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Short-Term Effect of Tillage Methods, Residue Levels, and Forward Speeds on Soil-Water Characteristic Curve (SWCC): A Case Study on the Eastern Soils of Karun River, Khuzestan Province, Iran

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Abstract

The current study was conducted to investigate the effect of tillage methods, residue rates, and forward speeds on the soil-water characteristic curve (SWCC) of Haploustepts soil over the course of one crop year (2014-2015). The treatments consisted of conventional mechanized tillage (CT: moldboard plough+disc) and reduced tillage (RT1: chisel peker+plough and RT2: combined tillage), different surface residues, including three levels of no residue, 40% residue, and 80% residue, and forward speeds at three levels: low (4 km/h), normal (7 km/h), and high (10 km/h). The experimental water retention data were fitted to uni-modal van Genuchten (termed uni-modal vG) and bi-modal Dexter (termed bi-modal Dex) models. No significant impact was observed on different physical parameters, except for parameter n. In the slope at the inflection point of SWCC, 11.8% and 8.9% reductions were observed in CT and RT1 treatments, respectively, compared to RT2. Based on the results, α measured under CT tended to be higher than that of other tillage treatments. Residual covers and higher forward speeds tended to increase both α and n. Changes in PSD were more pronounced in larger (macro) and medium (meso) pore diameter classes. The highest value of structural void ratio as transmission pores was observed in RT2. This finding indicates that with respect to PV_1, PV_2, h_1, and h_2 values, the soil PSD descriptive system is a bi-peak distribution such as H-L; therefore, due to the hierarchical nature of soil structure, van Genuchten equation cannot appropriately describe multi-modal soils inherently

Keywords: Inceptisols; Tillage; Soil hydraulic properties; Soil pore size distribution

1. Introduction

Over the recent decades, there has been an increase in documented research, particularly on various tillage practices generally comparing conventional mechanized tillage and no-tillage (Blanco-Canqui et al., 2017). This increase has led to scientists and producers' profound insight into the obtained results, changes in soil properties, and crop production (Blanco-Canqui et al., 2011). Recently, the capabilities of modern technologies in applying precision agriculture, managing efficient resources, and increasing yield production efficiency have enhanced our understanding and ability to investigate tempo-spatial variability of soil hydraulic properties (Strudley et al., 2008; Busari et al., 2015). Due to their repeated application, effective depth range extending up to tens of centimetres, and impact on type and residue management, tillage practices are deemed as the most important method for manipulating or changing the physical properties of agriculture soils (Blanco-Canqui et al., 2017). Accordingly, deliberate tillage practices in response to the tempo-variability of soil hydraulic properties can offer significant advantages, particularly in regions suffering from ineffective performance and resources (Raper et al., 2000; Strudley et al., 2008).

Khuzestan plain is the result of heavy textured sediments in Karun, Dez, and Karkheh river deltas which have a weak vegetation and low organic matters due to their arid and semi-arid climate and low annual rainfall. On average, less than 1% of organic matter exists in soil, bringing

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about numerous problems. Therefore, in spite of their high fertility, the Khuzestan soils have variable physical qualities under the influence of the existing conditions.

McKenzie et al. (2014) stated that soil physical quality is its ability to provide water and aeration for plants and eco-system over a period of time as well as resistance and recovery from processes limiting this ability. The most important indicators of soil physical quality, including plant-available water capacity, air capacity, macro-porosity, bulk density, organic matter content, and soil structural conditions are strongly influenced by management operations such as planting type and agricultural wheel traffic (Kiblwhite et al., 2008; Reynolds et al., 2009; Naderi Boldaji and Keller, 2016). The recent efforts to introduce a unique index of soil physical quality, able to reflect soil physical essence and compare soils in different conditions, have led researchers to employ soil water characteristic curve (SWCC) (Dexter, 2004 a, b, c; Keller et al., 2007; Li et al., 2011; Naderi Boldaji and Keller, 2016). SWCC describes the relationship between water content and matrix potential/suction and has been introduced as "the most important curve in soil physics" owing to its myriad applications in agriculture and the environment (Vogel, 2014; Hernandez, 2011; Vero et al., 2016).

Numerous studies have been conducted on the effect of different tillage system types and crop residue levels on the changes in soil physical properties (Strudley et al., 2008; Alvarez and Steinbach, 2009; Sharma and Abrol, 2012; Busary et al., 2015; and other references); however, only studies have focused on the effect of tillage system and residue cover on SWCC (Mahboubi et al., 1993; Abid and Lal, 2009; Schwen et al., 2011; Hartmann et al., 2012; Pena-Sancho et al., 2016). Mahboubi et al. (1993) in a 28 years long term experiment found that no-tillage resulted in higher water retention ability at saturation compared with conventional tillage on a silt loam soil in Ohio. In a 14-year-old experiment on an Ochraqualf soil, Abid and Lal (2009) reported that no-tillage had non-significant effect on water retention ability at saturation; however, the effect was significant at 30, 60, 100, 300, 1000 and 3000 cm water suctions. Pena-Sancho et al. (2016) found that no-tillage resulted in lower α van Genuchten (1980) SWCC parameter and higher soil physical quality (S-index) compared with conventional tillage after 23 years of tillage in a semiarid dryland. However, there is no documented research into the effect of forward speed of tillage implements on the changes in soil physical properties. The overall objectives of this work were to investigate the impacts of various short-term tillage experiments, residue levels, and forward speeds on (1) SWCCs obtained by uni-modal van Genuchten (termed uni-modal vG) and bi-modal Dexter (termed bi-modal Dex) models, (2) soil physical quality, (3) residual, matrix, and structural void ratios, and (4) capability of uni- and bi-peak pore size distribution (PSD) curves to describe the resulting changes.

