CONTRIBUTION OF MACROPOROSITY TO WATER FLUX OF A SOIL UNDER DIFFERENT TILLAGE SYSTEMS[1]

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SUMMARY

In view of the importance of the macroporosity for the water transport properties of soils, its quantitative assessment is a challenging task. Measurements of hydraulic conductivity (K) at different soil water tensions and the quantification of water-conducting macropores (θ_M) of a soil under different tillage systems could help understand the effects on the soil porous system and related hydraulic properties. The purpose of this study was to assess the effects of Conventional Tillage (CT), Chisel Plow (CP) and No Tillage (NT) on θ_M and on K; and to quantify the contribution of macroporosity to total water flux in a loam soil. A tension disc infiltrometer was used at two soil water pressure heads (-5 cm, and 0) to infer θ_M and K, during fallow. Macroporosity was determined based on the flow contribution between 0 and -5 cm water potentials (K_0, K_5, respectively), according to the Hagen-Poiseuille equation. The K_0 values were statistically higher for CT than for NT and CP. The K_5 values did not differ statistically among treatments. The mean K values varied between 0.20 and 3.70 cm/h. For CT, θ_M was significantly greater than for CP and NT, following the same trend as K_0. No differences in θ_M were detected between CP and NT. With CT, the formation of water-conducting macropores with persistence until post-harvest was possible, while under CP preparation, the water-conducting macropores were not persistent. These results support the idea that tillage affects the soil water movement mainly by the resulting water-conducting macropores. Future studies on tillage effects on water movement should focus on macroporosity.

Index terms: Tension disc infiltrometer, no tillage, chisel plow, conventional tillage, effective porosity.

RESUMO: *CONTRIBUIÇÃO DA MACROPOROSIDADE PARA O FLUXO TOTAL DE ÁGUA EM UM SOLO SOB DIFERENTES SISTEMAS DE PREPARO*

A importância da macroporosidade para o transporte de água no solo faz a sua avaliação de forma quantitativa uma tarefa desafiadora. Os valores da condutividade hidráulica (K) do solo em diferentes potenciais de retenção de água no solo e a quantificação de macroporos condutores de água (θ_M) em diferentes sistemas de preparo do solo proporcionarão melhor compreensão dos efeitos no arranjo de poros e nas propriedades físico-hídricas do solo. Dessa forma, o objetivo deste estudo foi avaliar os efeitos de um preparo convencional do solo com arado de aivecas (CT), com subsolador (CP) e utilizando um sistema com plantio direto (NT) sobre os atributos θ_M e K, bem como quantificar a contribuição da macroporosidade para o fluxo total de água em um solo franco. Um infiltrômetro de tensão no solo foi utilizado para emitir duas pressões ascendentes de água (-5 cm e 0 cm) para inferir θ_M e K, durante o pousio. A macroporosidade foi determinada com base na contribuição do fluxo entre os potenciais de água de 0 e -5 cm (K_0 e K_5, respectivamente), de acordo com a equação de Hagen-Poiseuille. Os valores da K_0 obtidos foram estatisticamente superiores no preparo CT, quando comparados aos valores do NT e do CP. Os valores da K_5 não diferiram estatisticamente entre os tipos de preparo. Os valores médios da K variaram entre 0,20 e 3,70 cm/h. A quantificação de macroporos condutores de água (θ_M) foi significativamente superior para o preparo CT em relação aos preparos CP e NT, seguindo a mesma tendência da K_0. Não foram detectadas diferenças significativas dos valores de θ_M entre os preparos CP e NT. Utilizando o preparo CT, foi possível a formação de macroporos condutores de água com persistência até a pós-colheita; já no preparo CP, os macroporos condutores de água não foram persistentes. Os resultados apresentados sustentam a hipótese de que o sistema de preparo do solo escolhido altera o movimento da água no solo, principalmente, devido à formação de macroporos condutores de água. Estudos futuros sobre o efeito do sistema de preparo relacionado ao movimento da água no solo devem-se concentrar nas condições de formação da macroporosidade do solo.

Termos de indexação: Infiltrômetro de tensão, plantio direto, subsolagem, preparo convencional, porosidade efetiva.

