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ARTICLE

Temporal changes in soil hydraulic conductivity in saturated and unsaturated fields

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Abstract
Soil hydraulic conductivity (K) is an important soil property that exhibits relatively large uncertainty. The temporal variability of K is often ignored when calculating water movement in soil. Various factors such as tillage, rain, temperature, wetting/drying, soil surface crusting, solution concentration, and biological activity can influence field K. We investigated soil K in a central Iowa field as a function of time and tillage by using tension infiltrometer measurements with pressure head tension settings of 0 cm and −3 cm. No clear relationship was found between bulk density (ρ_b) and K. Path analysis was conducted to assess the contribution ratios and causal relationships between factors affecting K. The K values were influenced by physical impacts such as tillage, precipitation, and surface crusting with contributions of 24%, −32%, and 49%, respectively, and with error of 60%. Soil surface crusting had a particularly large impact on saturated K. The maximum volume fraction influenced K. Earthworm activity that impacted the soil pore structure was also noticed in the field. Owing to this biological mechanism, no relationship was observed between ρ_b and K. It is important to recognize the multiple combined effects of soil physical processes and biological activities when documenting K in field soils.

Keywords Hydraulic conductivity · Temporal change · Tillage · Precipitation · Soil surface crust · Multiple combined effects

Introduction

Soil hydraulic conductivity (K) is an important property related to water and solute movement, and it has spatial (e.g., Nielsen et al. 1973; Mohanty et al. 1994; Strock et al. 2001) and temporal (e.g., Angulo-Jaramillo et al. 1997; Alletto and Coquet 2009; Soracco et al. 2018) variability. Temporal changes can result from various mechanisms (Mapa et al. 1986; Angulo-Jaramillo et al. 1997; Azevedo et al. 1998; Hu et al. 2009; Alletto and Coquet 2009; Soracco et al. 2015, 2018).

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Field K has been measured using various methods, such as infiltration methods, falling-head well tests, and pumping tests. Because measurements can be time consuming and laborious, K values are sometimes estimated using pedotransfer functions. Multidomain models have been used (Wilson et al. 1992; Durner and Flühler 1996; Gerke 2006; Stewart et al. 2016) to express soil structural differences. These models presume that soil hydraulic properties do not change with time.

Under actual field conditions, temporal changes can occur owing to tillage practices (Imeson and Kwaad 1990), soil surface sealing and crusting (Angulo-Jaramillo et al. 1997, 2000), irrigation (Mubarak et al. 2009), and biological activity (Imeson and Kwaad 1990; Willoughby et al. 1996). Tillage influences the physical and hydraulic properties of surface soil via impacts on surface residue, surface porosity, surface roughness, and soil structure (Freebairn et al. 1989). In general, tillage tends to loosen soil and increase K (Ciollaro and Lamaddalena 1998; Haruna et al. 2018). However, the opposite results are observed sometimes; tillage has been reported to decrease soil porosity (Bhattacharyya et al. 2006), disrupt the pore network (Logsdon et al. 1993; Reynolds et al. 1995; Azooz and Arshad 1996) owing to the absence of tillage, increase the connectivity of macropores (Schwen et al. 2011), and reduce K.

Because tillage effects on K are not consistent, complicated phenomena manifest over time. Following a tillage operation, soil compaction gradually increases as a result of subsequent rain events (Busscher et al. 2002; Hoorman et al. 2011). Sandin et al. (2017) reported that soil macroporosity and K were decreased by the first rainfall event following tillage. The impact of raindrops can also produce a soil surface crust (McIntyre 1958; Ndiaye et al. 2005) and influence surface soil hydraulic properties (Hillel and Gardner 1970; Freebairn et al. 1989; Romkens et al. 1990; Carmi and Berliner 2008).

Other mechanisms leading to temporal changes have been identified, such as changes in macropore content (Hu et al. 2009) and pore connectivity (Angulo-Jaramillo et al. 1997) and biological functions (Belnap et al. 2001; Belnap 2006; Faist et al. 2017). Temporal changes in soil structure related to these mechanisms may result in physical and biological impacts, i.e., complex phenomena that affect soil water infiltration in the field. However, previous research was not sufficiently comprehensive to address the complex phenomena in the field, and the length of the observation periods was too long to monitor gentle tillage effects. Thus, physical and biological impacts on temporal changes in K require further investigation.

We hypothesized that K would decrease after tillage as soil was compacted over time. Rainfall events increase bulk density (ρ_b) that in turn decreases K. The repetition of evaporative drying after wetting by a rainfall event may result in crust formation at the soil surface. This crust might be partially broken by biological activities, such as earthworms boring holes. This study aims to investigate temporal changes in saturated and unsaturated hydraulic conductivity after tillage through the continuous use of tension infiltrometers. Further, it determines the impacts of cumulative rainfall, tillage, and surface crusting.

