Geoderma 158 (2010) 268–274

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Porosity characterization of Argiudolls under different management systems in the Argentine Flat Pampa

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ARTICLE INFO

Article history:
Received 21 July 2009
Received in revised form 17 May 2010
Accepted 17 May 2010
Available online 19 June 2010

Keywords:
Tension infiltrometer
Water release curve
Silty-loam soils
Pore system

ABSTRACT

Soil pore network characteristics are influenced by management and tillage practices. The objective of this work was to verify if the simultaneous use of the information obtained from tension infiltrometers and water release curves contribute to a better understanding of the impacts of different long-term management systems on the pore space of agricultural soils. The study was carried out on the Flat Pampa in Santa Fe, Argentina, in two types of typical Argiudolls with a silty-loam surface soil texture. The following treatments were evaluated: a) no-till with corn–wheat/soybean rotation (NT-R), and b) conventional tillage with wheat/soybean sequence (CT-S) at Gálvez; and a) no-till with corn–soybean–wheat/soybean rotation (NT-R), and b) no-till with wheat/soybean sequence (NT-S) at Videla. Tension values of 0, 1.5 and 3 cm were applied using tension infiltrometers with the aim of obtaining soil hydraulic conductivity measurements (K_0, $K_{1.5}$, and K_3), and several hydraulic parameters (pore size, pore number, effective macroporosity, conducting macroporosity ($\varepsilon_{(a,b)}$), water flow and water flow decrease). Undisturbed soil cores were collected to determine water release curves (WRC) and soil bulk density (Db). The total macroporosity (Ma) and pore size frequency curve were determined from the fitted model of the WRC. Macropore connectivity was calculated using $\varepsilon_{(a,b)}$ and Ma. In Gálvez, the Db values, K at all tensions, the number of effective pores, the mean pore radius and the effective macroporosity were significantly higher for NT-R. The conducting and total macroporosity values were similar in NT-R and CT-S, but the pores had better continuity in NT-R. In Videla, only K_0 and $K_{1.5}$ showed statistical differences in favor of NT-R. This treatment also had a greater number of effective pores, and higher effective, conducting and total macroporosity values, apart from the overall better pore connectivity. There were no significant differences between the NT-R and CT-S for Db and K_3. The evaluated indicators determined that the pore network characteristics are affected not only by tillage system, but also by the crops chosen for the rotation. When used jointly, tension infiltrometers and water release curves can be very useful tools for monitoring the evolution of the soils physical conditions.

1. Introduction

In the central northern region of the Humid Pampa of Argentina, there has been a significant intensification of the cropping systems in recent decades. This process was accompanied by the replacement of traditional cattle production by continuous cropping or by mixed systems, which are prone to cause rapid soil structure deterioration (Ferreras et al., 2001; Viglizzo et al., 2002).

In the Santa Fe Province, one of the main productive regions in the Argentine Humid Pampa, the intensification is causing a strong edaphic degradation because of the low resilience of the silty-loam soils (Cosentino and Pecorari, 2002; Pilatti et al., 2006; Ghiberto et al., 2007; Taboada et al., 2008).

Soil structure deterioration involves an alteration of the soil pore system and, consequently, of the capability to function as support of vegetal and animal life. The total pore volume, its size distribution, connectivity and tortuosity determine the ingress, circulation and retention of water, the oxygen availability and the soil mechanical resistance to root penetration, among other processes (Dexter et al., 2008). Consequently, the degradation of the soil pore system can cause a decrease in crop production, favor water surface runoff and lead to soil loss because of erosion (Botta et al., 2006; Botta et al., 2007).

Water entry through the soil surface is mainly regulated by macropores, even though these constitute a small proportion of the total porosity (Moret and Arrúe, 2007a). In general, macropores represent the fraction that is first destroyed when the soil is physically degraded due to machine traffic or animal trampling (Botta et al., 2004). Soil tillage also alters macroporosity, although its effect depends on the tillage system; in this respect, contradictory information is found in the literature. Strudley et al. (2008), in a review

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doi:10.1016/j.geoderma.2010.05.005

of this topic, pointed out that the consensus is that the no-till system, unlike the conventional one, increases the connectivity between macropores; meanwhile, the results for total porosity and soil bulk density are variable.

Several methods, instruments and indicators were developed in order to detect changes in the soil pore network and in the movement of water associated with it (Radke and Berry, 1993; Bodhinayake et al., 2004; Dexter et al., 2008). These include tension infiltrometers and water release curves, which are used to quantify soil hydraulic properties, to detect changes in porosity, and to study the preferential flow that goes through macropores (Watson and Luxmoore, 1986; Perroux and White, 1988; Logsdon et al., 1990; Ankeny et al., 1991; Reynolds et al., 1995).

In recent years, researchers have begun using tension infiltrometers to evaluate the deterioration of the physical quality of soil resulting from the use of different agricultural management systems (Bodhinayake et al., 2004; Buczko et al., 2006; Moret and Arrúe, 2007a,b). Similar work has been conducted in Argentina (Weinzettel and Usunoff, 2001; Ghiberto et al., 2007). Aparicio and Costa (2007) found a clear relation between the soil hydraulic conductivity and its structural porosity, and they suggested the use of the latter to monitor soil degradation occurrence.