2. Materials and Methods

2.1. Study area

The current study was conducted over one crop year (2014-2015) in the research station of Ramin Agriculture and Natural Resources University of Khuzestan, Ahvaz, Iran (latitude: 31°36' N, longitude: 48°53' E, and altitude: 24 m). The climate is considered to be BWh according to the Köppen-Geiger climate classification with long and extremely hot summers and mild and short winters. According to the nearest meteorological station, the annual precipitation and temperature in the region add up to approximately 215 mm and 25 °C, respectively, and rainfall occurs mainly in January. The soil temperature and moisture regimes are hyperthermic and ustic, respectively. The soil at the experimental site was classified according to US Soil taxonomy (Soil Survey Staff, 1996) as Haploustepts. Due to the insignificant effect of soil formation factors, these soils are young and generally lack diagnostic and genetic soil horizons; moreover, in the majority of these soils, surface horizons do not undergo major changes in comparison to sub-surface horizons. The soil composition of 0-10 cm depth comprises 21% sand, 37% silt, 42% clay, pH of 7.6, and electrical conductivity of a saturated soil extract (EC_e) equal to 5.3 dS m^{-1}.

2.2. Experimental design

The field layout comprised a split-split-plot experiment arranged in a Randomized Complete Block Design with three replications involving three factors: I. tillage methods (CT: conventional mechanized tillage consisting of moldboard plough up to a depth of 30cm + offset disc with a maximum depth of 17cm to prepare the seedbed for planting, RT1: reduced tillage comprised of chisel plough (non-inverting action) up to a depth of 20cm, and RT2: reduced tillage using combined tillage (DELTA 5 HSP 220, non-inverting action) up to a depth of 30 cm) as the main plot; II. residue covers (no residue, 40% residue, and 80% residue) as the subplot, and III. forward speeds (low: 4 km/h, normal: 7 km/h, and high: 10 km/h) as the sub-subplot. Each plot was 3m × 20m considering the width of the utilized implements. Spring bread wheat (Triticum aestivum L.) was sown around December 2014 with the simultaneous incorporation of a chemical fertilizer. Harvesting operations were performed around April 2015. A quantitative assessment of crop residue levels was made by the line-transect method which has emerged as the preferred method for field use. This procedure involves stretching a line diagonal to the crop rows and recording whether or not residue intersects the line at specified points (Laflen et al., 1981; Laamrani et al., 2017). The site showed homogenous soil properties since it was conventionally tilled for > 30 years prior to the experiment setup. The cropping history included wheat, soybean, maize, and alfalfa.

2.3. Sampling

All measurements were included within an area of ≈ 2 m^2 defined outside the wheel tracks at two points of each sampling site. For each treatment, three undisturbed soil samples were obtained by sharp-edged steel cylinders (5 cm in height and diameter) with 98.2 cm^3 volume at 0–10 cm depth for bulk density and lower suctions (≤100 cm) of SWCC in late December 2015 (at the end of fallow). In addition, to measure SWCC at higher suctions (>100 cm), we used steel cylinders with a height of 2 cm high, a diameter of 6 cm, and a volume of 56.5 cm^3 . Determination of organic matter (OM) was performed on soils passed through a 0.5 mm sieve. The samples were carefully transported to avoid disturbance and stored in plastic bags in a cool room until required for measurement in the laboratory.

2.4. Determination of soil water characteristic curve (SWCC)

Undisturbed soil samples were saturated by capillary rise and successively drained to fixed soil water suctions (h) of 10, 20, 50, and 100 cm using the Haines apparatus suction method. Measurement of the rest of SWCC continued at suctions of 330, 1000, 5000, 10000, and 15000 cm by a pressure plate apparatus. Following equilibration, the samples were weighed before and after drying in an oven at 105 °C for 24 h, and gravimetric water contents were calculated. In accordance with Dexter et al. (2008), the time required to reach equilibrium moisture content was considered between 2 to 14 days depending on the applied suction.

2.5. Uni-modal vG SWCC

2.5.1. Soil physical quality index

There are many mathematical functions for describing SWCC, among which uni-modal vG equation (1980) has been extensively employed; also, Dexter (2004a) founded his S-theory upon this equation:

$$\Phi = \left[\frac{1}{1 + (\alpha h)^n}\right]^m \quad (1)$$

where α, n, and m are the equation parameters. α is the reverse of air-entry value (cm^{-1}), and n (-) is proportional to the slope of SWCC. Φ is normalized water content (-) and equal to $(w - w_r)/(w_s - w_r)$ where w_s and w_r represent gravimetric water content at the saturation point (h → 0) and residual gravimetric water content (h → ∞) (g g^{-1}), respectively. n and m parameters are generally utilized in conjunction with the Mualem (1976) restriction, m = 1- (1/n). Dexter and Bird (2001) and Dexter (2004a, b) introduced the slope of the SWCC at its inflection point as an index of soil physical quality.
According to Dexter and Bird (2001), water suction (h_i), gravimetric water content (w_i), and slope (S) at the inflection point of SWCC can be obtained as follows:

$$h_i = \frac{1}{\alpha}\left[\frac{1}{m}\right]^{1/n} \quad (2)$$

$$w_i = (w_s - w_r)\left[1 + \frac{1}{m}\right]^{-m} + w_r \quad (3)$$

$$S = -n(w_s - w_r)\left[\frac{2n-1}{n-1}\right]^{\left(\frac{1}{n}-2\right)} \quad (4)$$

To optimize the parameters of uni-modal vG equation (van Genuchten, 1980), including n, m, α, w_s, and w_r, we employed the soil physics package, which was proposed by de Lima et al. (2016) in the R programming environment (https://www.r-project.org). In this software package, the method applied to optimize the unknown model parameters from observed water retention data is the nonlinear (weighted) least-squares approach on the basis of the Gauss-Newton algorithm.