Materials and methods

Site description

A bare field was selected at the Agricultural Engineering and Agronomy Research Farm near Ames, IA, USA (42°01′03.1″ N, 93°45′42.8″ W). The soil type was Nicollet loam (0.40 sand, 0.39 silt, and 0.21 clay on a mass fraction basis). The total plot measured ca. 40 m × 40 m; half of this field (TILL) was rotary-tilled to a depth of 20 cm on July 17, 2017, and the other half was not tilled and served as a control area (CTRL). After tillage, ponded (0 cm pressure head) and tension (− 3 cm pressure head) infiltration measurements (Ankeny et al. 1991) were made in the field after every major rainfall event (Table 1). Four locations in the TILL area and four locations in the CTRL area were randomly selected for the infiltration measurements, although wheel-trafficked areas were avoided. Two of four locations were selected for infiltration measurements on the natural soil surface to investigate the crust effect, and two other locations were selected for infiltration measurements after the removal of the soil surface crust layer. The 0–2.5-cm-thick surface crust layer was removed before performing infiltration measurements at the locations studied for the un-crusted condition. The entire soil surface area was kept bare throughout the study period by applying herbicides and performing hand weeding as needed.

Infiltration measurements

Tension infiltrometers described by Ankeny et al. (1988) were used to measure field infiltration. These infiltrometers had disk diameters of 22 cm. At each measurement location, steady-state infiltration rates were determined at pressure heads of 0 cm and − 3 cm. After a 0 cm pressure steady-state measurement, the infiltrating pressure head was decreased to − 3 cm without moving the infiltrometer until steady flow was achieved (Logsdon et al. 1993; Casey et al. 1998). By using the steady-state infiltration fluxes at the two pressure heads, K values at 0 cm (saturated) and − 3 cm (unsaturated) pressure heads were determined using the approach described by Ankeny et al. (1991).

Table 1 Rainfall interval periods and infiltration measurement dates

Rainfall interval periods	20–21 July	22–26 July	29 July–16 August	18–23 August	26 August–20 September	23 September–11 October	12–15 October
Incremental precipitation (cm)	0.7	0.4	4.6	3.8	2.3	13.7	2.3
Infiltration dates	21 July	27–28 July	17–18 August	24–25 August	21–22 September	12–13 October	16–18 October

Immediately after each infiltration measurement, the soil water content (θ) and ρ_b were measured using soil core samples having a diameter and height of 7.3 cm and 2.5 cm, respectively, that were taken from the soil under the infiltrometer base. Soil core samples were wrapped in aluminum foil and sealed in plastic bags to prevent water evaporation. Wet samples were weighed and then reweighed after oven drying at 105 °C for 24 h.

Theory

K is calculated from steady-state infiltration rates at two pressure heads (Ankeny et al. 1991):

$$Q_1 = \left(\pi r^2 + \frac{4r}{A}\right)K_1, \tag{1}$$

$$Q_2 = \left(\pi r^2 + \frac{4r}{A}\right)K_2, \tag{2}$$

$$A \approx \frac{\ln\left(\frac{Q_2}{Q_1}\right)}{\Psi_2 - \Psi_1}, \tag{3}$$

where Q_i is the steady-state flow rate of the infiltrating water (cm^3 s^{-1}, $i=1$, 2); r is the radius of the infiltrometer base (cm); ψ_i is the pressure head (cm, $i=1$, 2) at the soil-infiltrometer interface; and K_i is the hydraulic conductivity (cm s^{-1}, $i=1$, 2) at the targeted pressure head (ψ_i). A given number i corresponds to the same pressure head for infiltration measurement tests, and A is a constant.

Soil hydraulic properties

ρ_b was calculated for each soil core sample obtained after every infiltration test by using the mass of the oven-dried soil and the volume of the soil core sample.

The maximum volume fraction (θ_m; cm^3 cm^{-3}) responsible for water movement at the particular pressure head was calculated following Watson and Luxmoore (1986):

$$\theta_m = \frac{8\eta\Delta K\left(r_1, r_2\right)}{\rho g\left(r_1\right)^2}, \tag{4}$$

where $\Delta K\left(r_1, r_2\right)$ is the difference in K values in the pressure head interval corresponding to pore radii r_1 and r_2, η is the dynamic viscosity of water (g cm^{-1} s^{-1}), ρ is the density of water (g cm^{-3}), and g is the acceleration due to gravity (cm s^{-2}). Pore radii are calculated from capillary theory. The pore radius is assumed to equal the minimum pore radius according to Lozano et al. (2016).

