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Soil water diffusivity: A simple laboratory method for its determination

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Abstract: Soil water diffusivity (D) is an important hydraulic property that is fundamental to characterize unsaturated water transport. Its determination is complex, time-consuming and requires expensive instruments. The objectives of this work were: to propose a simple and low-cost laboratory methodology to determine D function; and to analyze the influence of soil management systems on D and Sorptivity (S). The studied soil was classified as a vertic Paleudol. The first 10 cm of the soil under three different management systems (T1: Natural grassland, T2: direct drilling, and T3: Polyphitic Pasture) was sampled. The samples were sieved and packed into horizontal columns. The columns were analyzed under horizontal infiltration and D was determined by variations of water content as a function of time for fixed positions, obtained from low-cost soil moisture capacitance sensors. The results showed that the proposed methodology is valid in the studied soils. Soil management system significantly affected D and S. They were greater for T2 compared with T1 and T3 (D varied between 0.00033 and 0.0321 $cm^2.s^{-1}$). This means that the soil under T2 can transmit water faster under non-saturated conditions as compared with the soil under grazing. In conclusion, the proposed methodology allowed to determine D in a simple and low-cost way, and to determine the influence of these properties on productive conditions.

Keywords: unsaturated water movement, sorptivity, Richards' equation.

Difusividade da água no solo: Um método simples de laboratório para sua determinação

Resumo: A difusividade da água no solo (D) é uma importante propriedade hidráulica para caracterizar o transporte não saturado de água no solo. Essa determinação é complexa devido ao tempo gasto para isso e ao elevado custo dos equipamentos necessários. Os objetivos desse trabalho foram: propor uma metodologia simples e de baixo custo de laboratório para determinar uma função para D e para analisar a influência de sistemas de manejo do solo em D e na sortividade do solo (S). O solo estudado foi classificado como um Paleudol vertico. As amostras deformadas foram coletadas em três sistemas de manejos (T1: Campo Nativo, T2: Plantio Direto e T3: pastagem). Foram retirados os primeiros 10 centímetros do solo. Essas amostras foram peneiradas e depois foram acomodadas em colunas horizontais. As colunas foram submetidas a infiltração horizontal e D foi determinado pela variação do conteúdo de água em função do tempo, com auxílio de sensores de capacitância para a determinação da umidade do solo. Os resultados indicam que a metodologia proposta é válida para os solos desse estudo. O sistema de manejo do solo indicou diferença significativa em D e S. Foram melhores no tratamento T2 comparado com T1 e T3 (D apresentou variação entre 0,00033 e 0,0321 cm^2 s^{-1}). Isso indica que o solo na condição T2 conduz água mais rápida na condição não saturada, que o solo manejado com pastejo. Assim, a metodologia proposta permite determinar D em uma amostra e com baixo custo, além de verificar a influência dessas propriedades em condições produtivas.

Palavras-chave: movimento de água no solo não saturado, Sortividade, Equação de Richards.

Introduction

The effects of tillage on the water flux is describe generally by the study of infiltration (Ferreras et al., 2000; Álvarez et al., 2006; Sasal et al., 2006; Soracco, 2009) or saturated hydraulic conductivity (Bagarello et al., 2006; Soracco et al., 2010; Lozano et al., 2014; Riezner & Gandolfi, 2014; Shabtai et al., 2014). Both of this variables are based on saturated flux, which is not a representative of the reals field conditions (Hillel, 1980). Determination of soil water diffusivity (D) as a function of volumetric water content (θ) is important as this hydraulic property is fundamental in order to characterize unsaturated water and solute transport in soils (Wang et al., 2004). Determination of this property is complex, time consuming, and requires quite expensive instruments (Evangelides et al., 2010). For this reason the determination of D (θ) has been seldom carried out. Several methods were proposed for determining soil water diffusivity. Bruce & Klute (1956) proposed a method based on the water content distribution profile, determined by destructive gravimetric sampling, as a function of distance at an arbitrary time after water was introduced into a horizontal soil column. This water distribution is then used in a numerical integration in calculating D. Subsequently, Whisler et al. (1968) introduced a method that used the same theoretical analysis as that in the Bruce & Klute (1956) method, but D is based on the water distribution as a function of time at a fixed position instead of the water distribution with distance at a fixed time in a horizontal soil column. This method is nondestructive, and has the advantage of being simpler and faster than Bruce and Klute (1956) method (Selim et al., 1970). However, it requires a method of determining the water content in the soil column at different times. Usually gamma ray attenuation method has been used (Whisler et al., 1968; Klute and Dirksen, 1986). This method is expensive, difficult, implies radioactive hazard and requires a method to test the suitability of Richards' equation. Whisler et al. (1968) used for this problem an inaccurate method based on a visual analyze of graphics. For these reasons, Evangelides et al. (2010) proposed a method to estimate D (θ) that avoids the determination of the water content at different times. This method is based in the visual inspection of the wetting front distance versus time, together with initial and final water content, and cumulative infiltration data, using an empirical function. The problem of this approach is that requires a constant water content in the visually identified wetting front. Selim et al. (1970) stated that the water content which corresponds to a visually determined appearance of a wetting front may conceivably decrease as time increases. This introduces an inconsistence in Evangelides et al. (2010) method.