2.5.2. Soil PSD curves

Dexter (2004c) stated that representing water content according to the logarithmic expression of the suction is the most optimal state for determining the PSD curve and S index. According to Dexter (2004c), if an increment in water suction, Δh, is applied to the soil, then a volume of water will be drained. This amount of change in suction has a much higher effect on reducing soil water in low suctions compared to higher one. Therefore, it is preferred that the changes in suction be considered as $\Delta(\ln h)$. Based on what was mentioned above, the slope of the water characteristic curve will be equal to $dw/d\ln(h)$. The water suctions are converted into pore radius (r) values using the relation $r = 1490/h$, with r and h given in µm and cm, respectively. Following this transformation, $dw/d\ln(h)$ vs. ln r represents the PSD plots.

Despite the numerous systems for describing soil pore size classification, no standardized system is currently in use. Here, we classified the pore size based on da Veiga et al. (2008) as follows: (I) macro-porosity (macroP, transmission pores) corresponds to the difference in volumetric water content between saturated condition and 60 cm and is equivalent to the pores with diameters larger than 50 µm; II) meso-porosity (mesoP, storage pores) corresponds to the difference in volumetric water content between 60 and 14540 cm and is equivalent to pores with diameters ranging from 0.2 to 50 µm.

2.6. Bi-modal Dex SWCC

2.6.1. Structural, matrix, and residual void ratio

Dexter et al. (2008) believed that the parameters of uni-modal vG equation are almost completely inter-dependent. On the other hand, this equation often predicts the negative values of residual water content and has an unsuitable fit of water retention data for soils with clear bi-modal PSD. Based on this belief and through considering the hierarchy of compound particles, Dexter et al. (2008) presented the following double-exponential SWCC equation which is comprised of three stages: I) formation of micro-aggregates from a group of particles, II) formation of aggregates from a group of micro-aggregates, and III) formation of bulk soil from a group of aggregates:

$$w = C + A_1 \exp\left(-\frac{h}{h_1}\right) + A_2 \exp\left(-\frac{h}{h_2}\right) \quad (5)$$

where w represents water content (g g^{-1}) and C indicates residual porosity (g g^{-1}). The residual porosity is equal to the water fraction that remains in the soil as the applied suction increases toward infinity (the asymptote of the equation). A_1 and A_2 represent matrix and structural porosity (g g^{-1}), respectively. Furthermore, h_1 and h_2 indicate the suction value (cm) where the matrix and structural pore spaces are discharged, respectively. Accordingly, the second and third expressions in Eq. (5) represent a change of moisture in the matrix and structural pore spaces under the influence of suction changes, respectively (Dexter et al., 2008).

In the current study, the soil physics package was employed to optimize bi-modal Dex SWCC parameters (Dexter et al., 2008) (Eq. 5), including C, A_1, A_2, h_1, and h_2. To quantitatively analyze the comparisons drawn between different experimental treatments, the following dimensionless parameters can be defined based on the bi-modal SWCC equation (Ding et al., 2016):

$$S_r = \frac{C}{\emptyset} \quad (6)$$

$$S_m = \frac{A_1}{\emptyset} \quad (7)$$

$$S_s = \frac{A_2}{\emptyset} \quad (8)$$

where $\emptyset (g\,g^{-1})$ is the actual sum of C, A_1, and A_2 parameters. Therefore, S_r, S_m, and S_s represent residual, matrix, and structural void ratios, respectively.

2.6.2. Soil PSD curves

Soil PSD based on Eq. 5 can be obtained as follows:

$$\frac{dw}{d\ln(h)} = \left[-\frac{A_1}{h_1}\exp\left(-\frac{h}{h_1}\right) - \frac{A_2}{h_2}\exp\left(-\frac{h}{h_2}\right)\right] \times h \quad (9)$$

The peak value (PV), reflecting the height of the peak on the PSD curve, can be interpreted as an index according to the statements made by Ding et al. (2016). The PVs for each treatment can be calculated through substituting the related parameters (A_1, A_2, h_1, h_2) into Eq. 9, where PV_1 at h_1 and PV_2 at h_2 indicate matrix (textural) and structural peaks, respectively. When soil PSD conforms to mono-peak distribution, $PV_1 = PV_2$ and $h_1 = h_2$. When $PV_1 \neq PV_2$ and $h_1 \neq h_2$, the bi-peak distribution could be divided into two situations, namely high structural peak-low matrix peak (H-L) and low structural peak-high matrix peak (L-H). Ding et al. (2016) continued their classification as follows: when the related PSD is H-L and $|PV_1 - PV_2| \geq 0.043$, this system is called high structural peak-extremely low matrix peak (H-EL). When the related PSD system is L-H and $|PV_1 - PV_2| \geq 0.043$, the system is called extremely low structural peak-high matrix peak (EL-H).

3. Results and Discussion

The analyses of variance for various soil physio-hydraulic properties are shown in Tables 1-3. Generally, significant effects ($p<0.5$) were not found in most of considered soil properties except OM and n parameter. However, considering the dynamic variability of the soil properties (Voorheese and Lindstron, 1984), the patterns in results were discussed in below. Mean values of considered soil physic-hydraulic properties affected by tillage methods, residue levels, and forward speeds are presented in Table 4.