Statistical analysis

Simple regression analysis was performed to probe for a correlation between cumulative precipitation and soil hydraulic parameters (K, ρ_b, and θ_m) and between ρ_b and other hydraulic parameters. Covariance analysis (ANCOVA) was performed to investigate the significant main effects of precipitation, treatment (eight patterns with combinations of tillage, crust, and tension), and their impacts on ρ_b or K. Precipitation was treated as a covariate, and treatments were treated as categorical variables. The generalized linear model procedure of SAS University Edition (© SAS Institute Inc.) was used. We also performed Tukey's multiple comparison tests for K because we detected significant primary and interaction effects.

Path analysis model is a type of structural equation modeling (SEM) that was established and developed by Wright (e.g., 1918, 1921, and 1934) to assess contribution ratios and causal relationships between factors. The path analysis method hypothesized the causal model between some variables and the model evaluation was assessed. This analysis method was used to build a multivariate statistical model that predicted K using measured factors in this study. We built 18 different models by considering rain, hydraulic head pressure, and the existence of crust and earthworm holes as independent variables; ρ_b as a dependent or an independent variable as appropriate; and K as a dependent variable. The crust and earthworm effects were expressed as dummy variables that took a value of 0 or 1 depending on whether or not they were present, respectively. The pass coefficient indicates the strength of the influence of one variable on another variable, and it is calculated as a standardized regression coefficient that predicts one variable from another. The Chi-square test (χ^2), Akaike's information criterion (AIC), root mean square error of approximation (RMSEA), standardized root mean square residual (SRMR), goodness-of-fit index (GFI), adjusted goodness-of-fit index (AGFI), and Bentler–Bonett normed fit index (NFI) were considered for evaluating the strength of the models. The coefficient of determination (R^2) of K was also calculated to select the model. The analyses were conducted using the R package for SEM developed by Fox et al. (2017).

Results

Precipitation effects on hydraulic conductivity

Figure 1a–d shows hydraulic conductivities as a function of the cumulative precipitation at pressure heads of 0 and −3 cm in the TILL and CTRL areas with (crusted) and without (un-crusted) surface crusts. K values were converted to

