 2000; Li et al., 2019).

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



272 possible reason is that mean annual temperature mainly indirectly control K_{sat}
273 responses via other variables (e.g., biological processes and effective porosity). Based
274 on these results, we argue that in the cold and temperate regions, the improvement of
275 K_{sat} by tillage conversion will be greater than that in the tropical regions. Although
276 this study provided a global meta-analysis of the responses of K_{sat} to changes in tillage
277 practices under different experimental conditions, the magnitude of these responses
278 might be uncertain. For example, a relatively small number of observations were
279 obtained with the hood infiltrometer, which would affect the results of meta-analysis.
280 Nevertheless, this study emphasized the importance of experimental conditions in
281 judging the change of tillage practices for enhancing soil permeability.

282 **5 Conclusions**

283 Our global meta-analysis indicated that conversion from CT to CS had generally
284 positive effects on K_{sat} . However, these effects were related to experimental
285 conditions, especially the measurement technique, conversion period and MAT. The
286 increase of K_{sat} measured by single- or double-ring infiltrometer was substantially
287 larger than the other techniques. In addition, the K_{sat} under CS showed a greater
288 increase for a longer conversion period. Moreover, the lower the MAT, the more
289 obvious the improvement effect of tillage conversion on K_{sat} . Our findings should be
290 useful for understanding the underlying mechanisms driving the change of K_{sat} with
291 CS practices.

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



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

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

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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

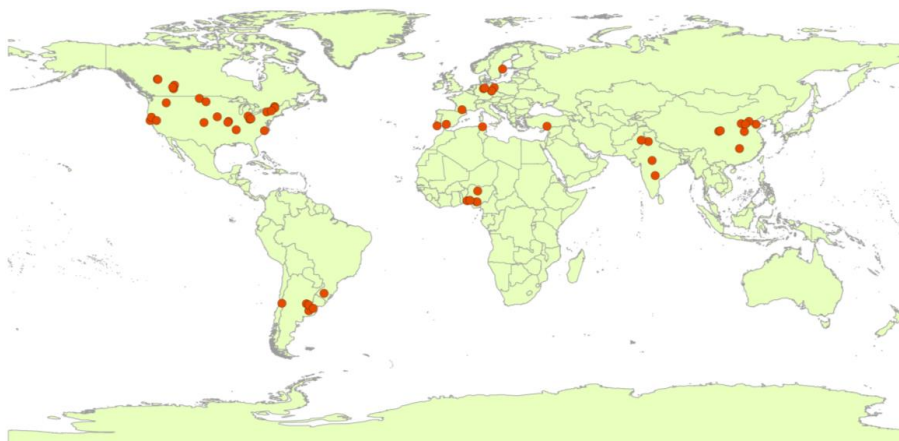
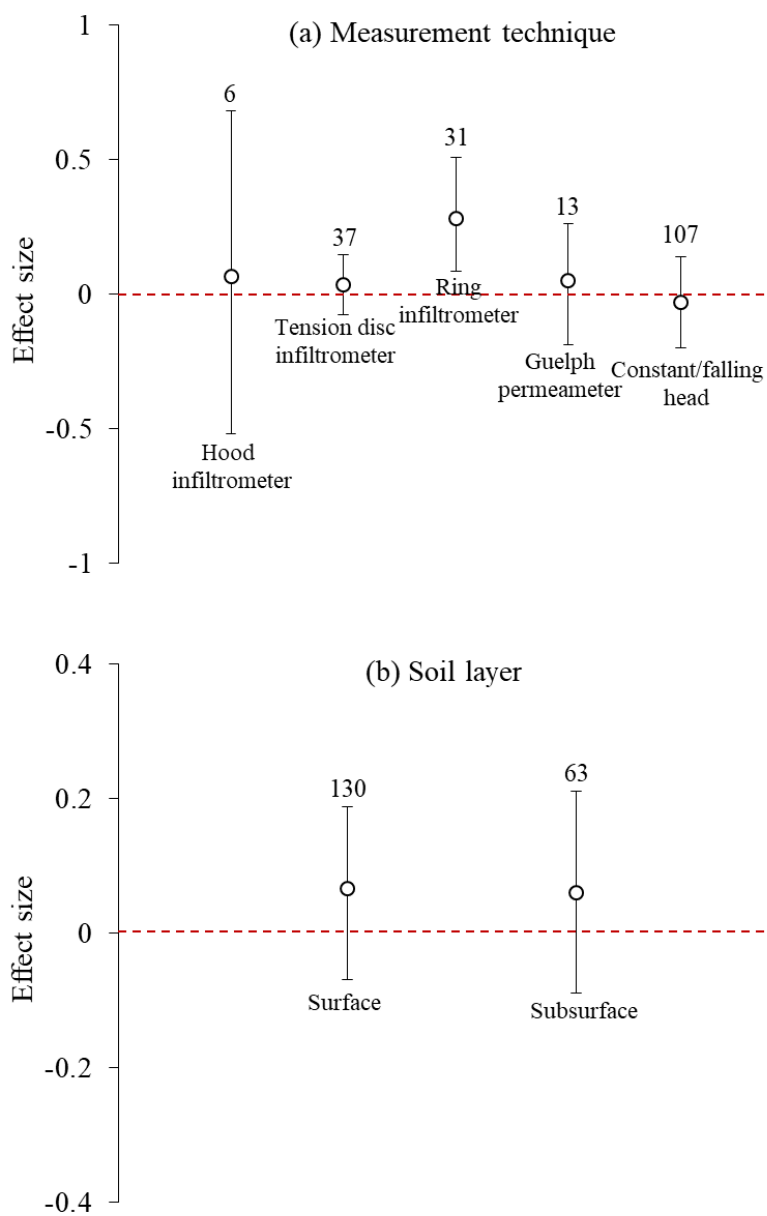
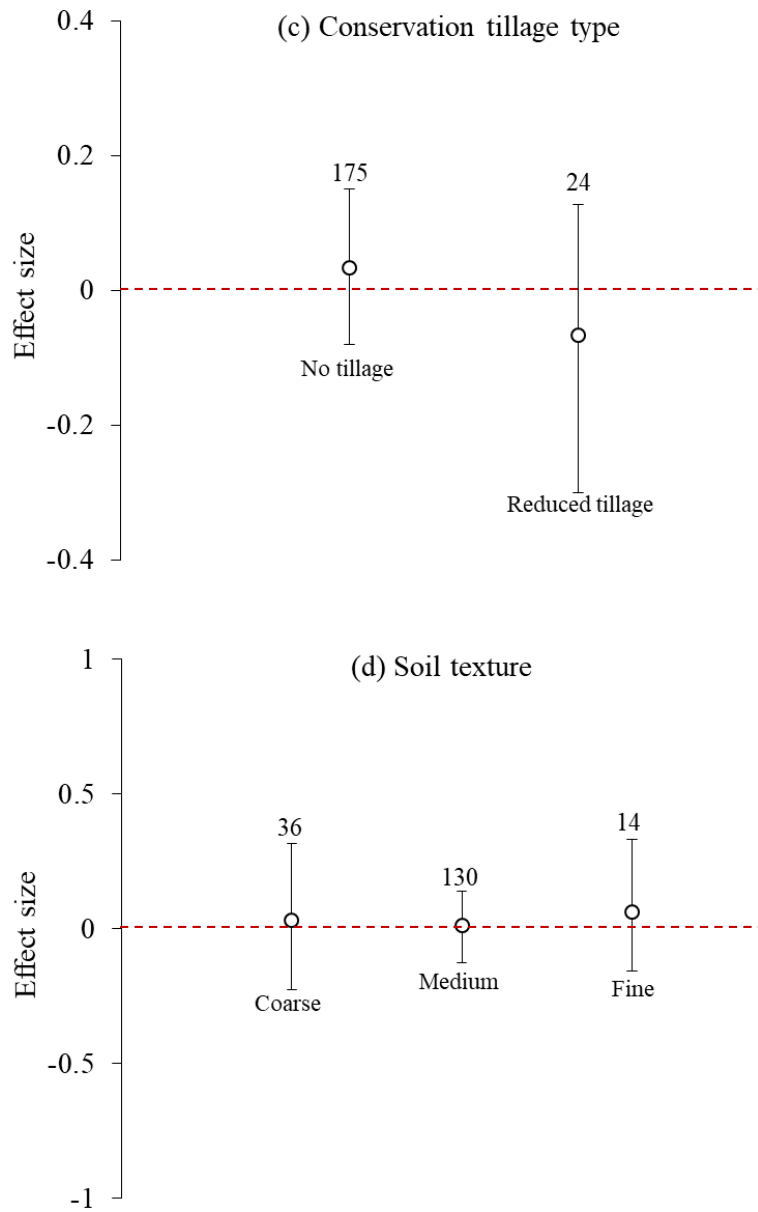