INTRODUCTION

The agricultural areas under no tillage (NT) have been continuously increasing in the last few years. In 1999, NT was used on about 450,000 km^2 worldwide, increasing to 720,000 km^2 in 2003, and to 1050,000 km^2 in 2009. The adoption rates of no-tillage systems have been highest in South America. Argentina is among the countries with an area as large as 200,000 km^2 under NT, representing about 70 % of the whole cultivated area of the country (Kassam et al., 2009).

Time and cost savings as well as soil conservation were the main driving forces for the widespread adoption of NT in Argentina since the 1990s (Álvarez et al., 2009a). Some authors have found that the replacement of Conventional Tillage (CT) by NT farming in Argentina and in other temperate regions of the world has resulted in better erosion control, water conservation, and nutrient cycling, time savings, reduction in the use of fossil fuels, and increased soil C sequestration (Díaz-Zorita et al., 2002; Bolliger et al., 2006; Steinbach & Álvarez 2006; Lal et al., 2007; Thomas et al., 2007; Strudley et al., 2008). However, the effect of adoption of NT on soil physical properties was not always consistent across locations, soils and experimental designs (Green et al., 2003; Strudley et al., 2008).

Some studies in Argentina stated a decrease in total porosity (TP) and greater bulk density (BD) under NT than CT (Ferreras et al., 2000; Elissondo et al., 2001; Díaz-Zorita et al., 2002; Fabrizzi et al., 2005; Costantini et al., 2006; Sasal et al., 2006). The compaction associated with NT affects the soil porosity, resulting in a reconfiguration of the porous system (Horton et al., 1994; Strudley et al., 2008). Strudley et al. (2008) reviewed tillage effects on soil hydraulic properties in space and time. They concluded that NT would increase macropore connectivity, while inducing no changes in TP and BD, compared with CT.

Several studies investigated the infiltration rate in soils under NT, with contradictory results. Some found that soils under NT have higher infiltration rates than under CT (Benjamin, 1993; Baumhardt & Lascano, 1996; Quiroga et al., 1998; Sanzano et al., 2005; Steinbach & Álvarez, 2007). Other studies reported lower infiltration rates in soils under NT than under CT (Ross & Hughes, 1985; Alegre et al., 1991; Horne et al., 1992; Azoos & Arshad, 1996; Ferreras et al., 2000; Álvarez et al., 2006). In soils of the Rolling

Pampa, Álvarez et al. (2009a) found that infiltration rates varied differently in loam (NT ≈ CT) from silt loam and silty clay loam (NT << CT) soils. In the silt loam and silty clay loam group, the water infiltration rate was approximately four times higher than at CT sites. Sasal et al. (2006) found higher or similar infiltration rates in a silt loam soil from the Rolling Pampa under Chisel Plow (CP) than under NT, depending on the crop rotation. Wahl et al. (2004) found that the saturated hydraulic conductivity (K_0) of a silty loam soil was similar under conventional tillage and conservation tillage. In all cases, the soils were under NT for at least 5 years, the minimum period cited as necessary for the stabilization of several soil properties (Álvarez et al., 2009a). Horton et al. (1994) emphasized that a more comprehensive understanding about effects of soil management practices on soil hydraulic properties is needed.

The measurements of hydraulic conductivity (K) at different soil water tensions and the quantification of water-conducting macroporosity (θ_M) are important to improve the understanding of soil physical behavior. The properties of the soil macropore network, i.e. macropore volume fraction, diameter and continuity of macropores, have a great impact on the infiltration characteristics of agricultural soils (Hillel, 1998). Studies to quantify macropore flow revealed that more than 70 % of the water flux can move through macropores (Watson & Luxmoore, 1986; Wilson & Luxmoore, 1988). In general, the water flow through structured soils is mainly conducted by macropores even though these constitute only a very small fraction of total porosity (Cameira et al., 2003). Macroporosity represents an important indicator of soil physical quality, particularly in relation to the site-specific water transmission properties, and can be used as a sensitive measure to assess soil structural degradation. The importance of soil macroporosity for the water transport properties of the soil still makes its quantitative assessment a challenging task (Bodner et al., 2010).