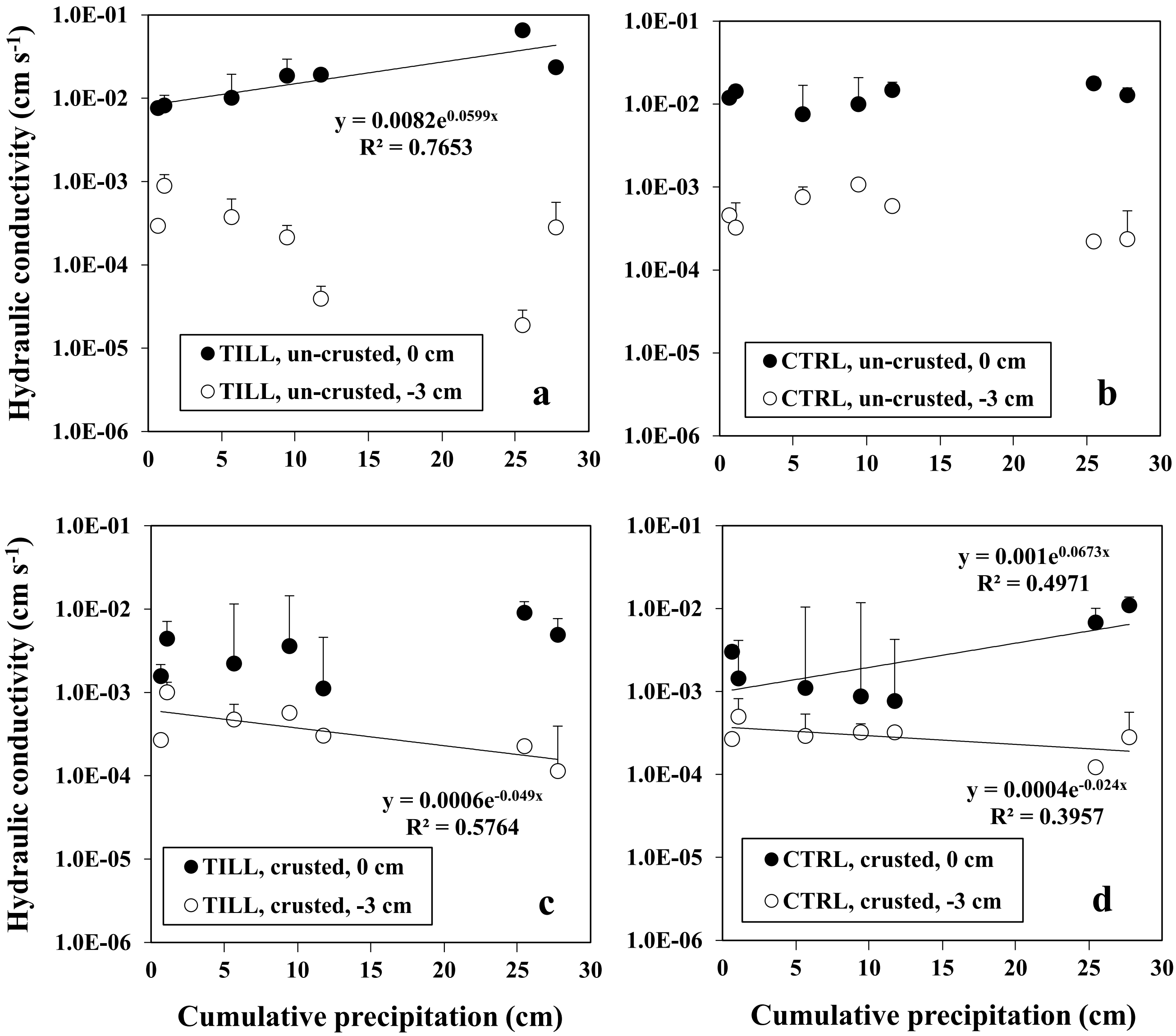

Fig. 1 Hydraulic conductivity with cumulative precipitation at pressure heads of 0 cm and −3 cm in **a** TILL, un-crusted, **b** CTRL, un-crusted, **c** TILL, crusted, **d** CTRL, crusted condition. *Each plotted point represents a mean measured value, and the error bars represent one standard deviation of uncertainty (only shown on the plus side)

the corresponding ones at 15 °C. Each plot of K is treated as an arithmetical mean in the figures.

From a simple regression analysis of K and the cumulative precipitation, a correlation was found in the following four conditions: TILL, un-crusted, 0 cm ($r=0.87$, $p=0.01$); TILL, crusted, −3 cm ($r=-0.76$, $p=0.04$); CTRL, crusted, 0 cm ($r=0.06$, $p=0.01$); and CTRL, crusted, −3 cm ($r=-0.63$, $p=0.10$). The variables r and p in the parentheses represent the Pearson correlation coefficient and p value of the regression analysis, respectively. Figure 1a–d shows the regression equations for the results.

ANCOVA showed that the interactions between precipitation and the eight conditions representing combinations of tillage, pressure head, and crust condition were significant. The significant primary effects of the treatments were also determined. Table 2 shows the results of Tukey's multiple comparison tests. The numbers in the table represent the significance levels of the tests. The difference in pressure head was significant without adjusting for tillage type and the existence of crust (e.g., at 0 cm vs. −3 cm under crusted condition in the CTRL area in Table 2). The crust effect on K at the 0 cm pressure head was significant in all combinations of both tillage types and between crusted and un-crusted conditions.

Table 2 The results of Tukey's multiple comparison test

			Dependent variable, hydraulic conductivities							
			TILL				CTRL			
			– 3 cm pressure		0 cm pressure		– 3 cm pressure		0 cm pressure	
			Un-crusted	Crusted	Un-crusted	Crusted	Un-crusted	Crusted	Un-crusted	Crusted
TILL	– 3 cm	Un-crusted		0.457	< .0001	< .0001	0.005	0.3484	< .0001	< .0001
		Crusted			< .0001	< .0001	0.9981	0.9793	< .0001	< .0001
	0 cm	Un-crusted				0.0003	< .0001	< .0001	0.999	< .0001
		Crusted					< .0001	< .0001	0.0024	0.9549
CTRL	– 3 cm	Un-crusted						0.728	< .0001	0.0003
		Crusted							< .0001	< .0001
	0 cm	Un-crusted								< .0001
		Crusted								

Effects of precipitation on bulk density and maximum volume fraction

A correlation between precipitation and ρ_b was not found from the simple regression analysis (Fig. 2a). ANCOVA showed that the interactions between precipitation and the treatments on ρ_b were not significant. Further, significant main effects of precipitation or the treatments were not found.

A correlation between precipitation and θ_m was found in the simple regression analysis under the following three conditions: TILL under un-crusted conditions ($r = 0.76$, $p = 0.04$), TILL under crusted conditions ($r = 0.72$, $p = 0.05$), and CTRL under crusted conditions ($r = 0.84$, $p = 0.01$) (Fig. 2b). ANCOVA showed that the interactions between precipitation and the effects of the treatments were significant. A significant main effect of precipitation was also found. The impact of the rain changed the soil structure and was related to the formation of macropores under these three conditions. θ_m was larger under un-crusted conditions than it was under crusted conditions throughout the duration of the test period. Crusts could be compacted, thereby stabilizing the soil structure. θ_m in the TILL area tended to be larger than that in the CTRL area. The TILL area experienced more soil structural changes than did the CTRL area. θ_m tended to increase over time, indicating that the macropore content could have increased with time.

Effects of bulk density on hydraulic conductivity and maximum volume fraction

A correlation between ρ_b and K was not observed (Fig. 3), and ANCOVA indicated that the interaction between ρ_b and the effect of treatments on K was not significant.