Table 1. Analysis of variance (ANOVA) of the effects of tillage methods (T), residue covers (RC) and forward speeds (FS) on soil bulk density (BD), soil organic matter (OM), macro-porosity (macroP), and meso-porosity (mesoP)

Source of variations	df	Mean squares			
		BD	OM	MacroP	MesoP
		g cm^{-3}	%	cm^3 cm^{-3}	
T	2	0.00396^{ns}	0.00938^{ns}	0.00058^{ns}	0.00131^{ns}
Error (A)	4	0.00712	0.00220	0.00155	0.00395
RC	2	0.00714^{ns}	0.02700^{*}	0.00315^{ns}	0.00126^{ns}
T * RC	4	0.00743^{ns}	0.03241^{**}	0.00133^{ns}	0.00528^{ns}
Error (B)	12	0.00518	0.01248	0.00144	0.00565
FS	2	0.00876^{ns}	0.00138^{ns}	0.00100^{ns}	0.00313^{ns}
T * FS	4	0.00416^{ns}	0.00581^{ns}	0.00134^{ns}	0.01207^{ns}
RC * FS	4	0.00424^{ns}	0.00298^{ns}	0.00131^{ns}	0.00444^{ns}
T * RC * FS	8	0.00644^{ns}	0.01374^{ns}	0.00139^{ns}	0.00447^{ns}
Error (C)	36	0.00606	0.00819	0.00135	0.00587
CV (%)		5.1	6.8	45.9	22.0

* and ** stand for significant at $p < 0.05$ and 0.01 probability levels, respectively. ^{ns} Not significant

Table 2. Similar to Table 1, but for water suction at the inflection point (h_i), the slope of SWCC at its inflection point (S) and parameters of α and n in uni-modal vG equation

Source of variations	df	Mean squares			
		Uni-modal van Genuchten			
		h_i	S	α	n
		cm	-	cm^{-1}	-
T	2	8589^{ns}	0.00089^{ns}	0.00061^{ns}	0.1645^{*}
Error (A)	4	10255	0.00063	0.00075	0.1046
RC	2	7010^{ns}	0.00057^{ns}	0.00061^{ns}	0.0168^{ns}
T * RC	4	5051^{ns}	0.00019^{ns}	0.00059^{ns}	0.0054^{ns}
Error (B)	12	12749	0.00082	0.00051	0.0410
FS	2	5132^{ns}	0.00084^{ns}	0.00031^{ns}	0.1141^{ns}
T * FS	4	6584^{ns}	0.00044^{ns}	0.00087^{ns}	0.0411^{ns}
RC * FS	4	7635^{ns}	0.00017^{ns}	0.00071^{ns}	0.0184^{ns}
T * RC * FS	8	8969^{ns}	0.00045^{ns}	0.00053^{ns}	0.0216^{ns}
Error (C)	36	9778	0.00050	0.00059	0.0378
CV (%)		75	26.1	115.6	21.2

* and ** stand for significant at $p < 0.05$ and 0.01 probability levels, respectively. ^{ns} Not significant

Table 3. Similar to Table 1, but for structural (S_s), matrix (S_m) and residual (S_r) void ratios and the suction values where matrix (h_1) and structural (h_2) pore spaces are discharged in bi-modal Dex equation

Source of variations	df	Mean squares				
		Bi-modal Dexter				
		S_s	h_2	S_m	h_1	S_r
		-	cm	-	cm	-
T	2	0.00380^{ns}	3725^{ns}	0.00157^{ns}	1733^{ns}	0.00890^{ns}
Error (A)	4	0.00299	3511	0.00055	6120	0.00227
RC	2	0.00704^{ns}	3178^{ns}	0.00113^{ns}	6295^{ns}	0.00438^{ns}
T * RC	4	0.00469^{ns}	4833^{ns}	0.00067^{ns}	2156^{ns}	0.00478^{ns}
Error (B)	12	0.00503	3427	0.00034	1977	0.00630
FS	2	0.00105^{ns}	3003^{ns}	0.00005^{ns}	1000^{ns}	0.00072^{ns}
T * FS	4	0.00392^{ns}	3697^{ns}	0.00028^{ns}	1881^{ns}	0.00277^{ns}
RC * FS	4	0.00853^{ns}	4264^{ns}	0.00015^{ns}	1638^{ns}	0.00813^{ns}
T * RC * FS	8	0.00191^{ns}	3212^{ns}	0.00074^{ns}	6984^{ns}	0.00244^{ns}
Error (C)	36	0.00535	4079	0.00067	1255	0.00607
CV (%)		19.3	29.2	9.8	92.2	21.7

* and ** stand for significant at $p < 0.05$ and 0.01 probability levels, respectively. ^{ns} Not significant

3.1. Uni-modal vG SWCC

3.1.1. MacroP

MacroP values in the tillage treatments, averaged for the residue levels and forward speeds, were in the following order: $RT1 = CT > RT2$. The data in Table 4 clearly show that over the one crop year, macroP in plots undergoing CT and RT1 increased by approximately 9% compared to RT2 (average of all residue levels and forward speeds). Such pores play an important role in transferring water. The presence of residue covers (average of all tillage systems and forward speeds) increased macroP in the order: $RC80 = RC40 > RC0$. As an example, 27.4% reduction was observed in soils under RC0 compared to RC40.

Table 4. Mean comparisons of soil organic matter (OM), bulk density (BD), macro-porosity (MacroP), meso-porosity (MesoP), and parameters of uni-modal vG and bi-modal Dex models as affected by tillage methods, residue levels, and forward speeds.

