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Effect of tillage practices on the hydraulic properties of a loamy soil

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ABSTRACT

The knowledge of soil hydraulic properties is essential for modeling the water flow in unsaturated porous media for hydrological applications and agricultural water management. Long-term tillage practices have been shown to affect the hydraulic properties of soil. In this study, a field experiment was conducted to evaluate the effect of roto-tillage and no-tillage practices on the hydraulic properties of a bare loam soil. Two field plots were used with different tillage practices. In the first one, the field has been in roto-tillage for three years and in the other in continuous no-tillage for two years. From the hydraulic properties determined, water retention curves indicated that the water retention capacity was greater in tilled than in no-tilled (NT) soil. Both soil–water diffusivity and hydraulic conductivity values were greater in tilled than in NT soil at relatively low to moderate water contents, and lower in tilled than in NT soil at relatively high water contents—near saturation. The hydraulic properties determined were compared with the predicted ones by the Mualem–van Genuchten (MvG) model. The comparison showed a weakness of MvG model to describe satisfactory the unsaturated hydraulic conductivity with fixed model parameter values.

Keywords: Water retention curve; Hydraulic conductivity; Tillage practices; One-step outflow

1. Introduction

Experimental work up to now has shown that the soil surface state and its properties, regarding to water movement away and into the soil mass, may affect its evaporation, infiltration, and distribution. It has been shown that soil tillage generally reduces soil dry-bulk density and increases porosity, due to loosening of surface soil [1,2]. Tillage affects water retention curves as well as the hydraulic conductivity (K), especially near saturation. Mapa et al. [3] had shown that the changes of water retention curve due to cultivation practices are presented in the suction range from 0 to 300 cm. Poulovassilis [4] found that the tilled soil has bigger soil–water content at saturation (θ_s) and is characterized by a smaller proportion of large pores than untilled soil and a bigger proportion of small pores than the latter. Reported changes on the hydraulic conductivity due to cultivation practices are not consistent. Some researchers reported an increase in K due to

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tillage [5–7], others reported a decrease [3,8–11], and a few researchers [4,12] reported that the *K* of untilled soil was higher than that in tilled soil at high water content whilst at low to moderate water content, *K* in the tilled soil was higher than that in the untilled soil. It seems that the magnitude and the direction of the changes depend on the soil type and structure, organic matter, the cultivation practices, fauna activity, and the antecedent soil–water content. The increase in porosity is the direct outcome of changes induced in the pore size distribution from breaking down of soil clouds or aggregates to smaller ones due to tillage. Consequently, these changes may cause alterations to the water retention curve as a whole.

It has also been shown that the effects of cultivation practices on the hydraulic properties of the upper soil layer are not permanent and that these effects can diminish with time, [1,13–15]. Schwarzel et al. [16] investigated the temporal pore-space evolution following tillage. Many researchers have shown that the hydraulic properties of the upper soil layer change with time after tillage not only as a result of the tillage but also by the influence of natural factors [15,17–19]. Schwen et al. [19] observed a decrease in the hydraulically effective pores after tillage in response to rainfall during the winter period, which gradually increased in spring and summer periods. This may be due to the rainfall intensity, which causes destruction of the soil aggregates as well as to the successive wetting–drying cycles.

For the arid and semi-arid areas, where water is a limited resource, the changes of the hydraulic properties of the upper soil layer caused by agricultural cultivation practices may exert a serious effect on the overall volume of water which can be infiltrated, stored, and redistributed in the upper soil profile during the rainy season of the year [20].

In the present study, the hydraulic properties, soil–water retention curve, and unsaturated hydraulic conductivity, of the upper soil layer of a bare loam soil under two different cultivation practices were experimentally determined. While the water retention curve can be easily determined in lab, the direct measurement of unsaturated hydraulic conductivity is rather laborious and time consuming. In this work, the one-step outflow method, which is an indirect laboratory method easily applied and adopted into routine laboratory work, was used for determining the soil–water diffusivity relationship $D(\theta)$ and consequently, the $K(\theta)$ relationship from the available water retention data.