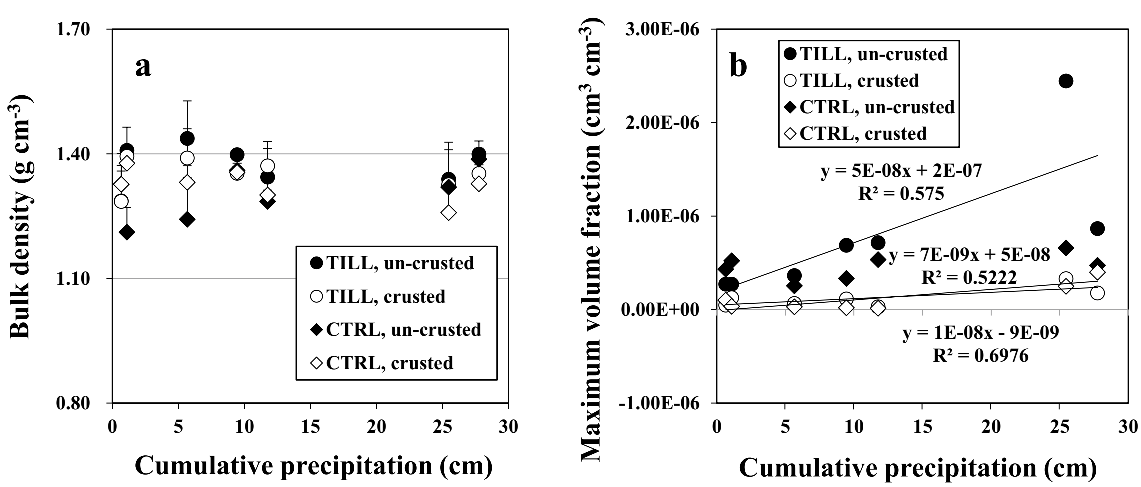

Fig. 2 **a** Bulk density and **b** maximum volume fraction with cumulative precipitation. *Each plotted point represents a mean measured value, and the error bars represent one standard deviation of uncertainty (only shown on the plus side)

