Soil Strength and Water Infiltration Under Reduced and Conventional Tillage in a Typic Haplustepts of Lamongan District

Kekuatan Tanah dan Infiltrasi Air akibat Olah Tanah Terbatas dan Konvensional pada Typic Haplustepts di Kabupaten Lamongan

Achmad Rachman*

Peneliti Badan Litbang Pertanian di Balai Penelitian Tanah, Jl. Tentara pelajar No. 12 Cimanggu Bogor 16114

INFORMASIARTIKEL

Riwayat artikel:
Diterima: 22 Juni 2016
Direview: 01 Juli 2016
Disetujui: 09 Agustus 2016

Keywords:
Soil strength
Water infiltration
Conventional tillage
Reduced tillage

Kata kunci:
Kekuatan tanah
Infiltrasi
Olah tanah konvensional
Olah tanah terbatas

Abstract. The ability of upland non-irrigated soil to absorb and store water is critical to provide sufficient moisture for crop grown in dry season. The objective of this study was to evaluate the effects of tillage, reduced (RT) and conventional tillage (CT), on infiltration rate and soil penetration resistance (soil strength) in soil with ustic moisture regime planted with corn. The experiment was conducted on a site, which had been continuously planted with corn twice a year. The predominant soil was Typic Haplusteps. Six positions, 15 meters a part, were chosen within each treatment to measure infiltration rate and soil strength. The mean infiltration rate values were higher under CT (91.87 ± 18.99 mm h^{-1}) than under RT (64.36 ± 30.97 mm h^{-1}). The amount of water infiltrated in CT is 1.4 times higher than in RT. The RT induced the formation of near surface compacted layer with a soil strength of 850 kPa, 2 times higher than under CT at the same depth. The compacted layer is expected to be responsible for lowering infiltration rate under RT. The highest correlation (R^2 = 0.83) between qs and Ksat under RT was found at the second depth (8 to 12-cm) and third depth (16 to 20-cm) for CT (R^2 = 0.73) indicating that soil layer with the highest soil strength was responsible to control water infiltration. The infiltration models tested (Parlange, the Green and Ampt, and Kostiakov) fit well with the measured data (r^2 = 0.99–1.00). It is recommended to conduct deep tillage (20 – 25 cm) once a year to maintain favorable soil structure for water infiltration and root growth.

Abstrak*: Kemampuan lahan tadah hujan untuk menyerap dan menyimpan air sangat penting dalam kaitannya dengan penyediaan kelembaban tanah yang optimum untuk pertumbuhan tanaman pada musim kemarau. Tujuan dari penelitian ini adalah untuk mengevaluasi pengaruh pengolahan tanah terbatas (RT) dan konvensional (CT) terhadap laju infiltrasi dan ketahanan penetrasi (kekuatan) tanah pada tanah dengan regim kelembaban ustic yang ditanami jagung. Penelitian dilaksanakan pada tanah Typic Haplusteps yang ditanami jagung 2 kali dalam setahun. Pengukuran infiltrasi dan kekuatan tanah dilakukan di enam titik, masing-masing berjarak 15 meter, pada tiap perlakuan. Rata-rata laju infiltrasi pada perlakuan CT adalah 91.87 ± 18.99 mm jam^{-1} lebih tinggi dibanding pada RT yaitu 64.36 ± 30.97 mm jam^{-1}. Volume air yang terinfiltrasi pada perlakuan CT adalah 1,4 kali lebih banyak dibanding pada perlakuan RT. Perlakuan RT menyebabkan terbentuknya lapisan padat dibawah permukaan tanah dengan kekuatan tanah sebesar 850 kPa, 2 kali lebih besar dibanding perlakuan CT pada kedalaman yang sama. Lapisan padat pada perlakuan RT diduga sebagai penyebab rendahnya laju infiltrasi pada perlakuan tersebut. Korelasi tertinggi (R^2 = 0.83) antara qs dan Ksat diperoleh pada kedalaman kedua (8-12 cm) untuk perlakuan RT dan pada kedalaman ketiga (16-20 cm) untuk perlakuan CT (R^2 = 0.73) menunjukkan bahwa lapisan tanah yang paling padat mengontrol laju infiltrasi. Ketiga model penduga infiltrasi yang diuji (Parlange, Green and Ampt dan Kostiakov) berkesesuaian sangat baik dengan infiltrasi hasil pengukuran (r^2 = 0.99–1.00). Berdasarkan hasil penelitian ini, direkomendasikan untuk melakukan olah tanah dalam (20 – 25 cm) sekali dalam setahun untuk menjaga agar tanah tetap gembur sehingga memperbaiki laju infiltrasi dan pertumbuhan akar.*