Water release curves (WRC) produce accurate information about pore size distribution (Dexter, 2004). From these curves, it is possible to fit mathematical functions that allow the determination of the structural and textural porosity of soils, apart from obtaining information about the way in which they are modified due to structural degradation (Sasal et al., 2006; Dexter et al., 2008).

However, it is worth mentioning that both methods have its greater sensitivity in different ranges of the scale of measurement. Although tension infiltrometers allow to measure big pores (radius bigger than 500 μm) with accuracy and precision, the WRC allow researchers to obtain more detailed information about pores smaller than 500 μm. An important aspect is that tension infiltrometers allow the evaluation of the water-conducting porosity while the water release curve provides information about the total porosity of soils. Macropores include, apart from interconnected pores, blocked, non-continuous and open pores with irregular geometry, but only the interconnected pores contribute to the fast water flow in the soil, which in turn determines the aeration conditions (Bodhinayake et al., 2004).

At present, the challenge is to find methods of crop production that assure high productivity and, at the same time, preserve environmental health. In order to reach this goal, it is necessary to have indicators that detect the occurrence of soil degradation early, especially of the pore system due to its impact on the essential functions that the soil must fulfill (Kay and VandenBygaart, 2002). Because a large total macroporosity value does not necessarily imply a better soil physical condition, the objective of this work was to verify if the simultaneous use of the information obtained from tension infiltrometers and water release curves contribute to a better understanding of the impact of different long-term management systems of the pore space in agricultural soils.

2. Materials and methods

This study was performed in Santa Fe Province (Argentina), in Gálvez (latitude 33° 03′south, 60° 39′ west) and Videla (latitude 30° 57′ south, 60° 40′ west), where there is a subhumid–humid mesodermic climate (C2B´3rd´, Thornthwaite, 1948) with an annual precipitation of 1000 mm.

Two situations with contrasting management history in agricultural soils were chosen in each place: a typical Argiudoll, Loma Alta series (Gálvez) and a typical Argiudoll, San Justo series (Videla). Both soils are Luvic Phaeozems (WSR, 2006). Soil maps (at a 1:50,000 scale) and satellite images were made available by the National Institute of Agricultural Technology of Rafaela (INTA Rafaela) and used to select the soils for this study. The soil series was corroborated using the "Cultural Profile Methodology" in the field (De Battista et al., 1993).

The treatments evaluated at Gálvez were: a) Treatment 1 — soil with 13 years of no-till with corn–wheat/soybean crop rotation (NT-R) and b) Treatment 2 — soil with 20 years of conventional tillage with wheat/soybean sequence (CT-S). At Videla, the treatments where: a) Treatment 1 — soil with 7 years of no-till with corn–soybean–wheat/soybean rotation (NT-R) and b) Treatment 2 — soil with 7 years of no-till with wheat/soybean sequence (NT-S).

Conventional tillage typically includes plowing, disking and harrowing the soil to produce a fine seedbed. This sequence is performed in fall (May), when wheat is planted, and in spring (December) to cultivate soybeans.

At each site, the sampling and the measurements were carried out simultaneously in the two treatments after harvesting the crops. In each of the treatments, soil hydraulic conductivity (K) was measured with tension infiltrometers (Perroux and White, 1988) applying 0 cm (K_0), 1.5 cm ($K_{1.5}$) and 3 cm (K_3) of tension ($|\psi|$) without moving the equipment (Ankeny et al., 1991). This sequence of measurements was performed in six locations (six repetitions). A descending sequence of tensions was adopted since an ascending one may produce errors due to hysteresis (Jarvis and Messing, 1995).

Before placing the tension infiltrometer in the soil, a 60 cm diameter surface was cleaned and leveled, and a thin sand layer was applied in an area that was similar to the tension infiltrometer disc (22 cm diameter). Once the sand was wet (30 s), measurements were made at 15 to 30-second intervals. Each test concluded when at least 5 consecutive readings showed similar results. The readings were used to calculate K according to Ankeny et al. (1991). Equilibrium was reached after about 1 h at the highest tensions. Tension values of 3 and 1.5 cm were applied consecutively to exclude pores with an equivalent radius greater than 500 and 1000 μm respectively from the transport process (Eq. (1)). In this study, large macropores are defined as those pores that drain at a $|\psi|<3$ cm (500 μm of equivalent radius) (Watson and Luxmoore, 1986; Buczko et al., 2006).

Using the assumption that the soil pore space consists of capillary tubes, the pore radius (r_a(L)) that corresponds to an applied tension ($|\psi|_a$, cm) was calculated according to the classical following expression (e.g. Or and Wraith, 2000):

$$r_a = \frac{2\sigma\cos\alpha}{\rho g|\psi|_a} \quad (1)$$

where σ is the water surface tension ($\mathrm{M\,T^{-2}}$) ($=73.4\,\mathrm{mN\,m^{-1}}$ at 15 °C); α, the contact angle between the water–air–soil interface (here $\approx 0°$); ρ, water density ($\mathrm{M\,L^{-3}}$) ($=1000\ \mathrm{kg\,m^{-3}}$); g, acceleration due to gravity ($\mathrm{L\,T^{-2}}$) ($=9.81\ \mathrm{m\,s^{-2}}$) and $|\psi|_a$, the applied tension (cm of water column).