The use of safe, cheap and accurate water content sensors, would allow determining D (θ) function in a precise, consistent, and low cost way. Capacitive sensors (also called frequency domain reflectometry) have the advantage of being cheaper than the more accepted time domain reflectometry (TDR) sensors, with a similar performance if a soil-specific calibration is carried out (Czarnomski et al., 2005).

Another important soil hydraulic property is Sorptivity (S) [$L.T^{-0.5}$]. S describes the ability of the soil to take water under capillarity forces (Koorevaar et al., 1983). For horizontal infiltration the gravitational component doesn't exist, so the flux is only under capillarity forces. Both D and S can be describe the pore materials ability to transport water and solutes (Zhou, 2014).

The hypotheses were: 1- it is possible to test the suitability of Richards' equation improving the method proposed by Whisler et al. (1968); and 2- it is possible to determine the effects of different productive situations on the water flux under non-saturated conditions by studying D and S.

The objectives of this work were to propose an improving on Whisler et al. (1968) methodology doing it simpler and more robust, providing a way to test the suitability of Richards' equation and their assumptions; and to determine the influence of different productive situations on D and S.

Materials and Methods

Theory

The Richards´ equation for horizontal absorption or, more generally, for water flow where the gradient of the gravitational component of soil water can be neglected, with the space coordinate x, and the time t, is

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\left(\frac{\partial\theta}{\partial x}\right)\right] \quad (1)$$

where D(θ) is the soil water diffusivity expressed as a function of the water content, θ, subject to the initial and boundary conditions with the initial water content, θ_i, and the surface water content, θ_0

$$\begin{aligned} \theta &= \theta_i \quad t = 0 \quad x > 0 \\ \theta &= \theta_i \quad t > 0 \quad x \to \infty \\ \theta &= \theta_s \quad t > 0 \quad x = 0 \end{aligned} \quad (2)$$

Essentially the theoretical analysis amounts to transforming the partial differential equation of diffusivity (1) to an ordinary differential equation by using the Boltzmann transformation λ = λ (θ), given by

$$\lambda = xt^{-\frac{1}{2}} \quad (3)$$

where λ is a function of θ. The use of the Boltzmann transformation λ of equation (3) in equation (1) assumes that the water content θ is a single-valued function of λ only. Also, the diffusivity equation (1) is based on the validity of Darcy's law to unsaturated water flow.. Applying (3) to equation (1) gives the following expression for D (θ)

$$D(\theta) = -\left(\frac{1}{2}\right)\left(\frac{d\lambda}{d\theta}\right)\int_{\theta_i}^{\theta} \lambda d\theta \qquad (4)$$

where θ_i is the initial water content. In the method of Whisler et al. (1968), x is fixed and t is variable. Then, the equation (4) becomes

$$D(\theta) = \left(\frac{1}{4}\right)\left(\frac{x_i^2}{t^{3/2}}\right)\left(\frac{dt}{d\theta}\right)\int_{\theta_i}^{\theta} \frac{1}{\sqrt{t}} d\theta \qquad (5)$$

where x_i is the fixed position at which the water content θ is being measured.

The diffusivity equation should be valid for many conditions except whenever a significant solute-water-particle surface interaction exists, whenever the soil swells upon wetting, or whenever the physical properties of the soil and the water change within the soil during infiltration caused by inorganic and/or organic solutes affecting wetting angles, viscosity, vapor transfers, etc. (Selim et al., 1970).

If the flow is described by the nonlinear diffusivity equation and the boundary and initial water contents are constants, the transformed water content-distance-time data should give a unique λ (θ) function, independent of the position x in the column (Klute and Dirksen, 1986). The diffusivity function D(θ) can be calculated for a fixed position in the column by replacing the differential and integral terms in equation (5) by finite differences and numerical integration (Whisler et al., 1968).