Introduction

Water infiltration is a process of water from rainfall or irrigation entering the soil surface (Scott, 2000). It is one of the critical processes in the hydrological cycle since infiltration determines the amount of surface runoff and subsurface recharge. In natural condition, rainfall intensity, antecedent soil water content, and soil physical properties control the infiltration rate. Hillel (1998) indicates that soil factors that affect the infiltration rates include time from the onset of rain or irrigation, initial water content, soil hydraulic conductivity, soil surface condition, and profile depth and layering. Previous studies indicated that soil management had more pronounced affect on infiltration than soil type (Sharma *et al.* 1980; Tricker, 1981; Azooz and Arshad, 1996). Soil management modifies many of the factors that control the

*Corresponding Author: arbb1@yahoo.com

infiltrability of a given soil including soil structural stability (Tisdall and Adem, 1986), bulk density (Patel and Singh, 1981), and pore structure (Ankeny *et al.* 1990; Rachman *et al.* 2004).

Tillage practice is a mechanical manipulation of soil, which could greatly alter soil density, infiltration characteristics and other physical properties to affect water runoff and soil erosion (Cassel, 1982; Kemper *et al.* 2012). However, previous studies reported contradictory results on the effects of tillage on water infiltration and other physical properties. Some studies indicate that tillage practices create more large flow-active pores and a greater continuity and connectivity of macro-pores than reduced or no-till, therefore, enhance water infiltration (Lipiec *et al.* 2006; Matula, 2003; Schwartz *et al.* 2010). Matula (2003) reported a significant reduction in water infiltration rate and saturated hydraulic conductivity due to reduced tillage (3 times) and no-till (6 times) treatments as compared to a conventional tillage treatment. The decrease in water infiltration and saturated hydraulic conductivity may increase surface runoff and erosion and decrease water storage.

Other studies reported a greater water infiltration rate under no-till management than conventional tillage (Fan *et al.* 2013; Kahlon *et al.* 2013; Roper *et al.* 2013;). Fan *et al.* (2013) found that infiltration rates under no-till treatment on a black soil (Mollisols) that has been under no-tillage (NT) for 6 years was 1.6 – 2.1 times as high as those under moldboard plough (MP). The establishment of more biological macro-pores found under NT than MP is believed to be the cause of higher infiltration rate under NT than those under MP. These macro-pores promote water infiltration through preferential pathways in NT soil. Differences in infiltration rate between these two contradictory findings were probably governed by differences in location, soil type, soil density, and residue management.

Information of infiltration pattern under long-term continuous corn with different tillage managements is essential for understanding water availability of the upland corn system. Little is known regarding the effect of tillage practices on water infiltration and soil compaction of upland tropical soils. The objective of this study was to evaluate the effects of tillage management on soil strength and infiltration in soil with *ustic* moisture regime planted continuously with corn.

Materials and Methods

Site Description

This study was conducted at the Solokuro Agro-techno Park (112^o 25’ 13.7” E, 6^o 55’ 25.9” S) in Banyubang village, Solokuro sub-District, Lamongan District, East Java Province. The study site is located within the humid tropics. The mean annual temperature is 30^{o}C, and that the mean annual precipitation is 1342 mm, occuring mostly from November to May, while the rest of the year is mostly dry. The soil is Typic Haplustepts with slope ranging from 3 to 8 %, bench terraces has been applied for years. Selected soil chemical properties of the soil surface are summarized in Table 1. The Solokuro sub-District and four other neighboring sub-districts are the major corn producers in the country with around 20,000 ha of land devoted for growing corn twice a year since early 1990s. The majority of farmer in the village plows the soil before planting the first corn in late November or early December, while the second corn is planted in late February about 2 weeks before the first corn is harvested to reduce the risk of drought. However, some farmers adopted minimum tillage for the first corn since 2010. After the second corn is harvested in early June, the field is basically left bare because of very dry conditions. Corn yields in this area is reported to be 6 – 7 ton ha^{-1} during the rainy season (first corn). The yield for the second corn is as high as 8 ton ha^{-1} when the soil moisture is sufficient or <5 ton ha^{-1} when the soil is dry.