The number of hydraulically effective macropores per unit area (N_m) and hydraulically effective macroporosity (θ_m) were calculated combining Poiseuille's law for laminar flow and Eq. (1) (Watson and Luxmoore, 1986):

$$N_m = [8\eta K_m] / \left[\pi\rho g r_a^4\right] \quad (2)$$

$$\theta_m = N_m \pi r_a^2 \quad (3)$$

where K_m ($\mathrm{L\,T^{-1}}$) is the difference between K_0 and K_3; η is the water dynamic viscosity ($\mathrm{ML^{-1}\,T^{-1}}$) ($=0.0015\ \mathrm{Pa\,s^{-1}}$ at 15 °C); and r_a (L) is the minimum macropore radius (500 μm). See Eq. (1) for the rest of the symbols.

To calculate the contribution of different pore size to the flow, the index called "mean pore radius for two consecutive tensions" by Moret and Arrúe (2007a), $\lambda_{\Delta\psi}$, was determined with Eq. (4). See Eq. (1) for the rest of the symbols.

$$\lambda_{\Delta\psi} = [\sigma(K_0 - K_3)] / [\rho g(\phi_0 - \phi_3)] \quad (4)$$

where ϕ is the matric flux potential at 0 and 3 cm tension, calculated according to Ankeny (1992).

Therefore, the number of effective pores per unit area, $N_{\Delta\psi}$, was calculated with Eq. (5) and the effective porosity between two tensions (0 and 3 cm), $\theta_{\Delta\psi}$, with Eq. (6) (Moret and Arrúe, 2007a). See Eq. (1) for the rest of the symbols.

$$N_{\Delta\psi} = [8\eta(K_0 - K_3)] / \left[\rho g \pi \left(\lambda_{\Delta\psi}\right)^4\right] \quad (5)$$

$$\theta_{\Delta\psi} = N_{\Delta\psi}\pi\left(\lambda_{\Delta\psi}\right)^2 \quad (6)$$

Furthermore, conducting macroporosity was estimated ($\varepsilon_{(a,b)}$) (Eq. (7)) with the method proposed by Bodhinayake et al. (2004), which considers the hydraulic conductivity $K(|\psi|)$ in a certain tension range that corresponds to the pore radii a and b. See Eq. (1) for the rest of the symbols.

$$\varepsilon_{(a,b)} = \frac{2\eta\rho g}{\sigma^2}\int_{\psi(a)}^{\psi(b)} \frac{dK(|\psi|)}{d|\psi|}|\psi|^2 d|\psi| \quad (7)$$

In this study, the analytic solution of Eq. (7) introduced by Bodhinayake et al. (2004) was used. As a value 0 cm tension cannot be related to an upper limit of pore size in the integral of Eq. (7), it was assumed, as Bodhinayake et al. (2004) did, that the maximum pore equivalent radius in the soil was 2500 µm due to no pores greater than this size being observed at the studied places.

Water flow (% flow) through macropores with an equivalent radius greater than 500 µm and the decrease of the conductive capacity ($\%D_{flow}$) in the treatments were calculated with Eqs. (8) and (9), respectively (Ghiberto et al., 2007). The equations for the site at Gálvez with CT-S and NT-R are included as examples.

$$\%\ flow = 100 - (K_3 / K_0) \times 100 \quad (8)$$

$$\%D_{flow} = [100 - (K_{0LC-S} - K_{3LC-S}) / (K_{0SD-R} - K_{3SD-R}) \times 100] \quad (9)$$

where $K_{0LC\text{-}S}$ and $K_{3LC\text{-}S}$, $K_{0SD\text{-}R}$ and $K_{3SD\text{-}R}$ are the K_0 and K_3 in conventional tillage (CT-S) and no-till (NT-R) treatments, respectively.

The same equations were used to compare NT-R and NT-S for the site at Videla. In Eq. (9), the NT-R in Gálvez and NT-R in Videla were used because it was considered that in these treatments the soil would present a less degraded condition.

In each site where K was measured, undisturbed and disturbed soil samples were collected. The disturbed ones were used to determine the particle size distribution (Gee and Bauder, 1986), the organic matter (OM) content by the Walkley and Black method (Jackson, 1982), and the soil particle density (Dp) with a helium pycnometer.

The undisturbed soil samples (5×5 cm cores, appr. 100 cm^3, $n = 15$ per treatment) were used to determine the water release curves (WRC). Firstly, they were saturated in a tray by a gradual rise of water level. Once saturated, all samples were consecutively submitted to different matric potentials ($|\psi|$) using tension tables and pressure chambers, as described by Klute (1986). The values of $|\psi|$ were 0, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 20, 30, 60, 800, and 1500 kPa. After reaching the equilibrium, i.e., at the point when water stops leaving the chamber, the samples were weighted, oven-dried at 105 °C, and weighted again. For each sample, the gravimetric water content and soil bulk density (Db) were determined (Blake and Hartge, 1986). With this information, the volumetric water content was calculated for the production of the WRC.

