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Anisotropy of Saturated Hydraulic Conductivity in a soil under conservation and no-till treatments

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ABSTRACT

Saturated Hydraulic Conductivity (Ks) is an important parameter for agriculture. Some authors have studied Ks anisotropy in soils with different results. Several methods have been developed and modified with time for the determination of Ks. The aim of this study was to determine Ks anisotropy of a typic Argiudoll under conservation (T2) and no-till (T1) treatments by laboratory measurements on samples extracted in vertical and horizontal directions and to compare them with those obtained from field measurements with a tension disc infiltrometer. In order to determine Ks anisotropy undisturbed samples were collected at different depths (0–15 cm and 15–30 cm) and orientation (vertical and horizontal). Ks was also determined from field infiltration tests. Additionally bulk density (ρ_b) was determined by gravimetric methods. Ks was anisotropic at 0–15 cm in both treatments (horizontal Ks was about five times larger than vertical Ks in both treatments), and isotropic at 15–30 cm. Ks determined from field infiltration tests did not differ from vertical Ks for all treatment-depth combinations. To summarize, mean values of Ks varied between 0.51 and 9.48 cm h^{-1}. Mean values of bulk density (ρ_b) ranged from 0.98 (T2, surface) to 1.23 (T2, subsurface). The ρ_b values were significantly greater at subsurface for both tillage systems. At this depth ρ_b was significantly greater for T2.

Water entry into the soil profile was conditioned by vertical Ks values. The values obtained from field measurements with a tension disc infiltrometer were similar to vertical Ks measured in laboratory in all cases.

1. Introduction

No tillage (NT) area has been increasing continuously in the last few years. Currently the global area under this soil management system occupies 700,000 km^2 worldwide. A half of this area is located on South America. Argentina is among the countries with the large area of 200,000 km^2 under NT that constitutes about 70% of the whole cultivated area of the country (Clarín, 2009).

Silty soils are predominant on the Rolling Pampas, the main cropland area under NT in Argentina. This kind of soil is characterized by the susceptibility to compaction and the propensity to develop a massive and homogeneous structure (Taboada et al., 1998; Aragón et al., 2000; Díaz-Zorita and Grosso, 2000).

The effects of adoption of NT on soil physical properties have been studied by many researchers. The results of these studies were not always consistent across locations, soils and experimental designs (Green et al., 2003; Strudley et al., 2008).

Some investigations in Argentina found a decrease in total porosity and greater bulk density (ρ_b) under NT (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 producing 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 generating inconsistent responses in total porosity and ρ_b when comparing with conventional tillage practices. Horton et al. (1994) emphasized that a complete understanding about effects of soil management practices on soil hydraulic properties is needed.

Several studies investigated the infiltration rate in soils under NT, with contradictory results. Some of them concluded that soils under NT have higher infiltration rates (Benjamin, 1993; Baumhardt and Lascano, 1996; Quiroga et al., 1998; Sanzano et al., 2005; Steinbach and Alvarez, 2007). Other studies reported lower infiltration rates in soils under NT (Ross and Hughes, 1985; Alegre

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et al., 1991; Horne et al., 1992; Azoos and Arshad, 1996; Ferreras et al., 2000; Álvarez et al., 2006; Sasal et al., 2006).

The presence of a surface laminar structure in silty soils under NT was reported by some authors (Ball and Robertson, 1994; Drees et al., 1994; Bonel et al., 2005; Sasal et al., 2006; Soracco, 2009). This kind of structure was characterized by the presence of thin and flat aggregates oriented parallel to the soil surface, with a preferential horizontal orientation of macropores near the surface. Hillel (1998) pointed that anisotropy on Saturated Hydraulic Conductivity (Ks) is generally due to the structure of the soil, which may be laminar or platy thus exhibiting a pattern of micropores or macropores with a distinct directional bias.

To improve soil physical properties Elissondo et al. (2001), Álvarez et al. (2006) and Soracco (2009) studied the effects of the loosening practice in soils under NT. Elissondo et al. (2001) found a decrease in ρ_b. Álvarez et al. (2006) and Soracco (2009) found an increase in the infiltration rate due to the loosening practice.

