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STABILIZATION OF SOIL HYDRAULIC PROPERTIES UNDER A LONG TERM NO-TILL SYSTEM[1]

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SUMMARY

The area under the no-tillage system (NT) has been increasing over the last few years. Some authors indicate that stabilization of soil physical properties is reached after some years under NT while other authors debate this. The objective of this study was to determine the effect of the last crop in the rotation sequence (1st year: maize, 2nd year: soybean, 3rd year: wheat/soybean) on soil pore configuration and hydraulic properties in two different soils (site 1: loam, site 2: sandy loam) from the Argentinean Pampas region under long-term NT treatments in order to determine if stabilization of soil physical properties is reached apart from a specific time in the crop sequence. In addition, we compared two procedures for evaluating water-conducting macroporosities, and evaluated the efficiency of the pedotransfer function ROSETTA in estimating the parameters of the van Genuchten-Mualem (VGM) model in these soils. Soil pore configuration and hydraulic properties were not stable and changed according to the crop sequence and the last crop grown in both sites. For both sites, saturated hydraulic conductivity, K_0, water-conducting macroporosity, ε_{ma}, and flow-weighted mean pore radius, R_{0ma}, increased from the 1st to the 2nd year of the crop sequence, and this was attributed to the creation of water-conducting macropores by the maize roots. The VGM model adequately described the water retention curve (WRC) for these soils, but not the hydraulic conductivity (K) *vs* tension (h) curve. The ROSETTA function failed in the estimation of these parameters. In summary, mean values of K_0 ranged from 0.74 to 3.88 cm h^{-1}. In studies on NT effects on soil physical properties, the crop effect must be considered.

Index terms: infiltration, crop rotation, water-conducting porosity, no tillage, texture.

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RESUMO: *ESTABILIDADE DAS PROPRIEDADES HIDRÁULICAS DO SOLO EM UM SISTEMA DE PLANTIO DIRETO EM LONGO PRAZO*

Nos últimos anos, o sistema plantio direto (NT) tem aumentado. Alguns autores indicam que os atributos físicos do solo ficam estáveis após anos cultivando nesse sistema, sendo esse fato discutido por outros autores. O objetivo deste trabalho foi avaliar o efeito do último cultivo após a rotação (1º ano: milho; 2º ano: soja; e 3º ano: trigo/soja) sobre a configuração do sistema poroso do solo e das suas propriedades hidráulicas de diferentes tipos de textura (solo 1: franco; e solo 2: franco-arenoso) da região do pampa argentino, em NT por um longo prazo, para determinar se a estabilidade das propriedades físicas do solo independe do momento da rotação. Adicionalmente, foram comparados os procedimentos para avaliar a macroporosidade, bem como avaliada a eficiência da função de pedotransferência ROSETTA, para estimar os parâmetros do modelo de van Genuchten-Mualen (VGM) desses solos. A configuração do sistema poroso do solo e as propriedades hidráulicas não foram estáveis e se alteraram em razão da rotação da cultura e do último cultivo utilizado na rotação em ambos os solos. Nos dois locais, a condutividade hidráulica do solo saturado (K_0), a macroporosidade (ε_{ma}) e o raio médio ponderado do poro por fluxo (R_{0ma}) aumentaram do 1º para o 2º ano da rotação de culturas e isso se atribuiu ao aumento de macroporos condutores de água pra as raízes de milho. O modelo VGM descreveu adequadamente a curva de retenção de água (WCR) nos dois solos, porém não foi adequada para as curvas de condutividade hidráulica (K) vs tensão (h). A função ROSETTA não foi eficiente para a estimativa dos parâmetros. Em resumo, os valores médios de K_0 variaram entre 0,74 e 3,88 cm h^{-1}. Com relação às propriedades físicas do solo no NT, o efeito do cultivo deve ser considerado.

Termos de indexação: infiltração, rotação de culturas, porosidade condutora de água, plantio direto, textura.

INTRODUCTION

The area under the no-tillage system (NT) has been increasing over the last few years. The area under this soil management system currently occupies 1,000,000 km^2 worldwide (Kassam et al., 2009). Half of this area is located in South America. Argentina is among the countries with a large area under NT, with 270,000 km^2, which constitutes about 78 % of the whole cultivated area in the country (AAPRESID, 2012). In South America this cropping system was incorporated en masse without carefully evaluation of its effects on soil properties. Economics, time savings, and soil conservation have been the main factors responsible for the widespread adoption of NT in Argentina since the 1990s (Álvarez et al., 2009).

To apply precision agricultural practices for efficient resource management and crop yield enhancement, it is necessary to improve our understanding of the temporal variability of soil properties under continuous management practices (Strudley et al., 2008). In general, it is assumed that stabilization of soil properties is reached after five years under NT (Wander & Bollero, 1999; Rhoton, 2000; Álvarez et al., 2009). Moreover, some authors have used this assumption to compare plots under NT regardless of the time in the crop sequence, and/or of the time under NT, if the plot has been under this management practice for more than five years (Wander & Bollero, 1999; Álvarez et al., 2009; Imhoff et al., 2010). Nevertheless, other authors have studied the temporal variability of soil physical properties under NT, without coming to general agreement.