Properties	Treatments								
	Tillage methods			Residue levels			Forward speeds		
	CT	RT1	RT2	RC0	RC40	RC80	Slow	Normal	Fast
BD (g cm^{-3})	1.51^{b}	1.53^{ab}	1.54^{a}	1.54^{a}	1.51^{b}	1.52^{b}	1.53^{b}	1.54^{a}	1.51^{c}
OM (%)	1.32	1.32	1.35	1.31	1.31	1.37	1.33	1.32	1.33
MacroP (cm^{3} cm^{-3})	0.125^{b}	0.127^{b}	0.115^{a}	0.106^{b}	0.135^{a}	0.126^{a}	0.112^{b}	0.129^{a}	0.126^{a}
MesoP(cm^{3} cm^{-3})	0.341^{b}	0.351^{ab}	0.341^{b}	0.357^{a}	0.344^{a}	0.346^{a}	0.361^{a}	0.347^{ab}	0.339^{b}
Uni-modal vG									
h_i (cm)	151^{a}	116^{b}	129^{b}	113^{b}	138^{a}	144^{a}	139^{a}	116^{b}	141^{a}
S (-)	0.082^{b}	0.084^{b}	0.093^{a}	0.081^{b}	0.089^{a}	0.088^{a}	0.080^{c}	0.087^{b}	0.091^{a}
α (cm^{-1})	0.026^{a}	0.021^{ab}	0.016^{b}	0.017^{b}	0.026^{a}	0.019^{b}	0.018^{b}	0.020^{b}	0.025^{a}
n (-)	1.53^{b}	1.55^{b}	1.68^{a}	1.56^{b}	1.61^{a}	1.61^{a}	1.51^{a}	1.61^{a}	1.64^{a}
Bi-modal Dex									
S_s (-)	0.383^{a}	0.365^{b}	0.383^{a}	0.360^{b}	0.387^{a}	0.388^{a}	0.374^{a}	0.376^{a}	0.385^{a}
h_2 (cm)	12.84^{b}	17.59^{b}	35.14^{a}	16.9^{b}	14.4^{b}	34.3^{a}	18.4^{b}	33.7^{a}	13.5^{b}
S_m (-)	0.260^{b}	0.258^{b}	0.272^{a}	0.268^{a}	0.256^{b}	0.265^{a}	0.265^{a}	0.263^{a}	0.262^{a}
h_1 (cm)	833^{b}	1374^{a}	883^{b}	948^{b}	1253^{a}	888^{b}	1049^{a}	878^{b}	1162^{a}
S_r (-)	0.358^{b}	0.377^{a}	0.341^{c}	0.371^{a}	0.357^{ab}	0.346^{b}	0.361^{a}	0.361^{a}	0.352^{a}

In each row, numbers with different letters indicate significant differences (LSD, $p < 0.05$).

The pattern of forward speeds was: high = normal > low. In other words, the concentration of macropores was greater at higher speeds. For instance, macroP in normal forward speed of implements was 15% higher than that in low forward speeds. Wheel traffic is a factor that can be investigated in this field.

Comia et al. (1994) reported that total porosity and water transfer pores (> 50μm) were higher at 25 cm soil surface in the layer ploughed by the conventional method compared with conservation method. They observed that the above-mentioned pattern could be reversed in the sub-surface layer. Noteworthy, many researchers have reported dynamic changes in PSD (Voorheese and Lindstron, 1984; Staricka et al., 1991; Mahboubi et al., 1993; Lal et al., 1994; Kay and Vanden Bygaat, 2002; Green et al., 2003; Strudley et al., 2008). Kay and Vanden Bygaat (2002) stated that the dynamic changes in total porosity during ploughing practices would ultimately reach a stable state. Based on their findings, in less-than-10-year periods, total porosity was often lower in no-tillage compared to conventional tillage. Therefore, as observed, macroP, created during the loosening of soil due to CT for one crop year, is still stable. It appears that despite the high amount of clay (42%) in the studied soils, weather conditions were effective in this case. In the study of Pena-Sancho et al. (2016), there were insignificant differences in bulk density measured in fields conventionally tilled by moldboard plough in two periods, after primary tillage but before any post-tillage rainfall events and after the first seasonal rainfall. They attributed these differences to the insufficient rainfall (25 mm) for soil reconsolidation. In contrast, the total rainfall of 97 mm during the late fallow period was able to return the soil under conventional and reduced tillage to pre-tillage bulk density values. Residue covers further reduced the destructive effects on soil fabric (Prosdocimi et al., 2016). Soil water retention data (not shown) indicated that approximately 45% of the total water held in soil in zero suction was depleted after reaching field capacity point (330 cm water suction). This rate of moisture depletion in 50 cm suction reached the approximate rate of 13%.

3.1.2. MesoP

According to Greenland (1977) and da Veiga et al. (2008), pores with diameter ranges of 0.5 to 50 μm and 0.2 to 50 μm, respectively, were storage pores and an available source for plants and microorganisms. The data in Table 4 show that low forward speeds, more effective than other treatments, increased mesoP by approximately 0.022 cm^3 cm^{-3} (average of all tillage systems and residue levels). da Veiga et al. (2008) found that the most significant change in PSD affected by different tillage treatments was under the influence of changes in macro- and meso-pores.

The results showed that after one crop year, the pattern of changes in meso-pores was the reverse of those in macro-pores. In other words, CT with high forward speed increases macroP (transmission pores) and reduce mesoP (pores holding available water for plants). Bhattacharyya et al. (2006) reported that effective porosity (volume fraction of total porosity with pores < 7.5 μm in diameter), associated with the retention of available water for plant use, was 0.079 cm^3 cm^{-3} under reduced tillage conditions and 0.071 cm^3 cm^{-3} under no-tillage conditions more than that of conventional tillage four years prior to the experiment.

3.1.3. Water suction at the inflection point (h_i)

Averaged for the residue levels and forward speeds, the values of water suction at the inflection point (h_i) in tillage treatments, were in the following order: $RT2 = RT1 < CT$ (see Table 4). Increasing the residual covers increased h_i values in the order: $RC80 = RC40 > RC0$. No specific pattern was observed in forwarding speeds treatment. Abu and Aboubakar (2013) reported similar findings related to the four systems of no-tillage, reduced tillage, contour ploughing, and conventional tillage.