The WRC data were fitted using the equation proposed by Van Genuchten (1980) (Eq. (10)), and the pore size frequency curve was calculated with the first derivative of this function (Libardi, 2005).

$$\theta = \theta_r + (\theta_s - \theta_r) / \left(1 + (\alpha\psi)^n\right)^{\left(1-\frac{1}{n}\right)} \quad (10)$$

where θ is the volumetric water content (cm^3 cm^{-3}), θ_s, the volumetric water content at saturation (cm^3 cm^{-3}), θ_r, the residual volumetric water content (cm^3 cm^{-3}), $|\psi|$, the applied tension (kPa), and α and n, the model parameters. The model was chosen because it better fits the data.

Total porosity, aeration porosity and total macroporosity were determined from WRC (Buczko et al., 2006). The lower limit of the pore radius adopted to define total macroporosity (Ma) was 500 µm ($|\psi| < 0.3$ kPa). The quotient between conducting and total macroporosity was used as an indicator of pore connectivity (Bodhinayake and Si, 2004).

Statistical analyses were performed with the SAS program (1991). A test for normality (Shapiro–Wilks test; $\alpha = 0.05$) was performed on the K values, the number of effective pores per unit area, the effective porosity, the conducting porosity and the Db. All the variables except Db showed logarithmic distribution. The data were then transformed to calculate mean values and to carry out the measurement comparisons (t test, $\alpha = 0.05$) between treatments (NT-R and CT-S, NT-R and NT-S). Lastly, the values were retransformed for the data presentation in the study. Non-linear regression was used to fit the WRC data (PROC NLIN, SAS, 1991). The first derivative of the function and the pore size frequency curve were obtained with Excel.

3. Results and discussion

The main characteristics of the soils at Gálvez and Videla are shown in Table 1. Both soils are characterized by high silt content and have a silty-loam texture. The soil bulk density (Db) values after 13 years of NT-R were significantly higher than those observed in CT-S at Gálvez. In long-term experiments, higher soil compaction was already observed in no-till when compared with conventional tillage (Logsdon et al., 1990; Sasal et al., 2006; Moret and Arrúe, 2007b). This was associated with a gradual consolidation of the soil matrix over time due to rain and the absence of annual loosening. At Videla, the Db did not show significant differences between treatments. This was expected because there was no difference in the tillage system between treatments. The organic matter values were not statistically different between treatments in either of the places. Total porosity values (TP), calculated from Db and Dp, were 50% and 51% for NT-R and CT-S in Gálvez, 47% for NT-R and NT-S in Videla. The lowest TP and the highest Db at Videla denote that soils show a higher level of compaction than the soils at Gálvez.

Table 1
Values of soil bulk density (Bd), particle density (Pd), organic matter (OM) and particle size distribution for the treatments in the typical Argiudoll, Loma Alta series (Gálvez) and typical Argiudoll, San Justo series (Videla).

Place and treatments		Texture (%)	Bd (g cm^{-3})	Pd (g cm^{-3})	OM (%)
Gálvez	NT-R	Sand: 4 Silt: 62	1.30a	2.58	2.55a
	CT-S	Clay: 34	1.26b	2.57	2.48a
Videla	NT-R	Sand: 7 Silt: 64	1.37a	2.60	2.39a
	NT-S	Clay: 29	1.36a	2.59	2.35a

NT-R = no-till, corn–wheat/soybean rotation. CT-S = conventional tillage, wheat/soybean sequence. NT-R = no-till, corn–soybean–wheat/soybean rotation. NT-S = no-till, wheat/soybean sequence. Values followed by the same letter in each column for each place are not significantly different ($P < 0.05$).

3.1. Soil hydraulic conductivity and porosity

Hydraulic conductivity values (K) for 0, 1.5 and 3 cm tensions for Gálvez are shown in Table 2.

K was significantly higher in NT-R at all tensions, which demonstrates a better physical condition of the soil when compared with CT-S. The greater water conduction in the soil under NT-R can be associated with a greater proportion and/or better continuity of macropores. Soil plowing, which characterizes conventional tillage, causes the pores to break, and as a consequence, a decrease of their continuity occurs, as described by Logsdon et al. (1990).

Continuous macropores, which are due to biologic activity, root death and the lack of soil disturbance, not only facilitate water infiltration but also become important stable waterways for preferential flow (Edwards et al., 1988; Lal and Vandoren, 1990). This mechanism of continuous macropore formation seems to be the most important in the studied soils. Some authors suggest that the increase of continuous pores in no-tilled soils is associated with cracks that are produced between structural elements (Ellis et al., 1979; Cerisola et al., 2005). Meanwhile, others indicate that earthworm activity, which is generally greater in soils under NT, is responsible for the formation of continuous macropores below the surface layer covered by plant residues (Barnes and Ellis, 1979).