Rhoton (2000) evaluated the number of growing seasons required for NT practices to improve soil properties. The author concluded that the differences in soil properties between conventional tillage (CT) and NT treatments were essentially independent of the crop. According to the author, NT practices can improve several fertility and erodibility-related properties of the soil within four years, and enhance its sustainability. Dick et al. (1989) indicated that changes in soil hydrology, created by the imposition of NT practices, are evident only three years after the last tillage operation. For aggregate stability, no changes were reported after five years (West et al., 1991); and for bulk density (BD), no differences were recorded after 10 years (Blevins et al., 1983; Edwards et al., 1992). In contrast, Moret & Arrúe (2007), in a 10-year trial, found increasing values of BD measured three consecutive years, while Díaz-Zorita et al. (2004) in a trial of more than 20 years under NT, found differences in soil BD measured two consecutive years. Abril et al. (2005) found increased contents of organic matter (OM) measured after five and after 10 years under NT. Yang & Wander (1998) found changes over time in the mean size of dry aggregates in a soil under NT for nine years, measured over two consecutive years. Fernández (2011) found changes in BD in soils under NT with a maize-soybean crop sequence, depending on the year. These changes were higher in Argiudolls with silty loam texture than in Hapludolls with loam or sandy loam texture. The author attributed these different behaviors to the more rigid structure of the sandy soil. She also found an effect of time on soil resistance to penetration, and on the infiltration rate. VandenBygaart et al. (1999) studying changes in the soil pore system under NT over time found no changes in macroporosity after four years under NT, and no changes in microporosity after six years. These authors found that rounded pores and biopores continued increasing in number after 11 years under NT.

Even when stabilization of soil properties for a long-term NT practice was reported (Rhoton, 2000; Ben Moussa-Machraoui et al., 2010), some authors found changes in soil physical properties due to the influence of previous cropping. Papadopoulos et al. (2006) stated that soil structure can be greatly affected by agricultural management practices, such as crop rotation. Different effects of alternate crops appear to be related to crop abilities in promoting soil structure regeneration and stabilization (Chan & Heenan, 1996). For example, exudates of maize (*Zea mays*) roots increased aggregate stability as of seven days (Gregory, 2006). Wheat (*Triticum aestivum*) roots were found to be more effective than pea (*Pisum sativum*) roots in promoting aggregation (Gregory, 2006).

Measurement of soil physical properties such as hydraulic conductivity (K) at different soil water pressure heads, and quantification of water-conducting macroporosity (ε_{ma}) and total macroporosity (θ_{ma}) is important for improving understanding of soil physical behavior. The properties of the soil macropore network, i.e., macropore volume fraction and diameter and continuity of macropores, have a big impact on the infiltration characteristics of agricultural soils (Hillel, 1998). Studies to quantify macropore flow revealed that more than 70 % of 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 they constitute only a very small fraction of total porosity (Cameira et al., 2003). The tension disc infiltrometer is a valuable tool for understanding water movement through macropores and the soil matrix near saturation (Watson & Luxmoore, 1986; Logsdon & Jaynes 1993; Moret & Arrúe, 2007), and for studying the effects of different practices on soil surface hydraulic properties (Malone et al., 2003; Moret & Arrúe, 2007). This device allows estimation of K from saturation to a few centimeters of suction head (Angulo-Jaramillo et al., 2000; Soracco, 2009) and quantification of the role of macropores during infiltration (Bodhinayake et al., 2004). This technique requires only minimal disturbance of the soil.

Measurement of K at different soil water pressure heads (h), and quantification of ε_{ma} and θ_{ma}, together with total porosity (TP) at different moments of the crop rotation and with soils of different texture under continuous NT practice, could help improve our understanding of the temporal variability of soil pore configuration and related hydraulic properties, and its dependence on alternate crops. In contrast, measurement of the K (h) curve and water retention curve (WRC) of soils is expensive, time consuming, and labor intensive; and that is why the use of pedotransfer functions (PTF - models that predict these curves from more available data such as particle size distribution, organic matter (OM) content, etc.) has become popular (Cornelis et al., 2001; Schaap et al., 2001; Soracco et al., 2010a). Due to the importance of the WRC and K (h) curve for many processes, it is important to evaluate the efficiency of a PTF that is available, easy to use, and created through the use of a wide database.

We hypothesized that after a long period under NT management, the soil porous system configuration and saturated hydraulic conductivity, K_0, reach stable values independent of the crop. This is applicable to soils of different texture. We also hypothesized that the van Genuchten-Mualem model (van Genuchten, 1980; referred to as the VGM model) adequately describes the water retention curve (WRC) and the K(h) curve in these soils, and that ROSETTA (Schaap et al., 2001) is a reliable program for estimating the parameters of the VGM model for these soils.

The objectives of this study were to determine the effect of the last crop on soil pore configuration and hydraulic properties in two different soils under long-term NT treatments using the tension disc infiltrometer and water retention curve (WRC) data in order to determine if stabilization is reached apart from a specific time in the crop sequence, to compare two procedures to evaluate water-conducting porosity, and to test the efficiency of ROSETTA in a single situation in both sites comparing the parameters of the VGM model obtained by inverse parameterization (IP) of data and the parameters estimated by ROSETTA from basic soil data.