Table 1. Selected soil chemical and physical properties of the study site, Lamongan in 2015

Tabel 1. Beberapa sifat kimia dan fisika tanah lokasi penelitian, Lamongan 2015.

Soil parameter	Value
pHw	5.4 (0.8)[§]
CEC (cml$_c$ kg^{-1})	13.79 (4.42)
Sand (%)	5.7 (1.4)
Silt (%)	14.2 (2.9)
Clay (%)	80.1 (3.4)
Organik matter (%)	1.06 (0.19)
Bulk density (Mg m^{-3})	1.08 (0.09)

[§] Numbers in parentheses are the standard deviation of the mean of six observations.

The study was conducted on November 25-27, 2015 on soil which has been planted continuously with corn for more than 10 years. During the study, the field was in preparation for planting for the first corn. Two farmer fields adjacent to each other that have been practicing reduced tillage (RT) for the last three years and continuous conventional tillage (CT) since 1998 were selected for soil strength and infiltration measurements. Both farmers apply 1.000 kg/ha of cow manure and chemical fertilizers as base fertilizer. The cow manure was applied on the soil surface around the planted seed. The RT treatment included minimum disturbance of the soil surfaces to place the corn seed using a wooden stick. No crop residues left on the soil surface for the first corn, while cornstalks, approximately 3 ton ha^{-1}, of the first harvested corn were left on the field for the second corn. The CT treatment included moldboard plow 2- 4 weeks before the first corn was planted, the depth of plow is 15-20 cm, no crop residues on the soil surface during plowing and no plowing for the second corn.

Infiltration Measurements and Analysis

Water infiltration was measured using single-ring infiltrometers (Bouwer, 1986) with a 30-cm inside diameter, a 18.5-cm length, and a 0.3-cm wall thickness for the two treatments with six replicates. The steel ring was driven carefully 15 cm into the soil; care was taken to make sure that the ring was inserted vertically into the soil. A positive head of 50 mm was maintained inside the ring using a Mariotte system during the infiltration test. Infiltration tests were conducted for 120 min. Water used to make infiltration measurements were collected from the city water.

The steady-state infiltration rate (*qs*) was calculated and used as the final infiltration rate. Three infiltration models were used to evaluate the fitness of measured infiltration data with the infiltration models for the three positions. The models were the Green and Ampt (1911), the Parlange *et al.* (1982), and the Kostiakov (1932). The Parlange *et al.* (1982) model was referred to as the Parlange model or equation throughout this paper. Clausnitzer *et al.* (1998) reported that the Green and Ampt gave the best parameter confidence interval for a two-parameter model, and that the Parlange equation fits infiltration data well for a two-parameter model. The Green and Ampt equation was modified by Philip (1957) for time (*t*) vs. cumulative infiltration (*I*), as follows:

$$t = \frac{I}{K_S} - \frac{[S^2 \ln(1 + 2IK_S / S^2)]}{2K_S^2} \quad [1]$$

The physically-based Parlange equation for *t* vs. *I* is as follows:

$$t = \frac{I}{K_S} - \frac{S^2[1 - \exp(-2IK_S / S^2)]}{2K_S^2} \quad [2]$$

The empirical Kostiakov (1932) infiltration model of infiltration rate (*i*) vs. *t* is as follows:

$$i = Bt^{-m} \quad [3]$$

where *t* (T) is time, *I* (L) is the cumulative infiltration, *S* (LT$^{-0.5}$) is the sorptivity, *Ks* (LT^{-1}) is the saturated hydraulic conductivity*, and B* and *m* are characterizing constants. The procedure for estimating the *S* and *Ks* for the two-parameter physically based Green and Ampt and Parlange equations used the method proposed by Clothier *et al.* (2002). The *B* and *m* parameters for the empirical Kostiakov equation were estimated by fitting the cumulative infiltration version of Eq. [3] to measured *I* vs. *t* data using a non-linear fitting procedure.