Ks is an important parameter for agriculture. Many mathematical models describing and simulating water movement and solute transport in soils require Ks. Thus, measurement of this parameter is essential. Several methods have been developed and modified through the years for the determination of Ks. This hydraulic variable could be obtained in laboratory (using Darcy's law) and *in situ* with a tension disc infiltrometer. For structured soils *in situ* measurements are preferable in order to minimize disturbance of the sampled soil volume and to maintain its functional connection with the surrounding soil. However, laboratory measurements have some advantages (Madsen et al., 2008). These advantages include: better control over sample saturation, use of well-defined sample sizes, and greater measurement precision. Some authors compared different methods to obtain Ks in laboratory (Bagarello et al., 2006; Iwanek, 2008; Madsen et al., 2008), in field (Bagarello et al., 2004; Buczko et al., 2006) and laboratory versus field methods (Reynolds et al., 2000; Basile et al., 2003; Zhang et al., 2007). Unfortunately, these methods often yield substantially dissimilar Ks values, since this parameter is extremely sensitive to sample size, flow geometry, sample collection procedures, and various soil characteristics. Methods for measuring Ks should therefore be evaluated carefully before use to ensure that they provide reliable results. On the other hand some authors have studied Ks anisotropy in soils with different results. Some of them reported larger Ks in the vertical direction than in the horizontal direction (Bouma, 1982; Hartge, 1984; Bathke and Cassel, 1991), particularly in well-structured soils. Other authors have reported higher conductivity in the horizontal direction than in the vertical direction, primarily for layered soils (Kanwar et al., 1989; Zhang, 1996) or compacted soils (Dörner and Horn, 2006). Dörner and Horn (2009) concluded that the presence of platy structure is of main importance for the existence of anisotropic properties and flow processes at the soil horizon scale. We are not aware of extensive studies comparing laboratory and field results of Ks with explicit analysis of anisotropy. We hypothesized that Ks anisotropy affects Ks values obtained from field measurements with a tension disc infiltrometer.

The objective of this study was to determine Ks anisotropy of a soil under conservation and no-till treatments by laboratory measurements on samples extracted in vertical and horizontal directions and to compare them with those obtained from field measurements with a tension disc infiltrometer.

2. Materials and methods

2.1. Site and treatments

The experiment was carried out near the town of San Antonio de Areco, Argentina. The soil was classified as fine, illitic, thermic Typic Argiudoll (USDA, 2006), Luvic Phaeozem (IUSS Working Group WRB, 2006), of Río Tala series (INTA, 1973). The granulometry of the A horizon gave 23% clay and 64% silt and was classified as silty loam. The studied plots, located at 34°18′10″ South and 59°56′58″ West, had a history of seven years under the studied treatments. The climate in the region is temperate (the temperature seldom goes below 0 °C) and the approximate annual rainfall amounts to 1100 mm. The experimental design was completely randomized, with two treatments: (a) no tillage (T1), (b) conservation tillage (T2), where a yearly loosening practice was carried out. There were three plots of 8 m wide and 25 m long, for each treatment. In T2 a wheel-mounted eight blades machine for working with hydraulic rear lift system was used. It worked the soil down to about 0.30 m into small fragments without major modifications of the natural structure thus keeping the mulch on the surface. Weeds were controlled with Gliphosate in both treatments. The loosening was performed every year in September.

2.2. In situ infiltration test

Tension disc infiltrometer (Perroux and White, 1988) was used in order to determine steady-state infiltration rate. The infiltration tests were carried out during fallow (April), after soybean harvest, seven months after the loosening.

The infiltrometer disc had a base radius of 6.25 cm. Infiltration measurements were conducted at two depths, surface and subsurface (15 cm depth), in four randomly selected sites for each plot. The measurements were made without tension. Near each infiltration test three samples were collected to determine the initial gravimetric water content. At the end of the infiltration the device was removed and a sample was collected within the wetted perimeter of the disc, in order to obtain the final gravimetric water content. An undisturbed sample was taken within the wet, using a cylinder of known volume to estimate the soil dry bulk density. The gravimetric water contents were converted into volumetric ones using the bulk density. 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 flatten with a spatula and a thin dry sand layer was spread on it. 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 for four consecutive measurements taken at 10 min intervals, steady-state flow was assumed and steady-state infiltration rate was calculated based on the last four measurements. The time necessary to reach the steady-state was around 2.5 h.

2.3. Field Saturated Hydraulic Conductivity (Ksf) determination

The method used to determine Ksf from infiltration data was based on Wooding's equation (Wooding, 1968):

$$q_\infty = \frac{Q(h)}{\pi r_d^2} = K(h) + \frac{4\phi(h)}{\pi}\frac{1}{r_d} \quad (1)$$

where q_∞ is the steady-state infiltration flux (L T^{-1}), Q (h) is the steady-state infiltration rate (L^3 T^{-1}), K (h) is the hydraulic conductivity at the water potential h, r_d (L) is the radius of the disc and ϕ (h) is the matric flux potential (L^2 T^{-1}) defined as:

$$\phi(h) = \int_{h_n}^{h_0} K(h)\,dh \quad h_n \le h_0 \quad (2)$$

where h_n is the initial soil water potential and h_0 is the soil water potential at the infiltrometer base.