Furthermore, the values of the hydraulic properties determined were compared with the values predicted by a widespread used closed-form analytical hydraulic model of Mualem–van Genuchten (MvG) [21,22] and the validity of the model was assessed.

2. Materials and methods

2.1. Site and experimental description

Experimental work has been conducted in the field of the Agricultural University of Athens, in Attica, where experimental plots have been established in order to study the effect of soil cultivation practices on hydraulic properties. The field is a loamy soil. The texture of the soil is given in Table 1 for the two experimental plots (A and B) studied. The common clay minerals were Illite and in a much lesser extent Chlorite.

During the year 2011, two experimental plots (A and B) with dimensions 5 m × 5 m, 5 m apart from each other, were established. In the centre of each plot, a plastic access tube of internal diameter 2.5 cm and length 120 cm was inserted into the soil mass for monitoring water content profiles using PR2 dielectric device [23]. Two treatments were examined. In the first, a roto-tillage was applied on 18 October 2011 to plot A while plot B remained untilled (NT). The tillage depth was about 10–15 cm. For the removal of vegetation in the RT and no-tilled (NT) plots, the pesticide glyphosate was applied. Residue was also removed, thus, exposing a bare surface.

The water content at tillage time was 0.153 cm^3 cm^{-3} in experimental plot A and 0.166 $cm^3\,cm^{-3}$ in experimental plot B.

2.2. Measurements of hydraulic properties

Experiments to determine the water retention curves followed by the one-step outflow laboratory procedure were performed in Richards' pressure cell chambers for undisturbed soil samples, 3 cm height and 7 cm diameter, taken from the experimental plots on 22 December 2011. From each experimental plot, one undisturbed soil sample was taken. A device of

Table 1
Soil particle size distribution results and textural classification of the soils

	A	B
Depth	0–10	0–10
Sand (%)	38.8	34.3
Silt (%)	39.5	40.3
Clay (%)	21.7	25.4
Textural classification	Loam	Loam

two concentric cylinders [24] was used for sampling, where the exterior cylinder was sharpened at the bottom. As the cutting head advances downward, soil enters in the inner cylinder.

The inner cylinder (4 cm height and 7 cm diameter) with the soil sample was placed on Richards' pressure cells to measure the hydraulic properties.

The water content at sampling time was 0.223 cm^3 cm^{-3} in experimental plot A and 0.226 $cm^3 cm^{-3}$ in experimental plot B. Note that the rainfall height during the period between tillage and sampling was 51.6 mm.

2.2.1. Richards' pressure cells

The Richards' cells used to water retention curve and $K(\theta)$ measurements have been constructed in the Laboratory of Agricultural Hydraulics (Fig. 1). This device differs from the Haines' apparatus in the fact that the sample is subjected to a pressure greater than the atmospheric pressure (e.g. positive pressure) and the water is forced to leave the sample and drain in the free atmosphere. In each device, only one sample can be investigated. These cells are made from plexiglass due to the relative ease with which one could manipulate this material in comparison with other materials, and also due to its transparency and its capacity to sustain relatively moderate to higher pressures. Each cell consists of two square and parallel plates with dimensions $(10 \times 10)\,cm^2$ and in between them a plastic cylinder is placed. The soil sample is retained in this cylinder. The width of the upper plate is 2 cm and the width of the bottom plate is 3 cm. In the center of the upper plate, an opening with a valve permits the connection or the disconnection of the cell to the pressure system (air compressor, pressure regulators, etc.). In the bottom plate, a shallow cylindrical space, with height 3 cm and diameter 7 cm, is used as a water reservoir. Just above this reservoir, the porous plate is placed and on top of this we place the soil sample. The cylinder is tightly fixed with the plates with four screws and two o-rings, one at each plate. The water reservoir at the bottom plate has two exits, one for the air escape, resting at the side of the plate and the other, at the centre of the bottom giving access to the water, through a flexible plastic pipe. This pipe is connected to another cylindrical reservoir made of plexiglass with dimensions 3 cm height and 1.5 cm diameter. At the upper place of this cylindrical reservoir a special opening exists at the same level as the bottom of the soil sample to permit water entering or leaving the soil sample.