Soil Penetration Resistance Measurements

Soil penetration resistance (soil strength) was measured inside the ring infiltrometer two hours after the infiltration rate measurements were completed and before the ring was removed. A digital penetrologger type No. ML3 (Eijkelkamp Agrisearch Equipment, 6987 EM Giesbeek) was used in the field. The penetrologger records electronically the value of soil penetration resistance at intervals of 1 cm up to 45 cm soil depth.

Saturated Hydraulic Conductivity and Bulk Density Measurements

When saturated infiltration rate measurements were completed, the water supply tube and the water flow control tube from the water reservoir were removed from the ring infiltrometer. Without removing the ring infiltrometer, intact soil samples were collected from undisturbed areas immediately outside the ring infiltrometer using a core sampler (76-mm inside diam and 40-mm length). Soil cores were taken from 3 depths 0 to 4-cm, 8 to 12-cm, and 16 to 20-cm. Three soil cores from each depth were collected for saturated hydraulic conductivity and bulk density measurements. The constant head method was used to measure saturated hydraulic conductivity (Klute and Dirksen, 1986). Attempt was made to eliminate preferential flow along the interface between soil and core sampler wall using silicon gel.

Result and Discussion

Ponded Infiltration Measurements

Typical steady-state infiltration rates (*qs*) under conventional and reduced tillage systems are shown in Figure 1. The highest infiltration rates occurred during the transient stage at 167 mm h^{-1} under CT and 91 mm h^{-1} under RT then declined gradually to reach the steady stage at 60 min for CT and 30 min for RT. The mean steady state infiltration rate values were found to be higher under CT (91.87 ± 18.99 mm h^{-1}) than under RT (64.36 ± 30.97 mm h^{-1}). The amount of water infiltrated in CT is 1.4 times higher than in RT during the 2 hours of measurement indicating that soil under conventional tillage store more water that those under reduced tillage management. Excavation of soil after completing infiltration measurements revealed that horizontal water movement under RT more dominant than the one under CT at zone of 5- to 10-cm soil depth.

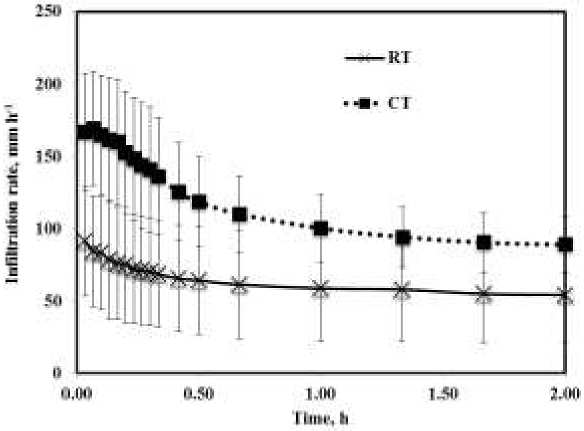

Figure 1. Geometric Mean of infiltration rates under reduced (RT) and conventional (CT) tillage in a Typic Haplustepts, Lamongan. Bars indicate standard deviation (n = 6).

Gambar 1. Rata-rata geometrik laju infiltrasi pada olah tanah terbatas (RT) dan konvensional (CT) pada Typic Haplusteps, Lamongan. Bar menunjukkan standar deviasi (n = 6).

The immediate increase of soil compactness under RT as indicated by soil strength measurements (Figure 3) was speculated to be responsible for the relatively lower water infiltration than under CT. Previous studies indicate that tillage practices create more large flow-active pores than reduced or no-till, therefore, enhance water infiltration (Lipiec *et al.* 2006; Matula, 2003). Matula (2003) reported a significant reduction in water infiltration rate and saturated hydraulic conductivity due to reduced tillage (3 times) and no-till (6 times) treatments as compared to conventional tillage treatment. Soils with a compacted layer near the surface may produce low crop yields because they frequently have excess water early and are droughty later in the cropping season. The decrease in water infiltration and saturated hydraulic conductivity under RT may also increase surface runoff.