The tension disc infiltrometer is a valuable tool to investigate the water movement through macropores and the soil matrix near saturation (Watson & Luxmoore, 1986; Logsdon & Jaynes 1993; Moret & Arrúe, 2007), and to study the effects of soil tillage practices on the soil surface hydraulic properties (Malone et al., 2003; Moret & Arrúe, 2007). This device allows the estimation of K from saturation to a very low suction head (Angulo-Jaramillo et al., 2000) and quantifies the role of macropores during infiltration (Bodhinayake et al., 2004). This technique requires only minimal soil disturbance. Measurements of K at different soil water tensions, and quantification of θ_M of a soil under different tillage managements could help understand the effects of these practices on the soil porous system and related hydraulic properties.

It was hypothesized that the tillage system affects K and θ_M values obtained in field measurements with a tension disc infiltrometer, being higher for CT and CP than for NT.

The objectives of this study were: i) to assess the effects of different tillage systems on water-conducting macroporosity and on hydraulic conductivity; and ii) to quantify the contribution of macroporosity to total water flux.

MATERIALS AND METHODS

Site and treatments

The experiment was carried out near the town of Azul, Argentina. The soil was classified as a fine, mixed, thermic Petrocalcic Paleudoll (USDA, 2006), Luvic Phaeozem (IUSS Working Group WRB, 2006). The A horizon had a loamy texture.

On the studied plots (36º 42' S and 59º 50' W), the treatments below and the same 2-yr crop sequence of maize (first year)-wheat and short-season soybean (second year) had been applied over 10 years. The climate in the region is temperate (temperatures rarely below 0 °C) and the approximate annual rainfall 1,000 mm. The experiment was arranged in a complete randomized block design with three treatments: a) conventional tillage (CT), in which the soil was moldboard-plowed to a depth of 0.19 m and disk- and tooth-harrowed to 0.10 m each year, b) chisel plow (CP) in which the soil was chiseled to a depth of 0.30 m (distance between chisel shanks: 0.35 m) and disk- and tooth-harrowed to 0.10 m each year, and (c) no tillage (NT), in which only a narrow (0.05 m) strip of the soil was drilled to sow crop seeds. There were three plots of (30 x 70 m) per treatment.

Soil bulk density (BD) was measured using the core method (Blake & Hartge, 1986). Undisturbed soil samples (height 10 cm, diameter 7 cm) were collected from the first 10 cm of each plot, near the infiltration points, avoiding plant rows and wheel tracks. Five replicates from each plot were collected (15 samples from each treatment, a total of 45 samples). Total porosity (TP) was calculated from BD, assuming a particle density of 2.65 Mg/m which is normal for mineral soils (Hillel, 1998), and close to values measured for similar soils in the Pampas region (Cosentino & Pecorari, 1992). Disturbed soil from the same depth was sampled in plastic bags to determine the soil particle size distribution using the pipette method (Gee & Bauder, 1986) and to determine the organic matter content by the Walkley-Black method (Walkley & Black, 1934).

In-situ infiltration test

A tension disc infiltrometer (Perroux & White, 1988) was used to determine the steady-state infiltration rate. The infiltration tests were carried out during fallow (August), four months after soybean harvest.

The infiltrometer disc had a base radius of 6.25 cm. Infiltration was measured at four randomly selected sites of each plot (12 replicates per treatment), avoiding plant rows and wheel tracks. To consider only the effects of tillage on soil water infiltration, the crop residues were removed from the soil surface. To ensure good hydraulic contact between the device and the soil, the surface was flattened with a spatula and a thin dry sand layer was spread on it. Infiltration runs were performed at two values of soil water pressure head, h (namely, -5, and 0 cm, applied in this order and at the same place). This sequence of supply water pressure heads was adopted, because a descending order may cause hysteresis, with progressive drainage occurring close to the disk while wetting continues at the infiltration front (Jarvis & Messing, 1995). Flow monitoring was continued until steady-state flow from the disc was attained. The cumulative infiltration was recorded every minute until 10 min, every 5 min until 30 min and every 10 min until the end of the test. When the amount of water entered into the soil did not change with time in four consecutive measurements at 10 min intervals, steady-state flow was assumed and steady-state infiltration rate was calculated based on the last four measurements. The time required to reach the steady state was around 1.5 h for each tension.