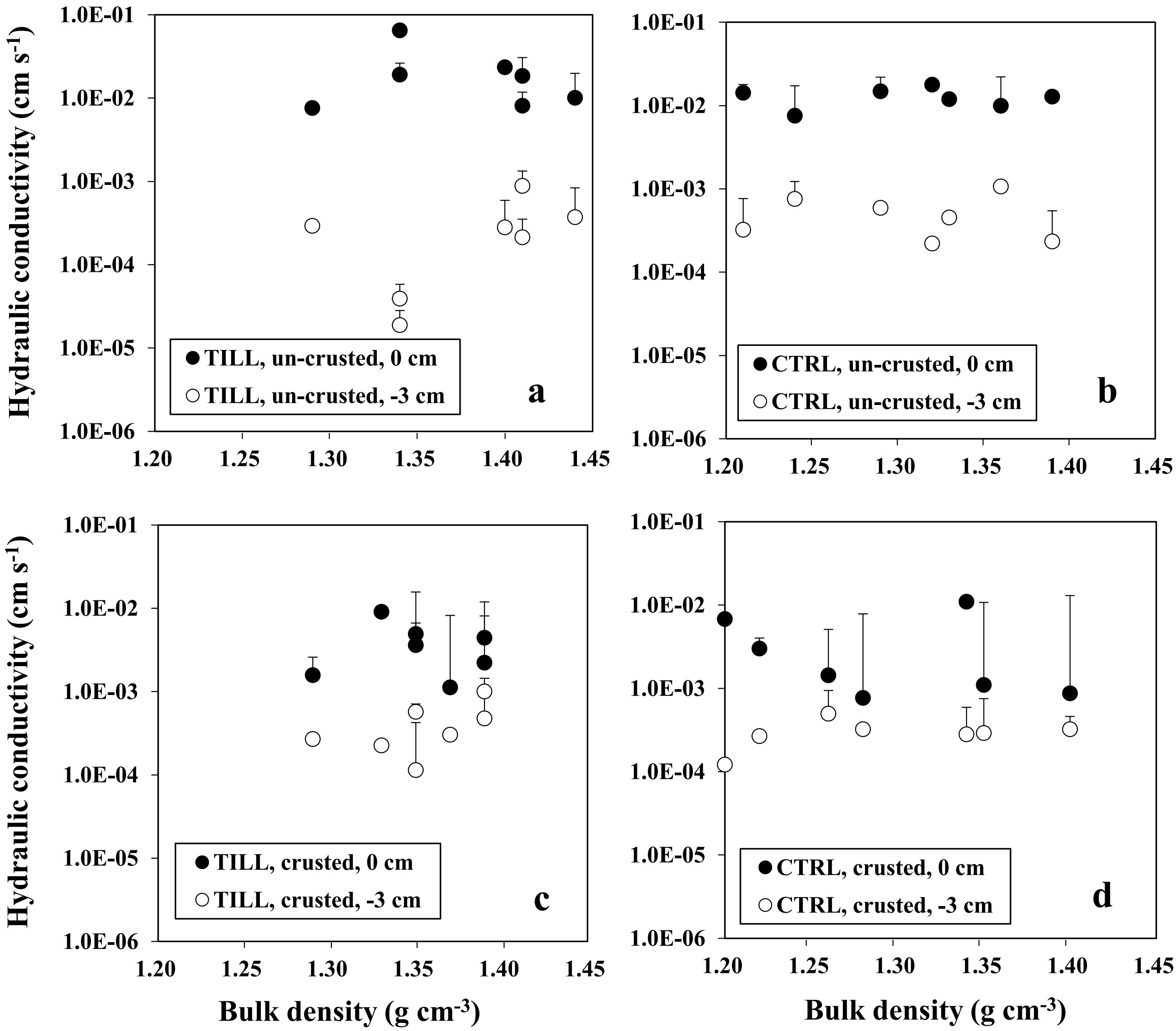

Fig. 3 Hydraulic conductivity with different bulk density at pressure heads of 0 cm and −3 cm in **a** TILL, un-crusted, **b** CTRL, un-crusted, **c** TILL, crusted, **d** CTRL, crusted condition. *Each plotted point represents a mean measured value, and the error bars represent one standard deviation of uncertainty (only shown on the plus side)

Significant direct effects of ρ_b or the treatments on K were not found. Our results were inconsistent with a general report indicating that a negative correlation was expected between ρ_b and K (Chen et al. 1998; Blanco-Canqui et al. 2004; Dec et al. 2008).

There was no apparent correlation between ρ_b and θ_m (Fig. 4). The covariance analysis indicated that the interaction between ρ_b and the effect of treatments on θ_m was not significant. A significant primary effect of ρ_b or the treatments on θ_m was not found.

Model validation and selected model

Figure 5 shows the path diagram for the most consistent model, and Fig. S1 shows the path diagrams for all 18 models considered. The model depicted in Fig. 5 was selected because of the R^2 value of the K estimation ($R^2 = 0.40$) and other indices of model compatibility (Model 9 in Fig. S1). χ^2, AIC, RMSEA, SRMR, GFI, AGFI, and NFI of this selected model are 0.07, 14, 0.00,

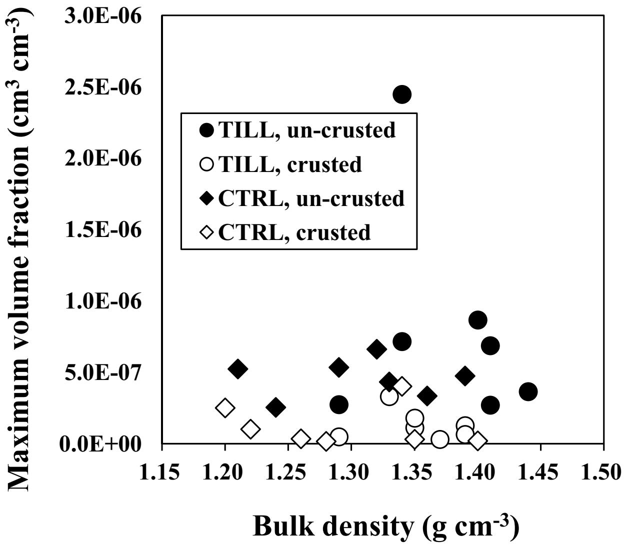

Fig. 4 Maximum volume fraction with cumulative precipitation with bulk density

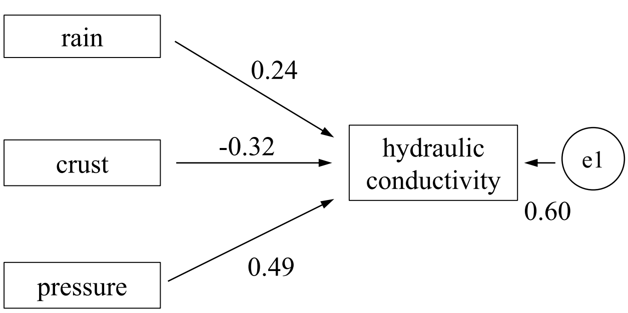

Fig. 5 Path diagram of proposed relationship between the soil hydraulic conductivity and measurable variations. The rain in the diagram represents accumulated precipitation

0.01, 1.00, 1.00, and 1.00, respectively. Table S1 shows the results of these indices for other models.