Three infiltration models fitted to measured infiltration data as a function of time for typical conventional tillage (CT) and reduced tillage (RT) replicate are shown in Figure 4. All models (Parlange,Green and Ampt, and Kostiakov) fit well the measured infiltration data with treatment average coefficients of determination (r^2) near 1.0 (range from 0.99 to 1.00). These data indicate that all three infiltration equations fit the data well for the CT and RT treatments. Therefore, the three models can be used to estimate cumulative infiltration on a similar soil with *ustic* moisture regime given that all parameters are available to run the models.

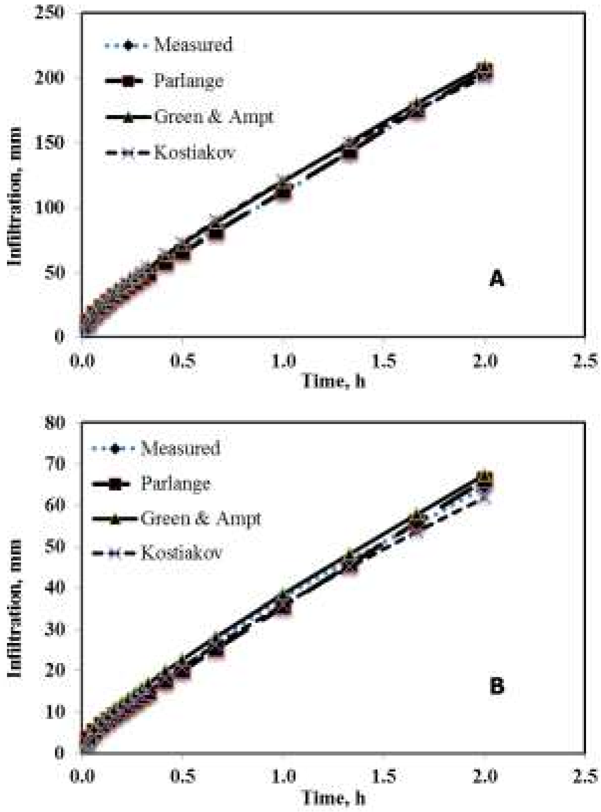

Figure 2. The models of Parlange, Green and Ampt, and Kostiakov fitted to measure ponded infiltration data for typical replicates under (A) conventional tillage and (B) reduced tillage.

Gambar 2. Model Parlange, Green and Ampt, dan Kostiakov yang dibangun dari data hasil pengukuran infiltrasi terseleksi pada olah tanah konvensional (A) dan terbatas (B).

Soil Penetration Resistance

Soil penetration resistance (soil strength) was measured up to 43 cm soil depth with depth increments of 1 cm for the CT and RT at 25 day after tillage and the results are presented in Figure 3. The soil water content throughout the profile was at *in situ* field capacity when the measurements were taken. Each value is a mean of 3 measurements. Presence of compacted zone at 8 to 10-cm soil depth is obvious for RT with soil strength of 850 kPa, increased from 120 kPa at the 2-cm soil depth. In contrast, the soil strength under CT increased gradually with depth from 70 kPa at the surface 2-cm to 600 kPa at 15-cm soil depth. The soil strength for both treatments reached the same level (1000 kPa) at 20- to 25-cm soil depth. The near surface compacted layer in the RT may have significant affect on restricting water entry into the soil profile. Previous studies indicated that tillage reduces soil bulk density and soil strength to enhance water infiltration (Ketcheson, 1980, Cassel, 1982; Agus and Cassel, 1992; Lipiec *et al.* 2006).

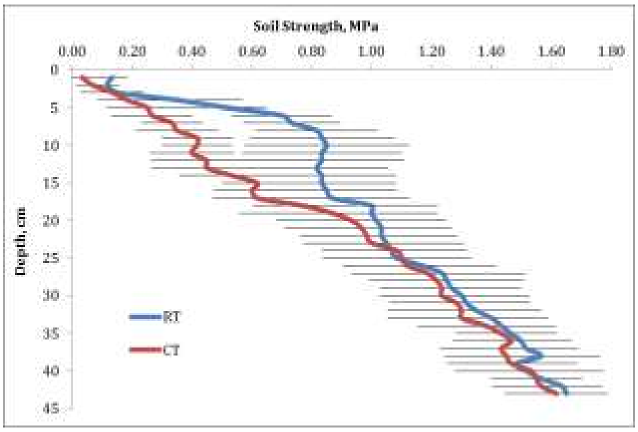

Figure 3. Soil resistance to penetration (soil strength) under reduced tillage (RT) and conventional tillage (CT) in a Typic Haplustepts, Lamongan. Horizontal bars indicate the standard deviation (n = 6)