For horizontal infiltration case, where doesn't exist the gravitational component, the cumulative infiltration is given by (Philip, 1957)

$$I = St^{1/2} \qquad (6)$$

where S is the sorptivity. If the gravitational component doesn't exist, the plot of I versus $t^{1/2}$ should be a straight line during all process.

Sites and treatments

The experiment was carried out near the city of La Plata, in the Research Field "Don Joaquin" belonging to the Faculty of Agricultural and Forestry Sciences, National University of La Plata (37º11' S, 57º50' W). The soil was classified as a fine, illitic, vertic Paleudol (Soil Survey Stuff, 2006), the texture of the upper layer was silty loam, with 61 % silt and 24 % clay. The organic matter content did not differ significantly between treatments and was 41 g kg^{-1}.The climate in the region is temperate with temperature seldomly dropping below 0 °C, so that freezing of soil does not occur, and with annual rainfall amounting to ~1000 mm. The first 10 cm of the A-horizon under three different productive situations (T1: Natural grassland, T2: direct drilling mayze, and T3: Polyphitic Pasture), in neighbor plots in the same relative position in the landscape was sampled. Both T1 and T3 were under cattle grazing.

The samples were air dried, and sieved through 2 mm sieve, and then the soil was slowly packed into horizontal PVC columns (three repetitions for treatment, a total of nine columns) (Figure 1) till a bulk density equal to 1,1 g cm^{-3}. The column consisted in a PVC tube 70 cm long and 10 cm inn diameter, with holes in the upper part, placed at 10, 20, 30, 40 and 55 cm from the inflow end. At both ends of the column a high conductance fine plastic screen was used to prevent the soil from dispersing during the experiment. In the inflow end a sponge was added in order to obtain a homogenous water distribution in all the soil section. The water pressure entering the column was maintained at atmospheric pressure by a Mariotte burette, which was connected to the column by means of a transparent plastic tube. Continuous monitoring of the water entering the column was made by direct measurement in the reservoir.

Water content and time was measured using 5 moisture sensors (EC-5 sensor, Decagon Devices Inc., Pullman, Washington, USA) placed at 10, 20, 30, 40 and 55 cm from water source connected to a data logger (Em50 data logger, Decagon Devices Inc., Pullman, Washington, USA). Previously, a soil specific calibration was carried out following manufacturer instructions. A linear equation was fitted between sensor output (mV) and volumetric water content (θ, m^3m^{-3}) with $r^2 \geq 0.99$. The water content versus time data for each sensor was fitted to a logistic function with two parameters with $r^2 > 0.98$. The data of λ versus θ at fixed selected θ: 0.1, 0.2, 0.3, and 0.4 $m^3.m^{-3}$ was derived from these functions for each x_i. The diffusivity function D (θ) was calculated for a fixed position in the column by replacing the differential and integral terms

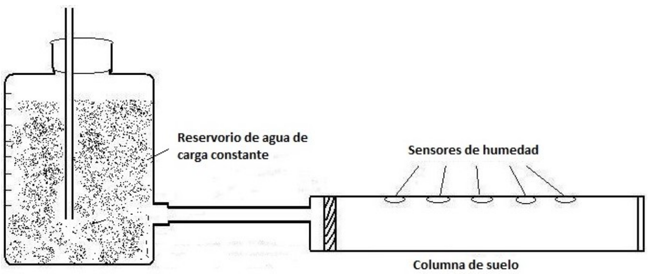

Figure 1. Schematic diagram of the device used to measure soil water diffusivity from horizontal infiltration runs.

in equation (5) by finite differences and numerical integration. The substitutions were made following Whisler et al. (1968).

Cumulative horizontal infiltration (I) was measured directly from a graduated reservoir, and sorptivity (S) was calculated as the slope of the I versus $t^{1/2}$ curve. To check that the gravitational component doesn't affect the water dynamic, a lineal fitting was made to the plots I versus $t^{1/2}$, with $r^2 > 0.99$ (Figure 2). This means that infiltration process were under only capillary forces.

To test the suitability and applicability of the diffusivity theory to the description of the water flow in the experiments, the soil water content θ was plotted versus the Boltzmann transformation λ. If the diffusivity theory is applicable, then for any one soil, θ vs λ relationship obtained for several positions x in the column should coincide (coalescent curves). In other words, the coincidence of such data will show that θ is a unique function of λ (Whisler et al., 1968; Selim et al., 1970; Guerrini and Swartzendruber, 1998).