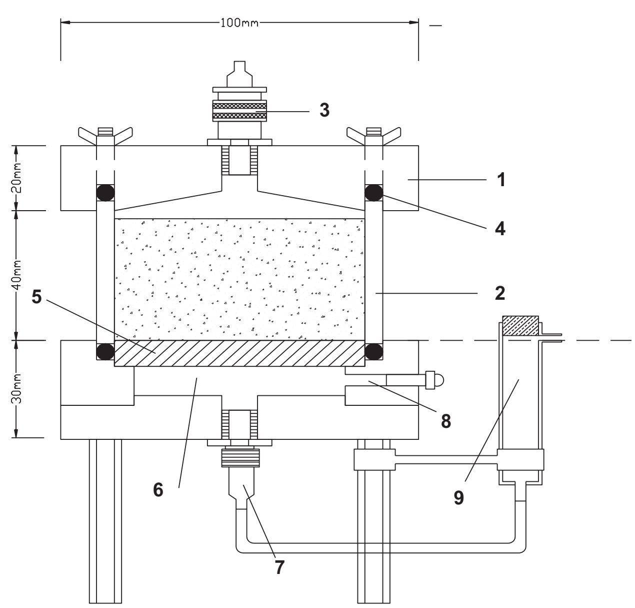

Fig. 1. Richards' pressure cell: (1) plexiglass plate, (2) cylinder, (3) connecting valve, (4) elastic O-rings, (5) porous plate, (6) water reservoir, (7) water exit, (8) air exit, and (9) water reservoir.

The undisturbed soil sample was placed in the Richards' cell and allowed to wet gradually until saturation. After that, the sample was subjected to a drying–wetting cycle and the determination of water retention curve (drying and wetting) was made by applying relative small gas-pressure increments to the soil sample, and the water lost at various pressure steps can be measured by weighting.

2.2.2. One-step outflow experiment

Once the water retention curves were determined, at the end of wetting, and while the samples were saturated, the one-step outflow procedure began. A large positive gas pressure step, h_f, was suddenly applied at the top of the samples and the cumulative outflow volume was recorded with time until the water content reached the final equilibrium value θ_f. The h_f value applied was equal to the highest gas pressure used in the determination of the retention curve. The experimental one-step outflow procedure gave a series of measured outflow volumes V_i in the relevant times t_i ($i = 1, 2, 3 \ldots N$). The experimental data obtained were converted in mean values of water content $\bar{\theta}_i$, as $\bar{\theta}_i = \theta_s - V_i/V_0$, where θ_s is the volumetric water content at saturation and V_0 is the sample volume.

Then, we plot the dimensionless variable S against the square root of time $\sqrt{t}$. S represents the fraction of remaining outflow water volume and is obtained from the original outflow data, $V(t)$, as follows:

$$S = \frac{\overline{\theta} - \theta_f}{\theta_s - \theta_f}, \quad 0 \leqslant S \leqslant 1 \tag{1}$$

From the plot of $S(\sqrt{t})$, the nonlinear portion of the curve (stage III, the portion of the curve where cumulative outflow ceases to be linear with $\sqrt{t}$), in which the effect of the porous plate impedance becomes negligible, was identified [25–27].

After identifying the curve-fitting region of the $S(\sqrt{t})$ plot, corresponding to stage III of the outflow, a simple regression of a three-parameter power function [27] was applied

$$S\left(\sqrt{t}\right) = a\left(\sqrt{t}\right)^b + c \tag{2}$$

and the a, b, and c curve-fitting parameters were obtained.