The soil hydraulic conductivity, K, at the different soil water pressure heads, h (i.e., K_5, and K_0) was then calculated from the cumulative water infiltration using the multiple-head method (Ankeny et al., 1991).

Water-conducting macroporosity

The classical capillary rise equation allows an approximation of the maximum water-filled pore size, r, [L] at a specific h [L]:

$$r = \frac{2\,\sigma\,cos\,(\alpha)}{\rho\,g\,|h|} \qquad (1)$$

where σ is the water surface tension [M/T^2], α is the contact angle between water and the pore wall (assumed to be zero), ρ is the water density [M/L^3], and g is the acceleration due to gravity [L/T^2].

It was assumed that the pores with radii smaller than r, calculated from equation (1), are full of water and responsible for the entire water flux under a given water pressure head, and that the pores with radii larger than the value calculated from equation 1 have no contribution to the water flux.

According to equation 1, infiltration at water pressure heads of -5 will exclude pores with diameters of > 0.6 mm. In this study, macropores were defined as pore draining at h > -5 cm (r > 0.3 mm).

The water-conducting porosity due to pores between two radii ra and rb (ra ≤ rb), θ (ra,rb), (assuming pore radius equals to the minimum pore radius), resulting in a difference in total soil water flux or hydraulic conductivity ΔK (ra,rb), is (Watson & Luxmoore, 1986):

$$\theta(a,b) = \frac{8\eta\,\Delta K(ra,rb)}{\rho\,g\,(ra)^2} \qquad (2)$$

Since ra is the minimum equivalent pore radius in the range, θ (ra,rb) is an estimation of the maximum water-conducting porosity, because pore radius (ra) appears in the denominator of equation (2). Implicitly assumed in (2) is a unit hydraulic gradient, i.e. steady-state conditions during infiltration (Wahl et al., 2004).

The contribution to flow of the water-conducting macroporosity, φ(%), was calculated as percentage of total flow occurring between 0 and -5 cm water pressure heads.

Statistical analysis

In order to determine the effect of treatments, BD, K_5, K_0, θ_M, and φ(%) were analyzed separately (five ANOVAs with treatment as factor) (Sokal & Rohlf, 1995). When a significant treatment effect was found, Fisher's least significant difference (LSD) test (Sokal & Rohlf, 1995) was used to compare the means of the different soil management practices. The Kolmogorov-Smirnov test was applied to determine if replicates of measured quantities within a treatment were normally or lognormally distributed. For all analyses, significance was determined at p = 0.05.

RESULTS AND DISCUSSION

The mean particle size distribution of the A horizon did not differ between plots and showed fractions of 21 % clay, 40 % silt and 39 % sand; the soil was classified as loamy, with an organic matter content of 5.5 %.

The statistical frequency distribution of the K data was log-normal, which is usual for this soil property (Bagarello et al., 2006), so the statistical analyses were performed with log-transformed values. The other normally distributed variables were not transformed.

Bulk density and derived TP did not differ significantly among treatments in the 0-10 cm layer (p = 0.05). The mean values and standard errors of BD were: CT: 1.21 ± 0.02 Mg/m^3; CP: 1.24 ± 0.03 Mg/m^3; NT: 1.22 ± 0.03 Mg/m^3. The values of TP were: CT: 46 %; CP: 47 %; NT: 46 %. This result is in agreement with several reports from the Pampas region, that show that tillage effects of BD do not persist until harvest (Ferreras et al., 2000; Sasal et al., 2006; Álvarez et al., 2006; Álvarez et al., 2009a, b; Soracco et al., 2010).