Using the proposed setup it is possible to carry out a second test to the validity of the diffusivity theory. It consists in plotting x_θ (distance from the water source to a wetting front of a determined water content θ) versus $t^{1/2}$. If the diffusivity theory is valid for the studied soil, this plot should be a straight line (Selim et al., 1970), and the slope of this line should be the Boltzmann constant λ at that soil water content (θ). This plot can be carried out for different soil water contents θ, with different slopes, and each slope would be λ at each correspondent θ. The obtained λ versus θ data obtained in this way should coincide with the data obtained from the experiments.

Statistical analysis

In order to test the validity of the proposed approach, the values of λ at different soil water contents (θ) (namely, 0.1, 0.2, 0.3, and 0.4 $m^3.m^{-3}$) obtained in two different ways were compared by analysis of variance (P = 0.05). The differences of means were assessed by the Student–Newman–Keuls (SNK) test (p = 0.05). The effects of the different treatments on D at different θ, and on S, were tested by analysis of variance (p = 0.05). The differences of means were assessed by the Student–Newman–Keuls (SNK) test (p = 0.05).

Results and Discussion

Validity of diffusivity equation for the studied soil

To test the validity and applicability of the diffusivity theory to the description of the water flow, the soil water content θ was plotted versus the Boltzmann transformation λ (Figure 3). The figure shows that for each column, θ vs λ relationship obtained for several positions x in the column coincided (coalescent curves). This means that θ is a unique function of λ, which demonstrates that the diffusivity equation (1) is valid for the studied soils (Whisler et al., 1968; Selim et al., 1970; Guerrini and Swartzendruber, 1998).

Additionally x_θ (distance from the water source to a wetting front of four water content θ: 0.1, 0.2, 0.3, and 0.4 m^3m^{-3}) versus $t^{1/2}$ was plotted (Figure 4). A linear equation with r^2>0.99 was fitted in each case. This is in agreement with Selim et al. (1970) who emphasized that if the diffusivity theory is valid for the studied soil, this plot should be a straight line. Table 1 shows the values of λ at the studied soil water contents (θ) calculated as the slope of these lines (λ_s), and λ calculated from the experimental data (λ_e). No significant differences (p = 0.05) between the values obtained using the two methods were found, showing that the proposed method is consistent and that the diffusivity theory is valid for the studied soils.

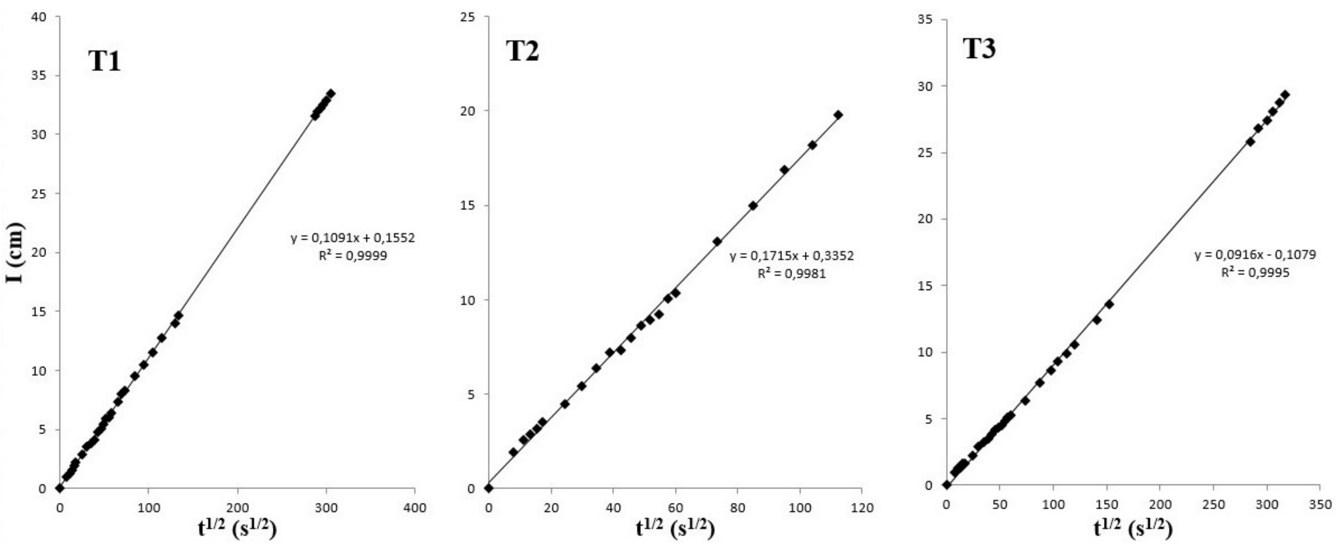

Figure 2. Cumulative infiltration (I) versus $t^{1/2}$, for one representative column of each treatment (T1: Natural grassland, T2: direct drilling mayze, and T3: Polyphitic Pasture). Solid lines are linear fittings.