Then, soil–water diffusivity as a function of mean volumetric water content $D(\overline{\theta})$ was calculated from the one-step outflow data using the Valiantzas et al. [27] equation:

$$D(\overline{\theta}) = -\frac{2L^2 a^{2/b}}{\pi^2}\left(\frac{\overline{\theta} - \theta_f}{\theta_s - \theta_f} - c\right)^{-2/b} \left[b - 1 - (b/2)c\left(\frac{\theta_s - \theta_f}{\overline{\theta} - \theta_f}\right)\right] \tag{3}$$

where L is the length of the sample, and a, b, and c fitting parameters.

The proposed equation has been validated for various types of soils and substrates [27,28].

Then, the $K(\theta)$ relationship was calculated using $K(\theta) = D(\overline{\theta})\mathrm{d}\theta/\mathrm{d}H$ [29]. The slope of $\mathrm{d}\theta/\mathrm{d}H$ was calculated from the experimental water retention curves.

The saturated hydraulic conductivity, K_s was determined independently by the constant-head method [30]. Each sample was subjected to a wetting–drying cycle prior to the measurement.

2.2.3. Calculation of hydraulic properties by MvG model

The hydraulic properties determined, water retention curve and unsaturated hydraulic conductivity, were compared with the predicted ones as were calculated using the pore size distribution model of Mualem [21] for the hydraulic conductivity in combination with a water retention function introduced by van Genuchten [22].

The soil–water retention curve, $\theta(H)$, is described by the following equation [22]:

$$\theta(H) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1 + |aH|^n)^m}, & H \leqslant 0 \\ \theta_s, & H \succ 0 \end{cases} \tag{4}$$

where θ is the volumetric water content at pressure head H, θ_s and θ_r are the saturated and residual water contents, respectively, α (>0) is related to the inverse of the air-entry pressure value, n (>1) is a measure of the pore size distribution and $m = 1 - 1/n$.

Combining Eq. (4) with the model developed by Mualem [21], the unsaturated hydraulic conductivity, $K(\theta)$, can be calculated by the following expression:

$$K(\theta) = \begin{cases} K_s\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^p \left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right]^m\right\}^2, & H \leqslant 0, \\ K_s, & H \succ 0, \end{cases} \tag{5}$$

where K_s is the saturated hydraulic conductivity and p is a soil-specific parameter that accounts for the tortuosity of the flow with a conventional value at 0.5 (proposed by Mualem) [21].

3. Results and discussion

3.1. Experimental hydraulic properties

The experimental drying and wetting branches of the water retention curves of the (NT) and roto-tilled (RT) bare soils are depicted in Fig. 2. It is worth to note that both the hydraulic properties, water reten-

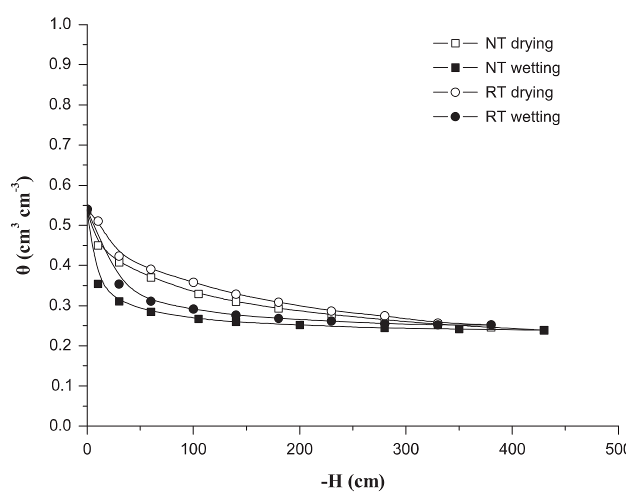

Fig. 2. Experimental water retention curves during drying and wetting for the NT and RT bare soils.

tion curve and soil diffusivity, were measured in the same soil sample and in the same apparatus. Usually, these soil hydraulic properties are measured in different soil samples resulting in difficulty to discriminate errors between those which come from different samples and those which come from different cultivation treatments.