Dexter and Bird (2001) explained that inflection point is a point where the pores filled with air are continuously expanded throughout the soil sample. The expansion of such regions in the soil increases soil friability, thereby introducing the optimum water content for tillage. Under such conditions, the tillage practice generates the highest amount of small aggregates and the lowest amount of large clods. Based on the capillarity relation ($d = 4\sigma/h$), increased water suction at the inflection point in soils undergoing CT treatment, reduces the equivalent diameter of pores with sizes around the inflection point. As shown by the pore classification in this study, such pores are usually macro-pores and micro-cracks with a diameter of approximately 50 μm.

Although soil loosening caused by CT practices can increase pore size, it significantly reduces pore continuity. The reduction in continuity would increase tortuosity and dead-end pores (Zachamann et al., 1987; Hussain et al., 1998). Douglas and Goss (1987) and Zangiabadi et al. (2019) reported that pore size and pore continuity (parameters on which fluid transmission characteristics depend) were among the most important soil physical properties for plant growth. Kay (1990) found that ploughing could disturb pore continuity, particularly in a ploughed area or even between a ploughed area and an un-ploughed one. Schjonning (1989) showed that reduced tillage augmented pore continuity and reduced tortuosity in pores larger than 200 μm compared to conventional tillage. Chen et al. (2014) reported that air permeability at 0-12 cm soil depth was reduced with the level of compaction. This reduction was associated with increased pore tortuosity and reduced pore continuity. MicroCT visualization and quantification of large pores carried out by Dal Ferro et al. (2014) showed that pore connectivity in the shallower layer (0-10 cm) was higher in the no-tillage treatment whereas conventional tillage disrupted the pore connectivity and reduced the pore branch length.

3.1.4. The slope of SWCC at its inflection point (S)

Based on a series of articles and by considering the amounts of clay, organic matter, bulk density, rootability, optimum moisture in agricultural practices, and soil hydraulic conductivity as the physical parameters, Dexter (2004a, b, c) presented his classification for the slope of SWCC at its inflection point (S) as an index of soil physical quality as follows: I. S < 0.02 shows extremely weak physical quality, II. 0.02 < S < 0.035 indicates weak physical quality, and III. S > 0.035 implies good physical quality. Based on the above-mentioned fact, all the values presented in Table 4 showed good physical quality in the studied soils. The S values in the tillage treatments, averaged for the residue levels and forward speeds, showed an increase in RT2 soils compared to RT1 and CT. Residual covers and higher forward speeds further increased the S index. Based on the studies performed by Shanmuganathan and Oades (1982) and Czyz et al. (2002), soils with high clay content (such as those studied in the present research) are ready for clay dispersion of soil aggregates, particularly when soil organic carbon is low and ploughing practices are conducted in inappropriate moistures. According to Dexter (2004b), such soils would have lower physical quality. Intensive ploughing practices also lead to reduced soil physical quality. As stated by Dexter (2004b), soils which underwent CT and handdrug operations for 120 years, had S values of 0.027 and 0.058, respectively. This clearly shows the effect of soil stress on the S value. The findings of Abu and Aboubakar (2013) revealed that S in loam textured soils and the great group of Haplustalfs undergoing no-tillage technique was 7.9%, 11.5%, and 18.3% (at 0-5 cm depth) and 0.1%, 1.6%, and 4.5% (at 5-15 cm depth), which was more than that of reduced tillage, contour tillage, and conventional tillage, respectively. In their study on Aridosols, Emami et al. (2012) found a significantly positive correlation between S values and available water. da Silva et al. (1994) and Tormena et al. (1999) had previously introduced available water as a soil physical quality index.

3.1.5. Parameters α and n

Averaged for the residue levels and forward speeds, the α values in tillage treatments were in the following order: CT = RT1 > RT2. Parameter n followed a reverse pattern, but CT and RT1 had similar values. Residue covers and forward speeds affected parameter α in (RC40 > RC80 = RC0) and (high > normal = low) orders. The highest α value in RC40 cover (average of all tillage systems and forward speeds) was 53% higher than the lowest α value in RC0 condition. The higher amount of residue covers and forward speeds tended to increase parameter n. The maximum α value in high forward speed treatment (average of all tillage systems and residue levels) was 35% higher than its minimum value in low forward speed treatment. These results are in agreement with the report of Pena-Sancho et al. (2016) on the reduction in parameter α under conservation tillage due to lower mechanical disturbance. However, Pena-Sancho et al. (2016) found a lower n value under conservation tillage. Higher values of parameter n reflected steeper SWCC (Fig. 1a-c) (Mallants et al., 1996). Schwen et al. (2011a, b), after ploughing, detected a significant difference in parameter α but insignificant differences in parameter n. Schwen et al. (2011a, b) stated that the changes in α were anticipated due to the effect of large pores and soil structure. Although parameter n is generally under the influence of soil texture, significant changes are not expected.

3.1.6. Uni-peak PSD curves

Figures 1 and 2 show SWCCs and the corresponding PSD curves based on uni-modal vG and bi-modal Dex models, respectively. According to PSD curves shown in Fig. 2a-c, changes in PSD were more pronounced in larger (macro) and medium (meso) pore diameter classes.