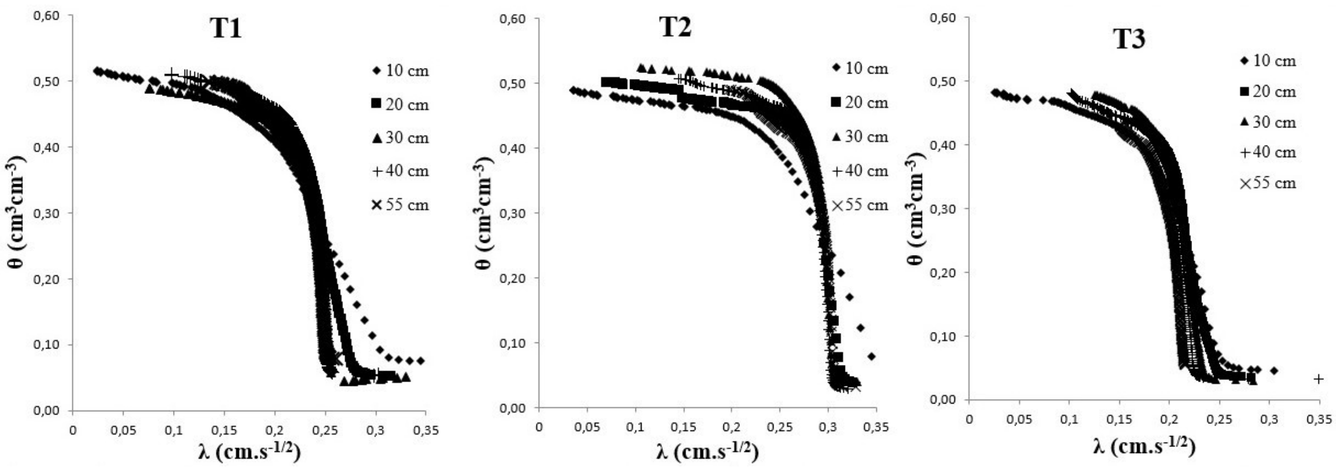

Figure 3. Volumetric soil water content (θ) versus Boltzmann constant (λ) for different fixed distances from water source, for one representative column for each treatment (T1: Natural grassland, T2: direct drilling mayze, and T3: Polyphitic Pasture).

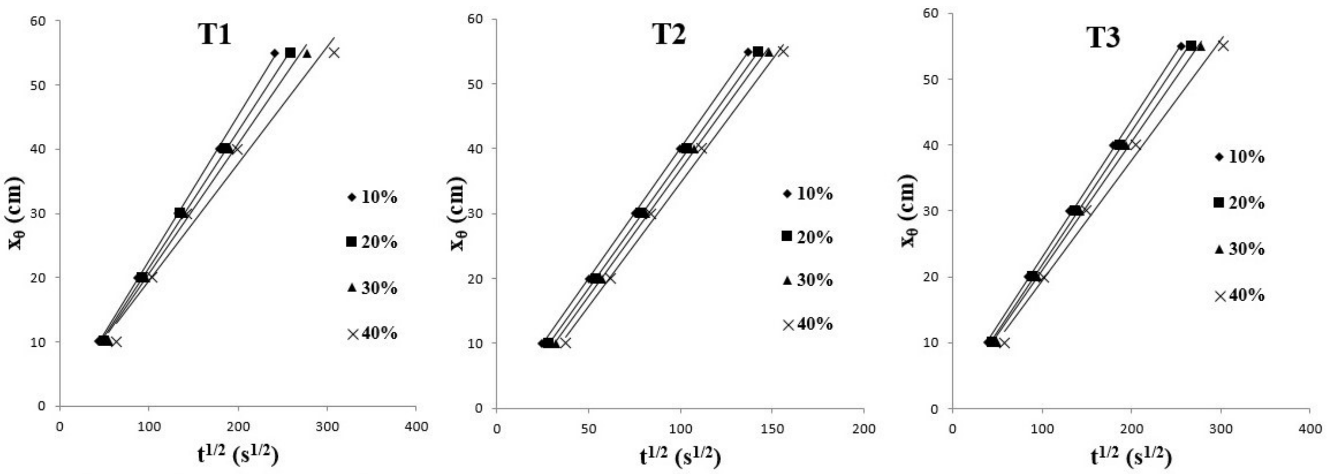

Figure 4. Distance from water source to the wetting front (x_θ) at different water contents (θ: 10, 20, 30, and 40 %) versus $t^{1/2}$, for one representative column for each treatment. Straight lines are linear fittings (r^2>0.99).