The comparison between RT and NT soil samples showed that the tillage led to the increase in water retention capacity. The total porosity (water content in 0 cm pressure head) was increased negligibly (0.537 $cm^3 cm^{-3}$ at NT and 0.540 $cm^3 cm^{-3}$ at RT).

Both water retention curves of the soil samples showed hysteresis with a similar order of magnitude hysteretic loop. Note that, due to the phenomenon of hysteresis, the greater differences between the water content values were observed for the range of pressure heads between −20 and −150 cm.

Due to the experimental outflow data used to calculate $D(\theta)$ were collected from stage III where the porous plate impedance is negligible, the $D(\theta)$ values near saturation were not determined. As shown in Fig. 3, the $D(\theta)$ values for RT soil were greater than those of NT soil (approximately 3-fold at water content 0.25 $cm^3 cm^{-3}$ and 1.5-fold at water content 0.35 $cm^3 cm^{-3}$).

For the same range of water contents (0.25–0.35 $cm^3 cm^{-3}$), the $K(\theta)$ values obtained by the experimental outflow data and water retention data are presented in Fig. 4. As shown, the hydraulic conductivity values of RT soil were greater than those of NT soil at relatively low water content (approximately 4-fold at 0.25 $cm^3 cm^{-3}$) and become equal at water content 0.35 $cm^3 cm^{-3}$, while the saturated hydraulic conductivity was bigger (approximately 2-fold) in NT (0.107 $cm\ min^{-1}$) than in tilled soil (0.049 $cm\ min^{-1}$).

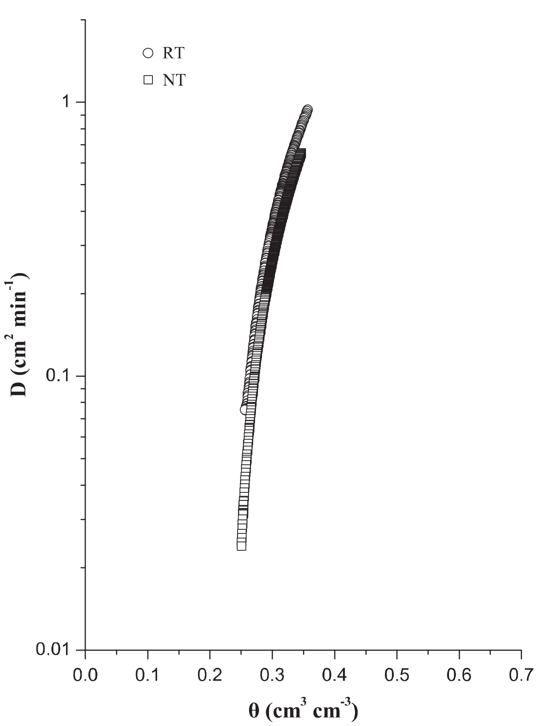

Fig. 3. Soil diffusivity as a function of water content for the NT and RT bare soils.

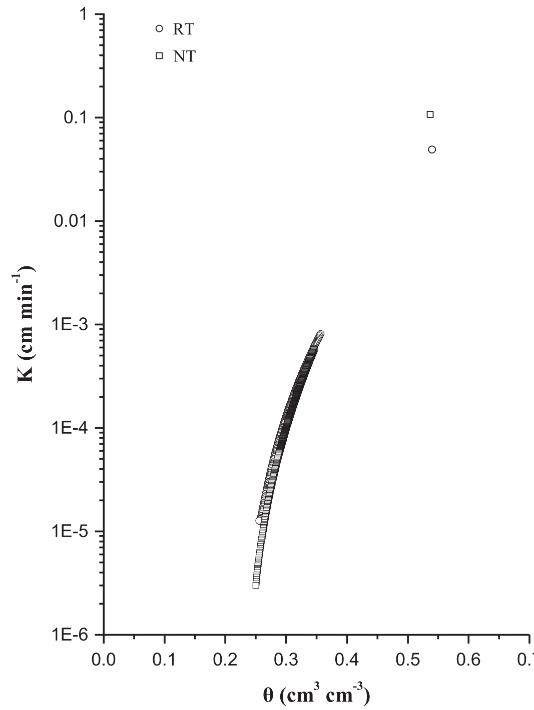

Fig. 4. Hydraulic conductivity as a function of water content for the NT and RT bare soils obtained by outflow data using the Valiantzas et al. equation (Eq. (3)) and water retention data.