Table 1 summarizes the statistical parameters of the K data set, calculated using the Ankeny method (Ankeny et al., 1991). The K_0 values obtained were significantly greater (p = 0.05) for CT than NT and CP. In Silty-Loam, Silty-Clay Loam and Loam soils of the Pampas region, Álvarez et al. (2009a) found a

similar behavior pattern for the Silty-Loam and Silty-Clay Loam group, but not for the Loam soils. In their study, the infiltration rates into Silty-Loam and Silty-Clay Loam soils were particularly high under CT (around 23 cm/h). Moreover, the ratio between the infiltration rates of CT and NT was 4. For the Loam soils, they found no differences between CT and NT. This discrepancy could be attributed to differences in the soil type (Argiudolls) and the method (single-ring method). In agreement with our results, Ferreras et al. (2000) found that K_0 was significantly higher under CT than under NT after harvest for a similar soil. They attributed the low K_0 values in both treatments and the lack of recovery under NT to intensive cultivation prior to the experiment. The soil studied here had been intensively cultivated prior to conversion to NT. No-tillage and CP did not differ statistically for K_0. In comparisons of CP vs NT of soils of the Pampas region, Sasal et al. (2006) found that the differences in the infiltration rates were associated with the crop rotation, being higher for CP when soybean was the predominant crop. In their study, infiltration rates under NT were the same as those under CP when soybean accounted for only one third of the crop rotation. In this study, soybean occupied a similar proportion of the crop rotation. Moreover, the infiltration rates measured by Sasal et al. (2006) were similar to the values found in this work. Álvarez et al. (2006) found no differences in infiltration rates between NT and vertical tillage after harvest in loam soils of the Pampas region.

The K_5 values did not differ significantly among treatments (Table 1). This shows that the water-conducting porosity with radii of <0.3 mm did not differ statistically among treatments. This result is in agreement with Kay & VandenBygaart (2002), who emphasized that soil disturbance by tillage would be expected to result in an increase in the macroporosity of the tilled zone.

Water-conducting macroporosity (θ_M) was significantly greater for CT than CP and NT, following the same trend as K_0 (Table 2). No differences in $è_M$ were detected between CP and NT. Conventional tillage formed water-conducting macropores that persisted until postharvest, whereas under CP no persistent water-conducting macropores were generated; during fallow, the θ_M fraction was the same as under NT. For soils under NT it would be expected that traffic-induced compaction may be compensated by progressive creation of macropores from roots and faunal activities with time, but this was not confirmed in this study. This lack of macropore formation under NT was previously reported for similar soils by Sasal et al. (2006). The relative contribution of macroporosity to total water flux was high and similar for all treatments (Table 2). This is in agreement with Cameira et al. (2003), who suggested that water flow of structured soils is mainly conducted by macropores, even though these constitute only a very small fraction of total porosity.

These results support the idea that tillage affects soil water movement mainly through the creation of

Table 1. Hydraulic conductivity values and coefficients of variation (CV) for different treatments and tensions

Tension	Conventional Tillage		Chisel Plough		No Tillage	
	Average	CV	Average	CV	Average	CV
cm	cm/h	%	cm/h	%	cm/h	%
0	3.70a†	39	2.33b	21	2.32b	31
5	0.28a	62	0.20a	32	0.20a	65

† The statistical analyses were performed with log-transformed values. Different letters of each water tension indicate statistically significant differences between treatments (LSD test; p=0.05).

Table 2. Total porosity (TP) corresponding to water-conducting macroporosity (θ_M), total contribution to flow (TF) and contribution to flow of the water-conducting macroporosity (φ)

Water-conducting macroporosity	Conventional Tillage			Chisel Plough			No Tillage		
	TP	TF	φ	TP	TF	φ	TP	TF	φ
	%	cm/h	%	%	cm/h	%	%	cm/h	%
θ_M	0.009a†	3.42a	92.4a	0.005b	2.13b	91.4a	0.005b	2.12b	91.4a

† Different letters indicate statistically significant differences between treatments (LSD test; p=0.05).

water-conducting macropores. Future work on the effect of tillage on water movement should focus on macroporosity.

CONCLUSIONS

1. The tillage systems affected the values of water-conducting macroporosity and saturated hydraulic conductivity, which were higher under conventional tillage than under chisel plow and no-tillage management.

2. Although tillage affects water-conducting macropores, no effects of tillage were observed on smaller pores.

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