Table 1. Boltzmann variable (λ, cm.$s^{-1/2}$) values obtained as the slope of the wetting front versus $t^{1/2}$ for different soil water contents (θ) (λ_s), and obtained from the experimental data (λ_e), for different treatments (T1: Natural grassland, T2: direct drilling mayze, and T3: Polyphitic Pasture)

Treatment	θ=0.1 m^3m^{-3}		θ=0.2 m^3m^{-3}		θ=0.3 m^3m^{-3}		θ=0.4 m^3m^{-3}	
	λ_s	λ_e	λ_s	λ_e	λ_s	λ_e	λ_s	λ_e
T1	0.23a	0.25a	0.23a	0.23a	0.22a	0.21a	0.21a	0.19a
T2	0.36a	0.38a	0.36a	0.36a	0.35a	0.34a	0.35a	0.31a
T3	0.23a	0.29a	0.22a	0.24a	0.22a	0.22a	0.19a	0.20a

Different letters for each treatment and water content means significant differences between λ_s and λ_e (t test, p = 0,05).

Diffusivity (D(θ)) and Sorptivity (S) for different productive situations

Both S and D at different soil water content (θ) were significantly affected by the treatment (Table 2). S and D were significantly greater (p = 0.05) for T2 as compared with T1 and T3. The results are in agreement with Shaver et al. (2013) who found that the accumulation of crop residues on the soil surface will have the indirect effect of increased S via improvements in soil aggregation, bulk density, and porosity that are conducive to water infiltration. Arevallo et al. (1998) found that cattle grazing affected negatively S through soil compaction, which is in agreement with our results of lower S values on T1 and T3. These results are in agreement with other authors that reported an increase of S in soils under tillage (Starr, 1990, Murphy et al., 1993). The D values were significantly higher for T2, especially at relative low soil water contents. This is in concordance with Hamblin (1982) who found higher values of D in soils under conventional tillage compared with no tillage. Those authors mentioned that at high soil water contents values, there no difference between treatments. The higher D and S values in T2 can be attributed to the crop. The maize roots are

Table 2. Sorptivity (S, $cm.s^{-1/2}$) and diffusivity (D, $cm^2.s^{-1}$) at different soil water contents (θ: 0.1, 0.2, 0.3 y 0.4 $m^3.m^{-3}$) ($D_{10\%}$, $D_{20\%}$, $D_{30\%}$, and $D_{40\%}$, respectively), depending on the treatment (T1: Natural grassland, T2: direct drilling mayze, and T3: Polyphitic Pasture).

Treatment	S	$D_{10\%}$	$D_{20\%}$	$D_{30\%}$	$D_{40\%}$
T1	0.1027a	0.000095a	0.000475a	0.002594a	0.01564a
T2	0.1571b	0.000419b	0.001682b	0.007125b	0.03213a
T3	0.0972a	0.000033a	0.000261a	0.002219a	0.02135a

Different letters in the same column means significant differences between treatments for the correspondent parameter (SNK test, $p = 0.05$).

strong and create continuous macropores that improve the soil water movement (Lozano et al., 2014). Also, S and D followed the same trend, showing that both parameters are related and represent the water flow under unsaturated conditions.

Conclusions

The use of a simple and low cost lab setup with the use of water content sensors that measures the dielectric constant of the media (capacitive sensors) allowed determining D (θ) function in a simple and consistent way that includes the possibility of testing the suitability and applicability of the diffusivity theory for the studied soil.

Soil water diffusivity (D) and Sorptivity depends on the soil productive situation, being negatively affected by soil activities that include cattle grazing.

The proposed method is a reliable way to estimate D in a low cost and consistent way. The results also improve the knowledge about the effects of different soil productive situations systems on unsaturated water flow, with emphasis on S and D.

Future studies should focus on the development of field determination of D in a reliable way, including temporal variation of this variable, as well as the relationship between this parameter and other soil physical properties related to water flux.

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