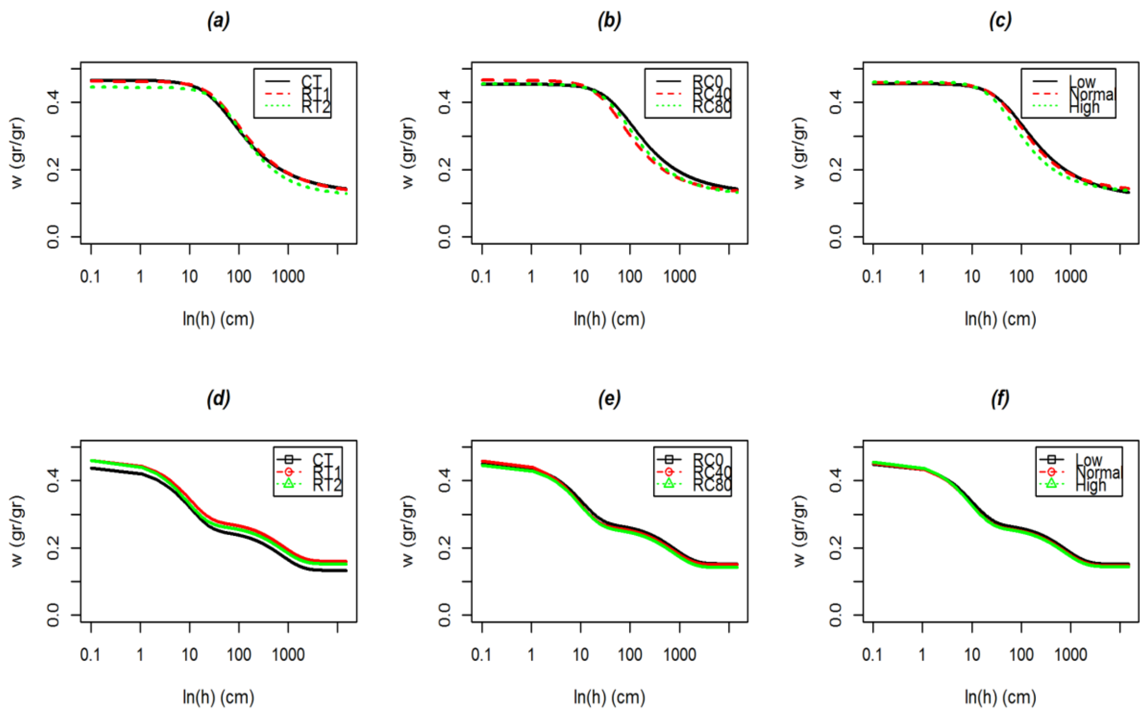

Fig. 1. Effects of tillage treatment, surface residue levels, and forward speeds on the SWCCs obtained by uni-modal vG and bi-modal Dex models

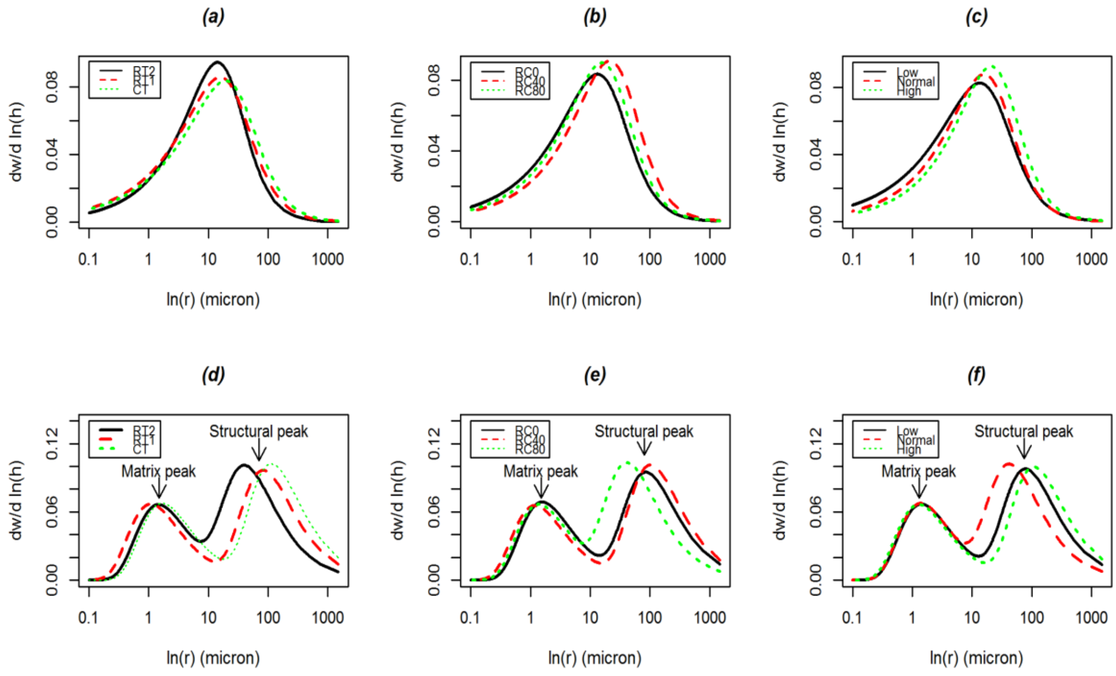

Fig. 2. Similar to Fig. 1 but for pore size distribution (PSD) curves obtained by uni-modal vG and bi-modal Dex models

Based on uni-peak PSD curves, forward speed and residue level treatments played a more important role than tillage systems regarding the short-term changes in PSD. From a dynamics perspective, it can be concluded that short-term changes made in pore system geometry and configuration (including size distribution, shape, orientation, and continuity) under the influence of machine traffic and compaction stress have more stability in comparison with the soil loosening caused by tillage techniques. Alakoko (1996) reported that soil compaction below 10 cm could persist for three years despite cropping, deep cracking, and freezing. Berisso et al. (2012) showed that the soil PSD changes caused by agricultural machinery and compaction stresses might persist for at least 14 years, negatively affecting air permeability and gas diffusivity.