Gambar 3. Ketahanan tanah terhadap penetrasi (kekuatan tanah) pada olah tanah terbatas (RT) dan konvensional (CT) pada Typic Haplustetps, Lamongan. Bar menunjukkan standar deviasi (n=6)

Bulk Density and Saturated Hydraulic Conductivity

The effect of tillage on bulk density (BD) and saturated hydraulic conductivity (K_{sat}) are presented in Figures 4A and 4B. The mean BD, averaged across depth, were 1.09 ± 0.007 Mg m^{-3} for CT and 1.11 ± 0.07 Mg m^{-3} for RT. Simple t-test indicated that the bulk density between CT and RT were not significantly different, however, there is a tendency that bulk density under CT was lower than under RT at the surface 0 to 4-cm depth (Figure 4A). The relatively higher BD under RT than under CT agreed with soil strength measurements (Figure 3). However, it appears that the use of soil strength data measured with penetrologger is more sensitive to identify soil compaction than using soil bulk density data. The use of small hand tractor to till the field once a year as is mostly practiced by farmers in this area, does not show any formation of a dense layer below the soil surface.

The mean K_{sat}, averaged across depth, was 48.23 ± 22.57 mm h^{-1} for CT and 51.01 ± 26.00 mm h^{-1} for RT Simple t-test indicated that there is no significant different for K_{sat} for the two treatments. The highest K_{sat} (69.63 mm h^{-1}) was found under CT at the soil surface then decreased substantially to 37.88 mm h^{-1} at the second depth (Figure 4B). The significant reduction of K_{sat} in CT at the second depth probably was due in part to vertical soil consolidation enhanced by detachment of soil surface by raindrop impact or other physical disturbances, which clogged the pores as evidenced by increased bulk density (Beven and Germann, 1982; Rachman *et al.* 2004).

Correlation between *qs* and K_{sat}

Tabel 2 shows the linier correlation between steady-state infiltration rate (*qs*) and laboratory measured saturated hydraulic conductivity (K_{sat}) for CT and RT at 3 different depths. The highest correlation (R^2 = 0.83) between *qs* and *K*sat under RT was found at the second depth (8 to 12-cm), while the highest correlation (R^2 = 0.73) for soil under CT was found at the third depth (16 to 20-cm). We used soil strength data rather than bulk density data to explain these findings since soil strength were measured at 1-cm depth interval, while bulk density represents an average of 4-cm soil thickness. Compacted soil layer under RT occurred within 8 to 10-cm soil depth

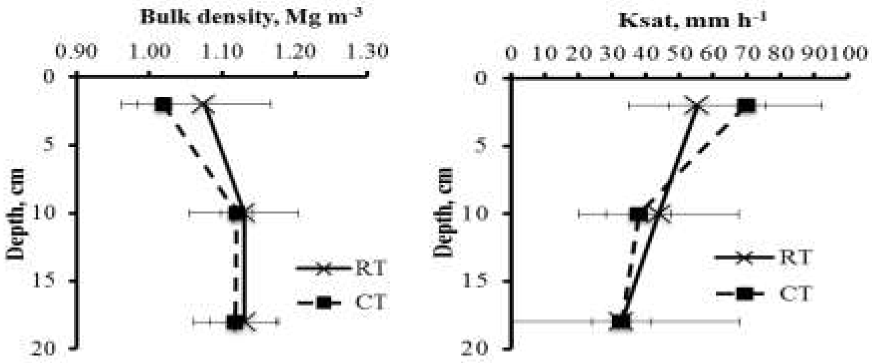

Figure 4. Geometric means of soil bulk density and saturated hydraulic conductivity under reduced (RT) and conventional (CT) tillage in a Typic Haplustepts, Lamongan. Bars indicate the standard deviation (n = 6).