From the data on Table 2, the water flow (% flow) through macropores with an equivalent radius of more than 500 µm was determined. The % flow that took place between 0 and 3 cm of tension was 95% and 95.5% for NT-R and CT-S, respectively. These results confirmed that these pores were the most important for the infiltration and movement of water in both systems, which is in agreement with the findings of Cameira et al. (2003) and Moret and Arrúe (2007b).

Despite the similar values of % flow, a decrease in the conductive capacity of these pores ($\%D_{flow}$) of 23% was observed in the CT-S treatment when compared with NT-R. This decrease is probably due to the pore blockage caused by soil particles that come off the aggregates because of raindrop impacts. The process is facilitated by the lack of cohesion among the silt particles and by the particular morphology of the illite, which is the type of clay that prevails (Cosentino and Pecorari, 2002).

Hydraulic conductivity values for 0, 1.5 and 3 cm tensions at Videla are shown in Table 3. K_0 and $K_{1.5}$ showed significant differences in favor of the NT-R treatment, in which the soil had higher hydraulic conductivity through pores of greater size than in the NT-S treatment. K_3 was not statistically different between treatments, and this indicates that there were no differences in the water flow that passes through pores with a radius smaller than 500 µm.

These results highlight the fact that the soil under crop rotation has a better physical condition, even though the same seeding system is used. Although differences in the soil organic matter content were not found, the greater proportion of graminaceous species in the crop rotation apparently had a positive effect on the pore network by generating more continuous pores, which in turn make possible a greater water infiltration. Similar results were obtained by Ferreras et al. (2001), who compared no-till to conventional tillage in two rotations, wheat/soybean and corn–wheat/soybean, and concluded that the rotation corn–wheat/soybean under no-till caused less soil degradation.

The % flow through macropores with an equivalent radius greater than 500 µm, determined from Table 3, was 94% and 86% for NT-R and NT-S, respectively. The $\%D_{flow}$ in the NT-S treatment when compared with the NT-R was 57%. In this soil, the water flow was regulated by macropores; consequently, its deterioration would cause a severe decrease in the water conductive capacity.

Regardless of the place and management system, the K values at 0 cm of tension were notably greater than those measured at 3 cm of tension. Important increases of K take place when there is an extensive macropore network that facilitates water drainage in the subsurface soil layers (Reynolds et al., 1995). Soils in both places exhibit an increase of clay content with depth, which is associated with the formation of strong blocks and prisms. These characteristics facilitate crack and fissure formation, which likely constitutes the pore network mentioned by Reynolds et al. (1995). The results also indicate that the destruction of that fraction of very large pores will cause a very low water conduction capacity, less than 1 cm h^{-1}, which would notably increase the risk of flooding.

The coefficients of variation (CV) of K_0 were NT-R = 25%, CT-S = 26%, NT-R = 12%, NT-S = 51% for Gálvez and Videla, similar to those found by Nielsen (1973), and Burden and Selim (1989). These authors reported that, both at plot and hydrologic basin levels, infiltration capacity and hydraulic conductivity show larger CV values due to the spatial and temporal variability of the soil matrix.

3.2. Water release curves and porosity

The coefficients of the equations that fitted the data of the water release curves (WRC) (Eq. (10)) for both places are presented in Table 4.

Fig. 1a and b shows the data and the WRC of the different treatments for both sites under study.

The θ_s values estimated with Eq. (10) indicate that total porosity was a little higher in CT-S at Gálvez and NT-R at Videla. These values coincided approximately with those calculated from the Db and Dp values. The air-porosity (Ap) value, which is the difference between

Table 2
Mean values of hydraulic conductivity (K, cm h^{-1}) at the tension values of 0, 1.5 and 3 cm in the typical Argiudoll, Loma Alta series.

	Gálvez NT-R	Gálvez CT-S
K_0	12.0a	9.2b
$K_{1.5}$	1.4a	0.8b
K_3	0.6a	0.4b

NT-R = no-till, corn–wheat/soybean rotation. CT-S = conventional tillage, wheat/soybean sequence. Values followed by the same letter in each line are not significantly different (P<0.05).

Table 3
Mean values of hydraulic conductivity (K, cm h^{-1}) at the tension values of 0, 1.5 and 3 cm typical Argiudoll, San Justo series.

	Videla NT-R	Videla NT-S
K_0	14.7a	7.0b
$K_{1.5}$	2.5a	1.8b
K_3	0.9a	1.0a

NT-R = no-till, corn–soybean–wheat/soybean rotation. NT-S = no-till, wheat/soybean sequence. Values followed by the same letter in each line are not significantly different (P<0.05).

Table 4
Parameters of the van Genuchten equation for all treatments in the typical Argiudoll, Loma Alta series (Gálvez) and typical Argiudoll, San Justo series (Videla).

Parameters	Place and treatments			
	Gálvez NT-R	Gálvez CT-S	Videla NT-R	Videla NT-S
θ_s	0.49	0.50	0.47	0.45
θ_r	0.01	0.01	0.01	0.01
α	0.065	0.060	0.026	0.027
n	1.167	1.180	1.244	1.201
Square sum	0.003537	0.001794	0.001296	0.002181
Variance	0.009459	0.010110	0.011757	0.009148

θ_s: volumetric water content at saturation (cm^3 cm^{-3}); θ_r: volumetric residual water content (cm^3 cm^{-3}); α and n are coefficients of the model. NT-R = no-till, corn–wheat/soybean rotation. CT-S = conventional tillage, wheat/soybean sequence at Gálvez. NT-R = no-till, corn–soybean–wheat/soybean rotation. NT-S = no-till, wheat/soybean sequence at Videla.