White and Sully (1987) derived an equation to calculate ϕ (h):

$$\phi(h) = \frac{bS^2}{\Delta\theta} \quad (3)$$

where b is a shape factor, $\Delta\theta$ is the change in soil water content during infiltration, and the sorptivity, S, can be estimated from the early stage of the cumulative infiltration versus square-root-of-time curve (Logsdon and Jaynes, 1993).

2.4. Cores extraction for laboratory determinations

The plots were sampled after soybean harvest, in fallow (April), seven months after the soil loosening.

In order to determine if the hydraulic properties of soil horizons had direction-dependent behaviour, undisturbed soil samples were collected in PVC cylinders (height 15 cm and in-diameter 5.88 cm), in vertical and horizontal direction (McIntyre, 1974; Petersen et al., 2008; Dörner and Horn, 2009; Soracco, 2009). The inner surfaces of the cylinders were coated with a thin film of lithium grease to facilitate the penetration into the soil and to prevent the by-pass flux of water between the cylinder wall and the soil core during the Ks measurements.

In each treatment, cylindrical cores at two depths of sampling, surface (0–15 cm) and subsurface (15–30 cm), were carefully collected at different orientations. For each experimental situation 12 cylinders were extracted; the total of samples was 96. The location of the sampling sites was chosen at random between crop rows where no wheel tracks were visible. The sampling cylinders were not completely filled with soil, but around 40% of them remained empty in order to be filled with water several centimeters above the top of the soil cores. The samples were covered with plastic caps to protect the soil from mechanical disturbances and evaporation.

2.5. Laboratory Saturated Hydraulic Conductivity (Ksl) determination

Laboratory saturated hydraulic conductivity (Ksl) was measured in vertical (Kslv) and horizontal (Kslh) samples using the constant head method (Klute and Dirksen, 1986). The undisturbed soil sample was positioned vertically. A constant height of water was maintained over the upper end, and the bottom end was open to the atmosphere.

The following relation was used to estimate Ksl (Hillel, 1998):

$$\frac{Q}{A} = q = -\mathrm{Ksl}\frac{\Delta H}{D} \quad (4)$$

where Q is the volume of water flowing per unit of time ($L^3\,T^{-1}$), A is the cross-sectional area of the soil column (L^2), q is the flux (LT^{-1}), Ksl is the Saturated Hydraulic Conductivity (LT^{-1}),

ΔH is the hydraulic head drop across the soil column (L), D is the length of the column (L), and $\Delta H/D$ is the hydraulic gradient (dimensionless).

The soil core with the sample was placed vertically inside a funnel with a barrier covered by a thinner weaver cloth to retain the soil in the core, at atmospheric pressure. On the top of the cores, distilled water was siphoned from a common supply through to the individual soil samples.

In addition, bulk density (ρ_b) was measured in each core by gravimetric method (Blake and Hartge, 1986).

2.6. Statistical analysis

All statistical tests on Ksf, Kslv and Kslh were carried out using the log of the data, as the statistical frequency distribution of the Ks data were log-normal, which is usual for this soil property (Bagarello et al., 2006). In order to determine the effects of treatments and depths; Ksf, Kslv, and Kslh were analyzed separately (three 2-way ANOVA with treatment and depth as factors). Methods were compared for each treatment-depth combination using t test (Ksf vs. Kslv, Ksf vs. Kslh, and Kslv vs. Kslh) (Sokal and Rohlf, 1995). The ρ_b was assumed normally distributed, and thus, no transformations were performed on this variable and a 2-way ANOVA was performed in order to determine the effects of treatments and depths on this variable. For all analysis significance was determined at $P = 0.05$.

3. Results and discussion

3.1. Laboratory Saturated Hydraulic Conductivity (Ksl)

There was no significant effect of treatment on both Kslv and Kslh. There was significant effect of depth on Kslh. Surface Kslh values were larger (Table 1).

Kslh was greater than Kslv at surface in both treatments. Dörner and Horn (2009) found an isotropic behaviour of Ks in a soil under conservation tillage for all depths. This disagreement could be attributed to the different moment of sampling. These authors sampled just after cultivation.

There were no differences between Kslv and Kslh below 15 cm (Table 1).