Based on the above-mentioned results, it may be claimed that in the RT soil more water volume will be stored compared with the NT soil, at least during rainfall period following autumn tillage, since the K values of RT soil were greater than those of NT soils for water content values during tillage.

3.2. Predicted hydraulic properties using the MvG model

In Fig. 5, a comparison between the experimental water retention data during drying and the retention curves predicted using the van Genuchten equation is presented. A detailed description of the curve-fitting parameters θ_r, a, and n of the van Genuchten equation, and the coefficient of determination, R^2, of the fitted curves is presented in Table 2. For both soils (NT and RT) examined, the results indicated a high correlation between experimental and fitted data.

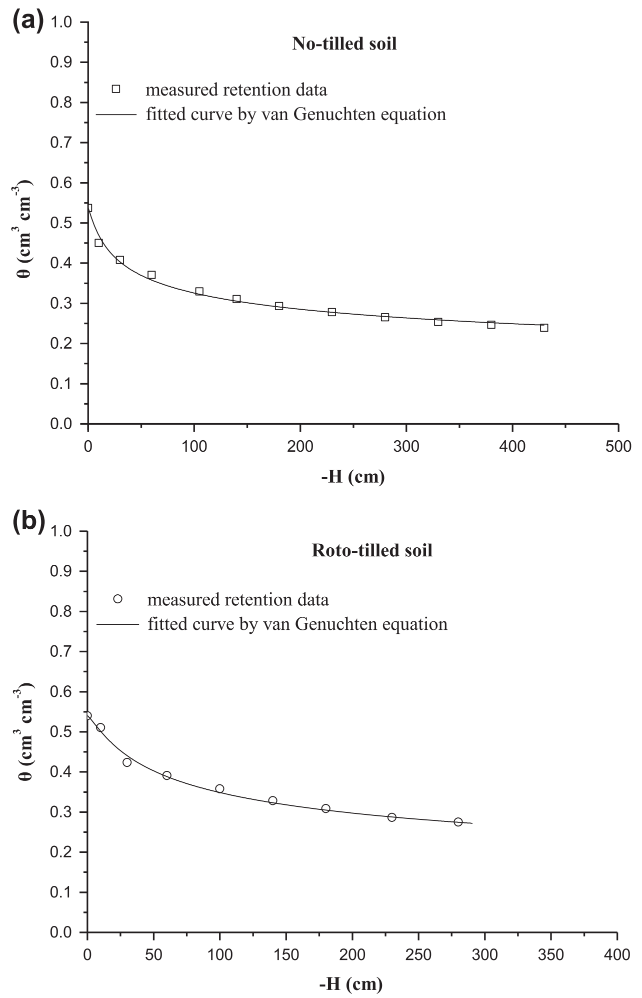

Fig. 5. Experimental and fitted (using the van Genuchten equation) water retention curves during drying for the NT (a) and RT (b) bare soils.

In Fig. 6, the $K(\theta)$ values for the NT and RT soils, determined from the outflow experimental data using Valiantzas et al. equation (Eq. (3)) and water retention data, were compared with the predictions obtained by MvG model (Eq. (5)). The results indicated that there is a significant deviation between the experimental data and $K(\theta)$ predictions obtained using the MvG model with fixed values for $p = 0.5$, K_s = measured value, and θ_r and n determined by the van Genuchten equation on soil–water retention data. The root mean squared errors (RMSE) between the determined and predicted $K(\theta)$ values for both NT and RT soils are given in Table 3.