Although a multiple regression equation was the most suitable method for evaluating the models, the indirect effects were not reflected in this case. ρ_b and earthworm holes did not contribute to changes in K. The contribution ratios of cumulative precipitation, crust existence, and pressure head were 0.24, −0.32, and 0.49, respectively. The hydraulic pressure was the most heavily weighted explanatory variable that we treated as a constant, and precipitation and crust explained 24% and −32% of the changes in K, respectively. The results showed that crust existence negatively affected K. However, these three factors explained only 40% of the factors affecting K.

Discussion

Precipitation effects on hydraulic conductivity

The statistically significant interactions of different treatments (tillage, pressure head, and crust) with the effect of precipitation on K mean that there exists a complex mechanism for water movement in the soil (Fig. 1). A unified result was not found for individual conditions such as tillage type, crust condition, and pressure head from the simple regression analysis. Therefore, we must consider the influences of mixed effects on K, including tillage type and existence of crust.

The results of Tukey's multiple comparison tests on pressure differences and crust conditions showed the important influences of macropores and surface crust on water movement (Table 2). The effect of the pressure head on K was significant in both the TILL and CTRL areas, whether or not a crust existed; this showed that the effect of pressure head differences overcame the crust effect.

However, the crust effect could not be considered negligible. The crust effect on K under the 0 cm pressure head in both TILL and CTRL areas showed that the near-saturated water movement was restricted by soil surface crust (Fig. 1c, d). Various researchers have reported that rainfall, specifically the wetting rate, raindrop impact, and rainfall pattern impact the soil surface crust (Fan et al. 2008; Nciizah and Wakindiki 2014). Nciizah and Wakindiki (2015) also reviewed the stage of crust formation by rainfall and drying processes. Formed crusts generally reduced the saturated K (e.g., Angulo-Jaramillo et al. 2000; Hussein et al. 2010). The results of the present study were consistent with these previous results. We should treat the soil surface crust and the soil under the crust differently when considering water flow.

Effects of precipitation on bulk density and maximum volume fraction

The effect of precipitation on ρ_b was not statistically significant (Fig. 2a). Soil compaction combined with increasing ρ_b owing to rainfall was expected. However, ρ_b was not linearly related to precipitation, and ρ_b did not always increase with time. It may have happened as a result of offsetting loosening caused by other mechanisms such as soil biological effects.

Precipitation did affect θ_m, and ANCOVA suggested that the nature of this effect was dependent on the treatments (Fig. 2b). Tukey's multiple comparison tests showed that the differences depended on the existence of a crust (Table 2). The simple regression analysis showed a positive relationship between precipitation and θ_m, and the soil macropore content was also influenced by rainfall. The relationship between precipitation and θ_m was not found in the CTRL area in the absence of crusting ($y = 6.0E - 09x + 4.0E - 07$, $R^2 = 0.2184$ are not shown in Fig. 2b). This meant that the soil structure was stable in the CTRL area. Throughout the test period, θ_m was larger under un-crusted conditions than it was under crusted conditions, and Fig. 2b shows that the crust has a strong structure.

However, the trend observed in the presence of crusted conditions was slightly positive (Fig. 2b). This might be caused by data taken late in the study that therefore reflected earthworm activity. Earthworms and earthworm casts were observed at the soil surface from the end of September (Fig. 6a, b), and earthworms are known to produce macropores and influence soil K (McCoy et al. 1994; Shipitalo et al. 2000). θ_m in the TILL areas tended to be larger than that in the CTRL area, implying that the CTRL area had a more rigid soil structure than the TILL area.

Effect of bulk density on hydraulic conductivity

Earlier studies reported that smaller K values in untilled soil are caused by increased ρ_b or a lower proportion of macropores (Heard et al. 1988; Haruna et al. 2018); however, others reported no differences in K resulting from tillage (Roth et al. 1988; Sauer et al. 1990). Our results indicate that there is no clear difference in K resulting from tillage alone (Fig. 3).

The interaction between ρ_b and the effects of treatments (data not shown) and the primary effects of ρ_b or treatments on K was not significant (Fig. 3a–d). Starr (1990) reported that saturated K decreased after tillage and suggested that the mean soil pore diameter continuously decreased during the early part of a growing season, which could be attributed to increasing ρ_b owing to soil reconsolidation caused by rainstorm events. However, the effect of ρ_b on K was not significant in this study. Thus, ρ_b was not the only factor affecting K (e.g., Gantzer and Blake 1978; Lozano et al. 2014).