Gambar 4. Rata-rata geometrik berat isi tanah dan konduktivtas hidraulik tanah jenuh pada olah tanah terbatas (RT) dan konvensional (CT) pada tanah Typic Haplustepts, Lamongan. Bar menunjukkan standar deviasi (n =6).

Table 2. Linear correlation between steady-state infiltration rate (*qs*) and laboratory measured hydraulic conductivity (*K*sat) under reduced (RT) and conventional (CT) tillage at 3 soil depths.

Tabel 2. Korelasi linier antara laju infiltrasi (qs) dan konduktivitas hidraulik tanah jenuh yang diukur di laboratorium (Ksat) pada perlakuan olah tanah terbatas (RT) dan konvensional (CT) pada 3 kedalaman tanah.

Soil Depth (cm)	Treatment	Parameter		
		Slope	Intercept	R^2
0 – 10	Reduced Tillage	0.67	22.12	0.36
	Conventional Tillage	0.30	70.83	0.15
10 - 20	Reduced Tillage	1.15	9.83	0.83
	Conventional Tillage	0.53	67.95	0.42
20 - 30	Reduced Tillage	0.41	41.00	0.43
	Conventional Tillage	1.23	54.58	0.73

with soil strength of 850 kPa, while soil strength under CT at the same depth was only 420 kPa or two times lower (Figure 3). A dense layer occurred at 10 cm soil depth under RT controls the vertical movement of infiltrated water to lower the infiltration rate. Therefore, high correlation between *qs* and *K*sat was found at the second depth (8 to 12-cm) under RT and third depth (16 to 20-cm) under CT with the same explanation. The correlations proved that soil layer with the highest density controls the downward movement of infiltrated water into the soil profile. Similar results were reported by Beven and Germann (1982) andRachman *et al.* (2004)who found that the formation of a dense layer reduces the availability of macropores, which is an important pathway in the process of infiltration of rainwater into the soil.

It was also found that the slopes of the regression were close to 1, 1.23 for CT and 1.15 for RT, indicating that *qs* can be estimated using *K*sat data obtained from a laboratory measurement. The undisturbed soil samples used for *K*sat measurements should be treated, in this study with silicon gel, to plug the rapid pipe flow through wormholes, old root channels, and preferential flow along the interface between soil and core sampler wall that extend all the way through cores (Reynolds *et al.* 2000; Blanco-Canqui *et al.* 2002). Previous studies reported a 4 to 4.7 times lower *K*sat values were obtained when short circuit flow through macropores were eliminated as compared to non treated cores (Blanco-Canqui *et al.* 2002; Rachman *et al.* 2004).

These results show that applying reduced tillage for 3 years in the row without crop residues left on the soil surface on this soil has triggered soil consolidation below the surface and conducting deep tillage once a year is sufficient to create favorable soil structure for water infiltration and root growth.

Conclusions

The mean steady state infiltration rate values were found to be higher under CT (91.87 ± 18.99 mm h^{-1}) than under RT (64.36 ± 30.97 mm h^{-1}). The amount of water infiltrated in CT is 1.4 times higher than in RT. An increased in soil strength up to 850 kPa below the soil surface is evidence under the reduced tillage treatment, which is expected to be responsible for lowering infiltration rate under RT. Higher correlation (R^2 = 0.83) between *qs* and *K*sat under RT at the second depth (8 to 12-cm) and third depth (16 to 20-cm) for CT (R^2 = 0.73) as compared to the other 2 depths indicating that soil layer with the highest density controls the downward movement of infiltrated water into the soil profile. The reduction in water infiltration under RT limit water storage to produce low crop yields due to frequent excess water early and are droughty later in the cropping season. Applying reduced tillage for 3 years in the row on this soil has triggered soil consolidation below the surface. It is recommended to conduct deep tillage once a year to create favorable soil structure for water infiltration and root growth.

References

Agus, F., D. K. Cassel. 1992. Field-scale bromide transport as affected by tillage. Soil Sci. Soc. Am. J. 56:254-260.

Ankeny, M. D., T.C. Kaspar, and R. Horton. 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J. 54:837-840.

Azooz, R.H., and M.A. Arshad. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can. J. Soil Sci. 76:143-152.

Beven, K. J., and P. F. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18(5):1311-1325.

Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and F. Ghidey. 2002. Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Sci. Soc. Am. J. 66:1596-1602.