Inspection of soil structure in the field revealed the presence of horizontally oriented platy aggregates in the first 10 cm in both treatments (Fig. 1). Hillel (1998) pointed out that anisotropy on Ks is generally due to the structure of the soil, which may be laminar or platy thus exhibiting a pattern of micropores or macropores with a distinct directional bias. Dörner and Horn (2006) ascribed observed anisotropy of Ks in the plough pan to its platy structure. The presence of platy structure in soils under NT is in agreement with previous studies (Drees et al., 1994; Ball and Robertson, 1994; Bonel et al., 2005; Sasal et al. 2006; Álvarez et al., 2009).

In the present study the loosening practice performed in T2 did not affect Ks anisotropy after harvest. Álvarez et al. (2006) found in similar soils that the effect on infiltration rate of soil loosening previous to sowing did not persist after harvest. In the present study, Ks anisotropy was not measured at sowing.

Servadio et al. (2005) found development of platy structure, with thin elongated pores oriented parallel to the soil surface in the top few centimetres of a soil compacted by only one pass of a tractor with single tires. The authors emphasized that these few elongated pores were no vertically continuous, and hence much less useful for water infiltration. Then it is possible that the harvest traffic contributed to the development of platy structure in T2.

Table 1
Saturated hydraulic conductivity (Ks) (cm h^{-1}, mean values with standard deviations in parenthesis) measured in vertical samples (subscript lv), horizontal samples (subscript lh) and by field infiltrometry (subscript f), for each treatment-depth combination.

Treatment	Property	Depth	
		0–15	15–30
No Tillage (T1)	Ksf	1.97 (0.71)b	1.20 (0.48)a
	Kslv	1.03 (0.56)b	1.38 (0.67)a
	Kslh	7.39 (4.07)a	1.71 (0.68)a
Conservation Tillage (T2)	Ksf	1.92 (1.05)b	0.67 (0.27)a
	Kslv	1.98 (1.31)b	1.07 (0.70)a
	Kslh	9.48 (5.77)a	0.51 (0.27)a

Values with the same letters within each column and treatment are not significantly different at 5% significance level. The statistical analysis was performed using the Log-transformed values of Saturated hydraulic conductivity. See text.

Fig. 1. Macrophotographs of soil aggregates from the surface layer (0–10 cm) of the No Tillage (left) and Conservation Tillage (right) treatments. A platy structure is evident in both treatments. Frame length 70 mm × 24 mm.

Further studies, including Ks anisotropy in different moments of the cultivation cycle, are necessary to assess the effect of soil loosening on Ks anisotropy.

3.2. Field Saturated Hydraulic Conductivity (Ksf)

The Ksf values were calculated and compared for both treatments and depths. The ANOVA showed that there was no effect of the treatments on Ksf. The Ksf was modified by depth, being greater at soil surface (Table 1). Álvarez et al. (2006) found in similar soils that the effect on infiltration rate of soil loosening previous to sowing did not persist after harvest.

3.3. Ksf vs. Kslv and Ksf vs. Kslh comparisons

Comparisons (Ksf vs. Kslv, and Ksf vs. Kslh) using *t*-test were performed for each treatment-depth combination. Results are shown in Table 1.

The Ks values obtained in the field, using a tension disc infiltrometer, did not differ from those obtained in laboratory for vertical sampling direction. The Kslh values were significantly greater than Ksf at surface. Even when the flux from tension disc infiltrometer is unconfined, the Ks values obtained from this device were similar to Kslv for all treatment-depth combinations. This was in agreement with Sasal et al. (2006). They found, using a tension disc infiltrometer, that water entry into the soil profile under NT was mainly conditioned by pore orientation, and total macroporosity was not correlated with infiltration rate.

3.4. Soil bulk density

The values of the ρ_b determined in the horizontal direction were not different from values in the vertical direction for all depths and treatments indicating that the sampling technique did not affect the pore volume. Mean values and standard deviations were: 1.04 ± 0.03 (T1, surface), 1.13 ± 0.03 (T1, subsurface), 0.98 ± 0.04 (T2, surface) and 1.23 ± 0.05 (T2, subsurface).

The ρ_b values were significantly greater ($P = 0.05$) at subsurface for both tillage systems. At this depth ρ_b was significantly greater ($P = 0.05$) for T2. The difference in ρ_b at subsurface could be attributed to reconsolidation of soil after the loosening practice. For similar soils and management, Álvarez et al. (2006) found that the effect of soil loosening before seeding did not remain until harvest. At the surface ρ_b values were statistically the same ($P = 0.05$).

4. Conclusions

Saturated Hydraulic Conductivity was anisotropic at soil surface in both treatments, and isotropic at subsurface.

Water entry into the soil profile was conditioned by vertical Ks values. In all cases Ks values obtained from field measurements with a tension disc infiltrometer were similar to vertical Ks measured in laboratory.

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