Large differences in K between the 0 cm and − 3 cm pressure heads were occasionally observed (Fig. 3), such as for $\rho_b = 1.34$ g cm^{-3} in Fig. 3a or for $\rho_b = 1.34$ g cm^{-3} in Fig. 3d. Those data were obtained on days when earthworm activity was observed. There was no interaction and significant primary effects of ρ_b or the treatments on K even if we eliminated the data obtained after the earthworm activity was observed. However, from simple regression analysis performed after eliminating earthworm effects, a correlation was found between ρ_b and K for the following areas: TILL, crusted, 0 cm ($r = 0.67$, $p = 0.08$); TILL, crusted, − 3 cm ($r = 0.81$, $p = 0.02$); and CTRL, crusted, 0 cm ($r = -0.92$, $p = 0.00$). The tendency of increase in ρ_b caused an increase in K in the TILL area under crusted conditions with the − 3 cm pressure head (Fig. 3c). This meant that there were numerous smaller pores supporting unsaturated water movement in the crust layer. The opposite phenomenon was found in the CTRL area under crusted conditions with the 0 cm pressure head (Fig. 3d). The near-saturated water movement was restricted by crust formation. The result in the TILL area under crusted conditions with the 0 cm pressure head could not be explained by these simple phenomena. Earthworms might alter the soil structure and produce macropores, resulting in the failure to observe a relationship between ρ_b and K.

The interactions between ρ_b and the treatments were not significant even after eliminating biological effects. However, the simple regression analysis revealed a correlation between ρ_b and θ_m in the CTRL area under crusted conditions (Fig. 4; $r = -0.81$, $p = 0.02$). This reflected the negative relationship between ρ_b and K (Fig. 3d).

The study results indicate that physical compaction is not the only factor impacting K. The increases in soil ρ_b and soil surface crusting over time that lead to decreases in K are offset by earthworm activity that creates large pores mitigating the effects of compaction on K.

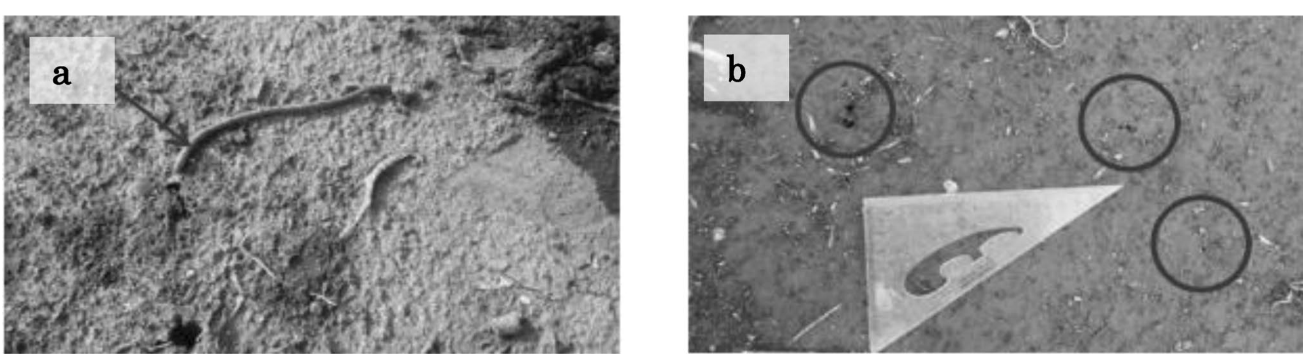

Fig. 6 Soil surface photographs at the field sites; **a** earthworm in TILL area on September 21, **b** earthworm holes at the CTRL area on October 12

Model validation and model selection

Multiple regression equations with precipitation, crust existence, and pressure head as independent variables but without ρ_b and earthworm effects were suitable for estimating K (Model 9 in Table S1). However, these three factors explained only 40% of the change in K, and 60% was deemed insufficient (Fig. 5). This meant that other factors such as interrelated effects between ρ_b and earthworm activity should have been considered to estimate K in the field. In the models, the earthworm activity did not account for K because the effect was set as a dummy variable. ρ_b was not interrelated with precipitation possibly because earthworm holes might compensate for the increased ρ_b caused by the impact of rain.

Although Model 14 showed a positive relationship between rainfall and ρ_b and a negative relationship between earthworm activity and ρ_b, the fitness indices for this model were poor (Fig. S1). Originally, Model 14 was constructed to study the relationship between rainfall and ρ_b and the relationship between earthworm activity and ρ_b. However, the quantitative evaluation of earthworm activity was labor intensive; therefore, it was necessary to find parameters such as K over time that could be measured on-site more easily. Further research is required to determine which factors are easily observable for estimating K.

Conclusions

K was expected to decrease gradually after tillage because of soil compaction combined with increasing ρ_b resulting from rainfall. It was not influenced significantly over time by changing ρ_b. However, it was influenced by the interaction of precipitation and other factors, such as infiltration pressure head, crust condition, and tillage. Saturated K clearly differed from unsaturated K. The effect of surface crusting due to precipitation was evident in determinations of saturated K. Our observations indicated that earthworms made macropores in this field, and the mixed effects of soil crusting and macropores had complex effects on water flow. This conclusion was supported by the results from a path analysis. It was important to consider multifunctional effects of soil physical processes and biological activities (such as those of earthworms) when measuring field K over time.

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