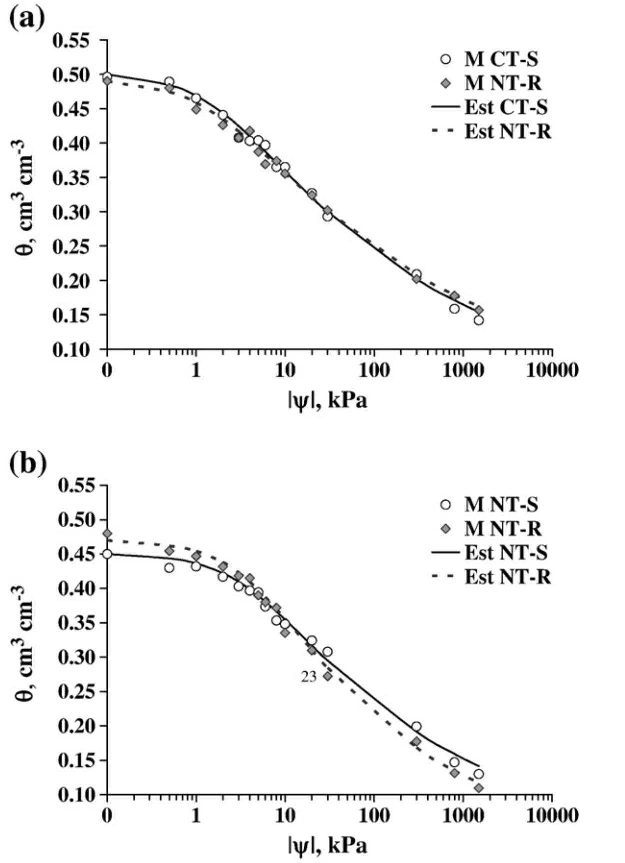

Fig. 1. Measured (M) and estimated (Est) water contents (θ, $cm^3\ cm^{-3}$) versus the applied water tension ($|\psi|$, kPa) for the treatments: (a) no-till with crop rotation (NT-R) and conventional tillage with wheat/soybean sequence (CT-S) at Gálvez; (b) no-till with crop rotation (NT-R) and no-till with wheat/soybean sequence (NT-S) at Videla.

the estimated θ_s and the water content in field capacity ($|\psi|=10$ kPa), was a little lower in NT-R (Ap = 13.4%) than in CT-S (Ap = 14.1%) at Gálvez, whereas it was higher in NT-R (Ap = 11.5%) than in NT-S (Ap = 9.5%) at Videla.

A value of 10% air-porosity is necessary to provide a sufficient amount of air for root respiration and soil biological activity (Grable and Siemer, 1968). Based on this critical threshold, all the treatments except the NT-S showed adequate aeration conditions for root growth. Kay et al. (2006) suggested that 15% would be a safer Ap value to ensure a convenient oxygen flow to the roots. Taking into account this new critical value, the results suggest that the soil at Gálvez presents a better structural condition than the soil at Videla.

Similar results were obtained by Abid and Lal (2009), who mention that the tillage system has little or no effect on the water content at saturation. Moreover, these authors found that the greatest impact of tillage on the soil pore network occurs mainly up to a soil water tension value of 6 kPa (pore radius > 25 µm), although some effects can be observed up to 300 kPa of water tension. From this value and until a water tension of 1500 kPa is reached, the differences in water retention that occur in a specific soil are mainly due to differences in the nature of the organic matter.

In this study, there were differences in the soil water retention curve until a tension value of 4 kPa in favor of CT-S at Gálvez and NT-R at Videla, which corroborates what Abid and Lal (2009) mentioned. In addition, the information suggests that the crops that take part in the rotation can affect the soil water retention differently, probably because different root systems induce the formation of pores' networks of distinct characteristics and stability.

The pore size frequency curve was calculated with the first derivative of the fitted function of the WRC for all treatments at Gálvez and Videla (Fig. 2).

The greater pore size frequency (peak of the curve) shows that in NT-R pores of larger size ($r\cong500$ µm) prevail compared with CT-S ($r\cong375$ µm) in Gálvez, which correspond to water tension values of $|\psi|\cong0.3$ kPa and $|\psi|\cong0.4$ kPa, respectively. The difference in the proportion of pores that predominate (difference of height between peaks) is very small. These results indicate that the highest K in NT-R is mainly caused by the presence of pores of larger size, which make possible greater infiltration and distribution of water in the soil profile. Wahl et al. (2004) reached a similar conclusion when comparing conventional and conservation tillage systems.