Due to this deviation, the MvG model was also studied in the case of no-fixed values of the MvG fitting parameters p and K_s, ($p \neq 0.5$, $K_s \neq$ measured value). The comparison showed that the MvG model underestimated the unsaturated hydraulic conductivity for water content greater than $0.3\,cm^3\,cm^{-3}$ and overestimated it for water content less than $0.3\,cm^3\,cm^{-3}$, for both soils studied. The fitting parameter p, in both NT and RT soils, had a negative value with remarkable deviation from the conventional value of $p = 0.5$ (Table 3). The value of fitted parameter p is in the same order of magnitude with the p value reported by Schaap and van Genuchten [31] for loam soils. With regard to K_s, in the case of NT soil, the fitted K_s value was greater (almost two fold) than the experimental K_s value, and in the case of RT the fitted and the measured values were equal (Table 3). Due to the deviation between the measured and fitted K_s values, in the case of NT soil, the RMSE value was greater than this calculated in the case of fitting with fixed p and K_s values (Table 3). The opposite was observed in the case of RT soil (Table 3).

Additionally, a fitting of the MvG model, without taking into account fixed values for p and K_s, as well as the van Genuchten equation fitting parameters (n and θ_r) on the water retention data, was presented in Fig. 6, in order to estimate the $K(\theta)$ values near saturation. The comparison showed well agreement between fitted and determined $K(\theta)$ values. The RMSE values were smaller than those of the other cases examined, for both NT and RT soils (Table 3). However, the fitting values of n and θ_r appeared considerably a deviation from these ones defined from the fitting van Genuchten equation on water retention data. With regard to K_s, in both soils examined, the fitted values observed were equal with the measured ones. The p values were also negative but different from the latter ones estimated (Table 3).

It is worth to note that the cost of this improvement (last mentioned fitting) is a poorer characterization of the water retention relationship.

Overall, while the MvG model has found widespread use it has a weakness to describe satisfactory the hydraulic conductivity. The soil–water retention equation and the hydraulic conductivity function of the MvG model have several limitations caused by the

Table 2
Fitted van Genuchten soil–water retention curve parameters θ_r, a, and n. R^2 is the coefficient of determination of the fitted water retention curves of the NT and RT soils

Soil	NT	RT
θ_r ($cm^3\,cm^{-3}$)	0	0
α (cm^{-1})	0.121	0.053
n	1.197	1.248
R^2	0.9912	0.9935