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

Cassel, D. K. 1982. Tillage effect on soil bulk density and mechanical impedence. P. 45-67. In P.W. Unger *et al.* (ed.) Predicting tillage effects on soil physical properties and processes. ASA Spec. Publ. No. 44. ASA and SSSA Madison, WI.

Clausnitzer, V., J.W. Hopmants, and J.L. Starr. 1998. Parameter uncertainty analysis of common infiltration models. Soil Sci. Soc. Am. J. 62:1477-1487.

Clothier, B., D. Scotter, and J. P. Vandervaere. 2002. Unsaturated water transmission parameters obtained from infiltration. p. 879– 898. In J.H. Dane and G.C. Topp (ed.). Methods of soil analysis. Part 4. SSSA, Madison, WI.

Fan, R., X. Zhang, X. Yang, A. Liang, S. Jia, and X. Chen. 2013. Effects of tillage on infiltration and preferential flow in a black soil, Northeast China. Chinese Geogra. Sci. 23 (3): 312-320.

Green, W.H., and G.A. Ampt. 1911. Studies on soil physics:1. Flow of air and water through soils. J. Agric. Sci. 4:1-24.

Hillel, D.1998. Environmental soil physics. Academic Press, San Diego, CA.

Kahlon, M. S., R. Lal, and M. Ann-Varughese. 2013. Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil and Tillage Research. 126: 151-158.

Kemper, W. D., C. E. Bongert, and D. M. Marohn. 2012. Corn response to tillage and water table depth. J. Soil and Water Conserv. 67(2):31A-36A.

Ketcheson, J. W. 1980. Effect of tillage on fertilizer requirements for corn on a silt loam soil. Agron. J. 72:540-542

Kostiakov, A. N. 1932. On the dynamics of the coefficient of water percolating in soils and the necessity of studying it from a dynamic view for the purpose of amelioration. Trans. 6th Congr. Int. Soc. Soil Sci., Russian part A:17-21.

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

Lipiec, J., J. Kus, A. Slowinska-Jurkiewicz, and A. Nosalewicz. 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil and Tillage Research 89 (2): 210-220.

Matula, S. 2003. The influence of tillage treatments on water infiltration into soil profile. Plant Soil Envion. 49 (7): 298-306

Patel, M. S. and N. T. Singh. 1981. Changes in bulk density and water intake rate of a coarse textured soil in relation to different levels of campaction. J. Indian Soc. Soil Sci. 29:110-112.

Parlange, J.Y., I. Lisle, R.D. Braddock, and R.E. Smith. 1982. The three-parameter infiltration equation. Soil Sci. 133:337-341.

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

Rachman, A., S. H. Anderson, C. J. Gantzer, and A. L. Thompson. 2004. Influence of stiff-stemmed grass hedge systems on infiltration. Soil Sci. Soc. Am. J. 68: 2000-2006.

Rachman, A., S. H. Anderson, C. J. Gantzer, and E. E. Alberts. 2004. Soil hydraulic properties influenced by stiff-stemmed grass hedge systems. Soil Sci. Soc. Am. J. 68: 1386-1393.

Reynolds, W.D., B.T. Bowman, R.R. Brunke, C.F. Drury, and C.S. Tan. 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 64:478-484.

Roper, M. M., P. R. Ward, and A. F. Keulen. 2013. Under no-tillage and stubble retention, soil water content and crop growth are poorly related to soil water repellency. Soil and Tillage Research. 126:143-150.

Schwartz, R. C., R. L. Baumhardt, and S. R. Evett. 2010. Tillage effects on soil water redistribution and bare soil evaporation through-out a season. Soil and Tillage Research. 110(2): 221-229.

Scott, H. D. 2000. Soil Physics: Agricultural and environmental application. Iowa State University Press.

Sharma, M.L., G.A. Gander, and C.G. Hunt. 1980. Spatial variability of infiltration in a watershed. J. Hydrology 45:101-122.

Tisdall, J. M. and H. H. Adem. 1986. Effect of water content of soil at tillage on size-distribution of aggregates and infiltration. Aust. J. Exp. Agric. 26: 193-195.

Tricker, A.S. 1981. Spatial and temporal patterns of infiltrations. J. Hydrology 49:261-277.