3.2. Bi-modal Dex SWCC

3.2.1. Structural void ratio (S_s)

According to the results shown in Table 4, the S_s values in the tillage treatments, averaged for the residue levels and forward speeds, were in the following order: RT2 $=$ CT $> RT1$. In addition, the treatment residue levels, averaged for the tillage systems and forward speeds, increased S_s in the order: RC80 $=$ RC40 $> RC0$, and there was no difference between the treatments of forwarding speeds. The h_2 values (pore water suction at which the structural pore spaces empty) in the tillage treatments, averaged for the residue levels and forward speeds, were in the following order: RT2 $> RT1 =$ CT. It can be concluded that the soils under $RT2$ had structural pores with larger size distribution heterogeneity compared with CT. The highest h_2 value, averaged for the tillage systems and forward speeds, was 34.30, appearing at 80% residue level. Normal forward speed, averaged for the three residue level applications and tillage methods, had the maximum h_2 amount, 33.70 cm. One also should not overlook the fact that the large and non-stable pores result from loosening of soil during conventional mechanized practices may be considered as structural porosity and the SWCC equations fail to specify any difference between these pores and real structural pores. As shown by Ding et al. (2016), both macro-pores and pores around sand particles may represent the structural pore space.

Given the above-mentioned points, it can be concluded that combined tillage, a higher amount of residue cover, and a higher forward speed with the least destructive effects on soil aggregates can generate the largest number of structural pores with greater size distribution heterogeneity. Pagliai et al. (1995) reported that the size distribution of macropores was more homogeneous at 10 cm soil depth of in a no-tillage system.

Soil bi-peak PSD curves shown in Fig. 2d-f are related to tillage treatments, residue levels, and forward speeds, respectively. The curves are double-exponential and have structural and matrix peaks. The structural peak shifting to the right increases the size of pores in this category. For instance, the structural peak shifting to the right due to soil loosening in CT (Fig. 2d) indicates that structural pores created in these conditions were larger in mean size compared with those generated in RT1 and RT2. According to the PSD curves shown in Fig. 2d-f, the changes in PSD were more pronounced in structural pores (macro-pores) which are usually active as transmission pores. Accordingly, the mean sizes of structural pores were 38, 82, and 110 µm in RT2, RT1, and CT, 80, 100, and 40 µm in RC0, RC40, and RC80, and 75, 40, and 105 µm in low, normal, and high forward speed treatments, , respectively.

3.2.2. Matrix void ratio (S_m)

According to the results tabulated in Table 4, the S_m values in the tillage treatments, averaged for the residue levels and forward speeds, followed$\mathrm{RT2} > \mathrm{CT} = \mathrm{RT1}$ order. Moreover, no specific pattern was detected in relation to residue levels and forward speeds. Ding et al. (2016) further introduced this category of pores (matrix pores) as pores among silt particles. Nevertheless, it appears that micro-aggregates with the same size as silt particles are also able to generate such pores. Given the complex nature of the soil and lack of pure ideal states, macro-pores filled with smaller particles are no exceptions to this rule. It seems that the breakdown of aggregates influenced by intensive ploughing and leveling practices cannot generally lead to the production of matrix pores. Increased proportion of matrix pores can augment the quantity of water available for plants. Therefore, soil conditions under a combined tillage farming system can increase water availability.

According to the PSD curves shown in Fig. 2d-f, matrix pores, usually active as storage pores, are more influenced by tillage systems and residue covers. The PSD changes caused by forward speed treatments are negligible. In general, soils under combined tillage practices and without the retention of crop residues in one crop year have matrix pores with a larger PSD mean, indicating the promotion of water availability. Similar results can be achieved based on h_1 values summarized in Table 4. Based on the data obtained from the inflection point of matrix peak, the mean sizes of matrix pores were 1.4, 1, and 1.75 µm in RT2, RT1, and CT, 1.6, 1.2, and 1.4 µm in RC0, RC40, and RC80, and approximately equal to 1.4 in low, normal, and high forward speed treatments.

According to $\mathrm{PV_1}$, $\mathrm{PV_2}$, $\mathrm{h_1}$, and $\mathrm{h_2}$ values, the soil PSD descriptive system is a bi-peak distribution as H-L; therefore, uni-modal vG water retention equation cannot properly describe inherent multi-modal soils as a consequence of the hierarchical nature of soil structure. As reported by Dexter and Richard (2009), adjustable shape parameters in the uni-modal vG equation resulted in mono-modal models fit to water retention data.

3.2.3. Residual void ratio (S_r)

According to the results of Table 4, the $\mathrm{S_r}$ values in the tillage treatments, averaged for the residue levels and forward speeds, were in the following order: $\mathrm{RT1} > CT > RT2$. Residue covers tended to reduce $\mathrm{S_r}$, and there was no difference between forwarding speed treatments. Dexter et al. (2012) found that residual water is that which remains after the connected matrix pores has discharged and the water in isolated micro-bodies and thin water films on the clay surface. Similar results were reported by Ding et al. (2016). Considering the foregoing points and the results obtained in previous sections, it can be concluded that residual pore spaces can be generated by the loosening of soil due to conventional mechanized practices with high destructive effects on soil aggregates (clay dispersion of aggregates) and the resulting changes made in PSD. Increased proportion of residual pores can increase the quantity of water that is unavailable for plants.

4. Conclusion

In this paper, we studied the effects of tillage systems, surface residue covers, and forward speeds on the soil PSD and water retention curve of a Haploustept soil in one crop year (2014-2015). It was shown that PSD descriptive system in the soils studied under different treatments was a bi-peak as H-L; therefore, we could not obtain a detailed description of PSD by uni-modal vG water retention equation. According to the results, moldboard ploughing was able to generate higher amounts of structural porosity as transmission pores; however, it reduced plant-available water through increasing water holding in the isolated micro-bodies and thin water films on the particle surfaces as residual moisture. Synthesis of the obtained results using bi-modal model highlighted the need for an enhanced quantification of tillage-induced changes in soil PSD and water retention.

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