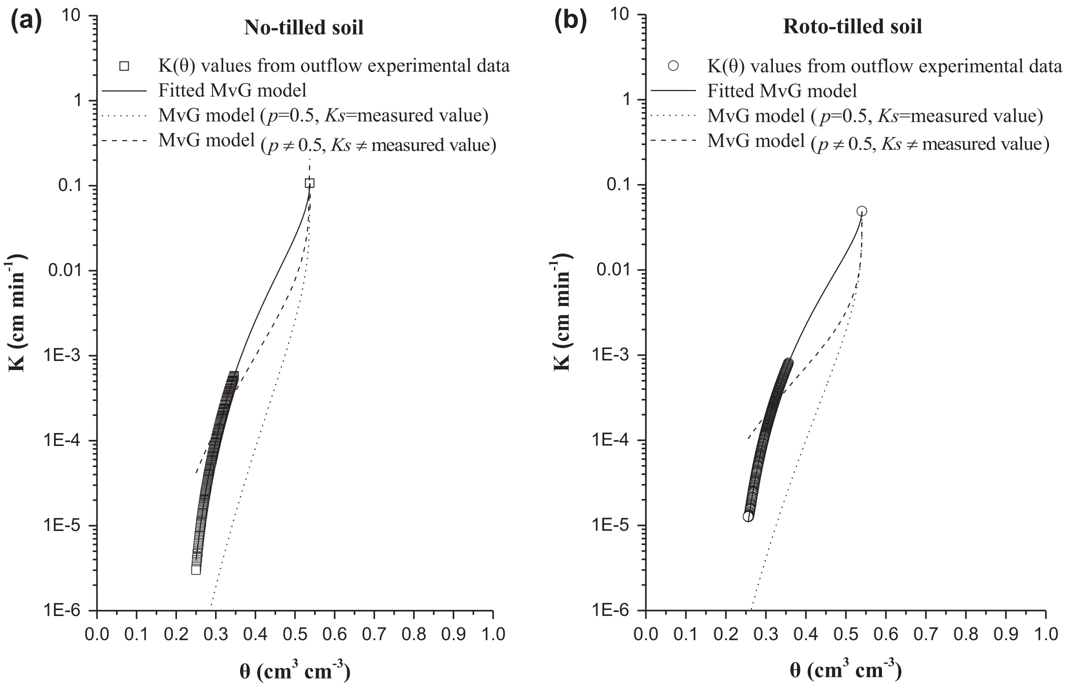

Fig. 6. Hydraulic conductivity as a function of water content for the NT (a) and RT (b) are soils obtained by: (1) outflow experimental data using Valiantzas et al. equation (Eq. (3)) and water retention data (square and circle symbols), (2) MvG model with fixed values $p = 0.5$ and K_s = measured value (dot line), (3) MvG model with $p \neq 0.5$ and $K_s \neq$ measured value (dash line), and (4) MvG model fitted without taking into account fixed values for p and K_s, as well as the van Genuchten equation fitting parameters on the water retention data (solid line).

Table 3
Fitting results of the MvG model for different values of fitting model parameters. MvG model with fixed values $p = 0.5$ and K_s = measured value, fitted MvG model with $p \neq 0.5$ and $K_s \neq$ measured value, and fitted MvG model without taking into account fixed values for p and K_s, as well as the van Genuchten equation fitting parameters on the water retention data. RMSE of the MvG $K(\theta)$ fitted curves as compared with the determined $K(\theta)$ values obtained by the experimental outflow and water retention data

Soil		n	θ_r (cm^3 cm^{-3})	p	K_s (cm min^{-1})	RMSE
NT	MvG model ($p = 0.5$, K_s = measured value)	1.197	0	0.5	0.107	1.6×10^{-4}
	MvG model ($p \neq 0.5$, $K_s \neq$ measured value)	1.197	0	−5.666	0.207	3.8×10^{-3}
	MvG model (without any fixed values)	1.768	0.205	−0.272	0.107	9.9×10^{-6}
RT	MvG model ($p = 0.5$, K_s = measured value)	1.248	0	0.5	0.049	2.6×10^{-4}
	MvG model ($p \neq 0.5$, $K_s \neq$ measured value)	1.248	0	−6.105	0.049	1.1×10^{-4}
	MvG model (without any fixed values)	2.152	0.208	−0.045	0.049	1.3×10^{-6}

particular mathematical properties of soil–water retention equation (Eq. (4)) or by the use of default values for K_s and p [31]. Efforts have been made from many researchers [31–33] to modify the MvG model in order to improve the description of the unsaturated hydraulic conductivity.

4. Conclusions

Both the basic hydraulic properties, $\theta(H)$ and $K(\theta)$, were determined using an easy methodology in the same soil sample for a range of water contents between saturation and field capacity.

Water retention curves indicated that the water retention capacity was greater in tilled than in NT soil. Saturated hydraulic conductivity was bigger in NT than in tilled soil. On the other hand, both $D(\theta)$ and $K(\theta)$ values were greater in tilled than in NT soil at relatively low to moderate water contents. The opposite was observed at relatively high water contents near saturation. It is worth to note that these results are referred to bare loam soils, specific sampling time period (winter) and tillage treatment. More research is needed for studying the temporal variability of the hydraulic properties between the two different tillage treatments.

The comparison between $K(\theta)$ values from experimental outflow data and the predictions obtained using the MvG model, with different fitting scenarios for both soils examined, showed a weakness of the model to describe satisfactory the unsaturated hydraulic conductivity.

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