From the $|\psi|\cong4$ kPa ($r\cong37$ µm) value and until $|\psi|\cong10$ kPa ($r\cong15$ µm), the CT-S pore size frequency curve goes slightly beyond the NT-R curve. This indicates that the soil in CT-S has a greater proportion of pores in the 37–15 µm range probably because soil loosening homogenizes soil porosity, which explains why this system presents a slightly greater Ap value. From $|\psi|\cong10$ kPa, both curves overlap, indicating a similar capacity to store water, which is expected because both treatments have the same soil and similar organic matter contents. However, after a rain or irrigation, the soil under NT-R will likely contain more available water to plants since it has a greater infiltration capacity, establishing a difference in soil quality in favor of the NT-R system.

In Videla, the peak of the pore size frequency curve corresponded to approximate values of $r\cong167$ µm and $r\cong188$ µm for NT-R and NT-S, respectively. In this case, pore sizes can be considered similar; however, there is an important difference regarding the proportion of pores that prevail in favor of the NT-R, exceeding the NT-S by 13%. This

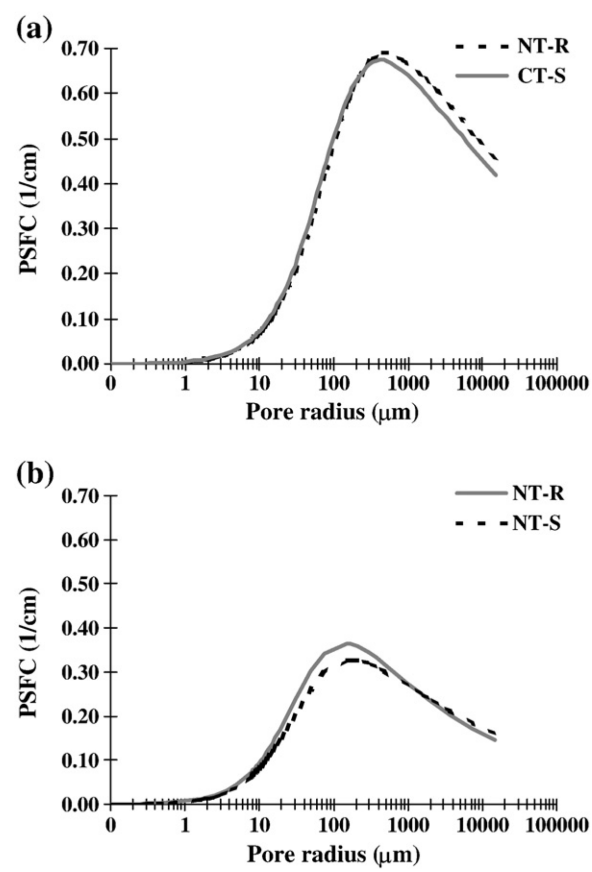

Fig. 2. Pore size frequency curve (PSFC, 1/cm) for: (a) no-till with crop rotation (NT-R) and conventional tillage with wheat/soybean sequence (CT-S) at Gálvez; (b) no-till with crop rotation (NT-R), and no-till with wheat/soybean sequence (NT-S) at Videla.

would explain the greater water retention verified in NT-R until $|\psi| \cong 10$ kPa. Starting from this value, the curves' positions are reversed, which indicates that the soil in NT-R has better capacity for supplying water to the crops.

The total macroporosity values (Ma; $|\psi| = 0.3$ kPa) were similar between the treatments in both places but greater in Galvez (NT-R Ma = 0.94%; CT-S Ma = 0.91%) than in Videla (NT-R Ma = 0.37%; NT-S Ma = 0.35%). On the other hand, conducting macroporosity ($\varepsilon_{(a,b)}$) showed significant differences between treatments (Table 5) in favor of NT-R at Gálvez and Videla. In general, $\varepsilon_{(a,b)}$ values were by a factor nearly 10 lower than Ma, which agrees with what other authors have determined (Bodhinayake and Si, 2004). The difference is attributed to the fact that Ma is determined from the WRC, and consequently it is associated with the soil capacity to hold water. Buczko et al. (2006) also found greater $\varepsilon_{(a,b)}$ values in soils under conservationist tillage than in those under conventional tillage.

Effective porosity values, θ_m and $\theta_{\Delta\psi}$, determined by Watson and Luxmoore (1986) and Moret and Arrúe (2007a) methods, were also significantly higher in NT-R at Gálvez and Videla. In addition, it was verified that the θ_m values were higher than the $\theta_{\Delta\psi}$, values by one to six times and than those of $\varepsilon_{(a,b)}$, by about five to ten times.

A possible explanation for these results is that to calculate θ_m, the minimum pore radius is used according to Eq. (1). Therefore, the calculation results in the maximum number of pores that will remain full of water at the applied tension and hence in maximum water-conducting porosity. Conversely, the mean radius of pores that effectively transport water in the soil at certain tensions is used to obtain $\theta_{\Delta\psi}$ (Reynolds et al., 1995). This process is very much affected by pore constrictions (entrapped air bubbles and differences in the size of the pore's neck) (Wahl et al., 2004). This means that the effective macroporosity values calculated with Eq. (1) should be greater than those determined with the mean radius or with equations that consider pores that effectively transport water, as shown by the results of this study.