Figure 2





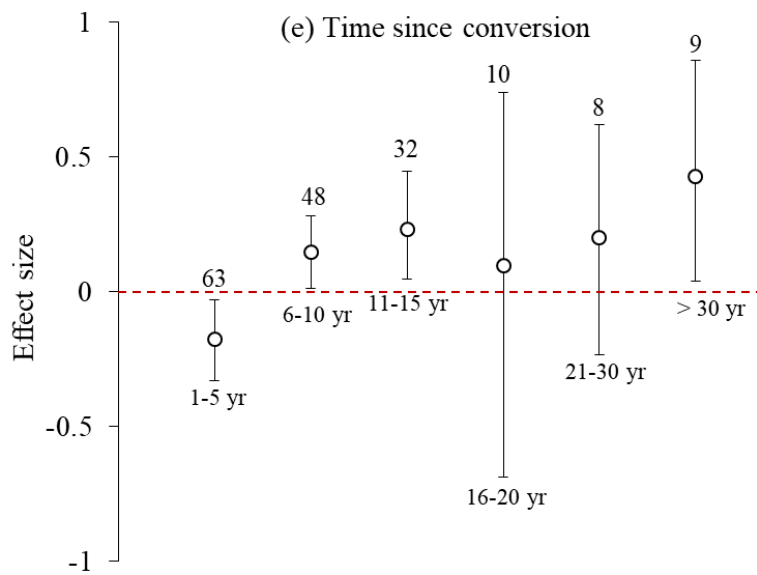




Figure 3