The conducting porosity calculated from TI data describes the soil capability to effectively transport water. In addition, WRC are drainage curves while the curve determined with TI is a wetting curve; then, the differences can be due to hysteresis. For this reason, Buczko et al. (2006) used the conducting macroporosity/total macroporosity ratio ($\varepsilon_{(a,b)}$/Ma) as an indicator of the pore tortuosity and the presence of blocked pores. The $\varepsilon_{(a,b)}$/Ma relationship was greater in NT-R (0.002) than in CT-S (0.001) at Gálvez, and in NT-R (0.005) than in NT-S (0.003) at Videla. These results confirm that in NT-R treatments soils have a better-developed and interconnected macropore network.

The mean pore radius, $\lambda_{\Delta\psi}$, was greater in NT-R at Gálvez, and in NT-S at Videla, contrary to what was expected (Table 5). However, the number of effective pores per unit area between two tensions, $N_{\Delta\psi}$, was significantly greater in NT-R at Gálvez and in NT-R at Videla (Table 5). An identical result was obtained for the number of macropores that transport water per unit area, N_m, although in all the cases, N_m was greater than $N_{\Delta\psi}$. These results indicate that the lowest effective porosity seen in the NT-S treatment at Videla was determined by a small number of pores that effectively transported water, although they had greater $\lambda_{\Delta\psi}$. In Gálvez, the greatest $N_{\Delta\psi}$ and $\lambda_{\Delta\psi}$ plus the lower tortuosity (greatest $\varepsilon_{(a,b)}$/Ma) are responsible for the greatest effective macroporosity in the NT-R treatment.

As a corollary of the analysis of all this information, it can be said that in Gálvez the soil shows better structural quality in the NT-R treatment because it has more hydraulically active pores of greater size and, consequently, better infiltration and redistribution of water along with appropriate aeration. In Videla, as the tillage system was identical, the differences between NT-R and NT-S can be attributed to the greater proportion of graminaceous species in the crop rotation, specifically, the corn.

These findings emphasize the importance of including a high proportion of graminaceous species of great root production into the crop rotation, especially in soils of low resilience, such as the studied silty-loam soils. The particular characteristic of the rooting system of the corn associated with the greater biomass production may have contributed to the generation of a large number of continuous macropores of smaller tortuosity, which was enough to ensure better water and air dynamics in NT-R.

Intensive farming of the soil with conventional tillage produced degradation of the physical quality, and the wheat/soybean sequence was not adequate to stop that process. Moreover, this sequence was not appropriate for maintaining or for improving the soil physical quality in the no-till systems. Similar results were determined by other authors in Argentina (Sasal et al., 2006; Aparicio and Costa, 2007).

An important aspect to be kept in mind is that in the WRC determination, the second point measured generally corresponds to a tension value of 0.5 kPa. This implies that the WRC have little sensitivity to evaluate soil porosity differences in the tension range from 0 to 0.5 kPa. The TI allows the evaluation of soil porosity in that tension range, which in fact corresponds to the interval in which the WRC do not provide information. The results of this study highlight the importance of using both methodologies jointly because they provide complementary information, which in turn allows a better evaluation of the soils physical quality.

4. Conclusions

The evaluated indicators showed that the soil pore network characteristics are affected not only by the tillage system but also by the crops chosen for the rotation. Soils show a better structural quality in no-till systems that contain a greater proportion of graminaceous species in the rotation. The pore network includes a greater number of

Table 5
Indicators of soil porosity calculated according to different methodologies for all treatments in the typical Argiudoll, Loma Alta series (Gálvez) and typical Argiudoll, San Justo series (Videla).

Treatment	WRC	Watson and Luxmoore (1986)		Moret and Arrúe (2007a)			Bodhinayake et al. (2004)
	Ma %	N_m num. m^{-2}	θ_m %	$\lambda_{\Delta\tau}$ µm	$N_{\Delta\tau}$ macr. m^{-2}	$\theta_{\Delta\tau}$ %	$\varepsilon_{(a,b)}$ %
Gálvez							
NT-R	0.94	152a	0.0119a	900	21a	0.0045a	0.0014a
CT-S	0.91	117b	0.0092b	800	12b	0.0030b	0.0010b
Videla							
NT-R	0.37	183a	0.0144a	700b	56a	0.0079a	0.0019a
NT-S	0.35	76b	0.0060b	1300a	2b	0.0009b	0.0011b

Ma: static macroporosity; N_m: number of hydraulically effective macropores per unit area; θ_m: hydraulically effective macroporosity; $\lambda_{\Delta\tau}$: representative mean pore radius between two tensions; $N_{\Delta\tau}$: number of effective pores per unit area; $\theta_{\Delta\tau}$: effective porosity between two tensions; $\varepsilon_{(a,b)}$: dynamic macroporosity. Values followed by the same letter in each column for each place are not significantly different ($P<0.05$).

hydraulically active big pores that make soils have better water and gases dynamics, and similar proportion of water storage pores in comparison with systems that do not include graminaceous species. Both methodologies, when used jointly, can be very useful tools in monitoring the evolution of the physical quality of the soils.

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