MATERIALS AND METHODS

Sites and experimental design

The study was carried out at two sites of the Pampas Region, located near the town of Lobos (35° 14' S, 59° 11' W) (altitude 23 m asl) and near the town of Norberto de la Riestra (35° 18' S, 59° 35' W) (altitude 40 m asl), Argentina.

The soil at the first site (site 1) was classified as a fine, mixed, thermic Typic Argiudoll (USDA, 2006), or Luvic Phaeozem (IUSS Working Group WRB, 2006). The soil at the second site (site 2) was classified as a sandy, mixed, thermic Entic Hapludoll (USDA, 2006), or Haplic Phaeozem (IUSS Working Group WRB, 2006). Argiudolls and Hapludolls are the most common soil types in the Pampas region (Rimski-Korsakov et al., 2004).

The plots under study (50 × 100 m) had a 20-year history under the NT system and under the same crop sequence. At both sites, a 3-year crop sequence of maize (first year), full-season soybean (second year), and wheat and short-season soybean (third year) was used for the past 20 years. Here NT system refers to a system in which only a narrow (0.05 m) strip of the soil is drilled to deposit crop seeds. Crops were mechanically managed and harvested. Prior to NT, both sites were under conventional tillage for more than 20 years.

The climate in the region is temperate (the temperature seldom goes below 0 °C) and approximate annual rainfall is 1,000 mm.

Infiltration runs and sample extractions were performed at the end of each year of the crop sequence at each site, immediately after harvest (during the month of June), a few months before seeding of the subsequent crop, for three consecutive years. We considered the last crop as a factor with three levels: maize (mz), full-season soybean (fssb), and wheat and short-season soybean (sssb).

In-situ infiltration test

The tension disc infiltrometer (Perroux & White, 1988) was used to determine the steady-state infiltration rate. Infiltration tests were carried out for three consecutive years during the fallow period (June 2008, June 2009, and June 2010) after harvest.

The infiltrometer disc had a base radius of 6.25 cm. Infiltration measurements were conducted at ten randomly selected sites in each plot. To consider only the effects of tillage on soil water infiltration, 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 three values of water pressure heads, h (namely, -6, -3, 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 continued until steady-state flow from the disc was attained. Cumulative infiltration was recorded every min until 10 min, every 5 min until 30 min, and every 10 min until the end of the test. When the amount of water entering the soil did not change with time for four consecutive measurements taken at 10 min intervals, steady-state flow was assumed and the steady-state infiltration rate was calculated based on the last four measurements. The time necessary 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_6, K_3, and K_0) were thus calculated from the cumulative water infiltration using the multiple-head method (Ankeny et al., 1991). Most of the decrease in water conductance is expected to occur at hydraulic pressure heads close to zero due to a reduction in different groups of macropores (Gebhardt et al., 2009). The procedure used to obtain K was based on analysis of steady-state flux from the tension disc infiltrometer and its dependence on the water pressure head. This dependence was described by Gardner's exponential model (Gardner, 1958).

Total and water-conducting macro- and mesoporosity and flow-weighted mean pore radius

Soil total macroporosity (θ_{ma}, %; r > 30 µm) was calculated from soil water retention at -50 cm water pressure head. This was measured using the tension table with a hanging water column on undisturbed soil samples (10 samples for each site and last crop, a total of 60 samples). The complete WRC, using a tension table (-10, -30, -50, -70, and -100 cm of water column) and water pressure chamber (0.333, 1.0, and 15 bar), was measured at both sites for the 2nd year of the crop sequence (fssb).

Water-conducting (or effective) macro- and mesoporosity (ε_{ma}, and ε_{me}, respectively) were calculated using the Watson and Luxmoore (WL) procedure and the Reynolds (Ry) procedure.

WL method

The classical capillary rise equation allows calculation of the maximum water-filled pore equivalent radius, r [L], at a specific soil water pressure head, h [L]:

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

where σ is the surface tension of water [M T^{-1}], α is the contact angle between water and the pore wall (assumed to be zero), ρ is the density of water [M L^{-3}], and g is the acceleration due to gravity [L T^{-2}]. We were aware of the fact that α could differ from 0°. Woche et al. (2005) analyzed the dependence between the contact angle and the soil texture and observed small contact angles of 0° to 20° for silty loam soils. Moreover, α strongly depends on water content and probably approached 0° after sufficient infiltration time (Buczko et al., 2006).

The WL procedure assumes that the equivalent pores with radii smaller than r calculated from equation 1 are full of water and are responsible for the entire flux of water under a given water pressure head, and that the equivalent pores with radii larger than the value calculated from equation 1 do not contribute to the water flux. The hydraulically active (or water-conducting) porosity, conducting water in the pressure head interval corresponding to the two pore radii ra and rb (ra ≤ rb) and ε (ra, rb) (assuming pore radius equal to the minimum equivalent pore radius), is then given by (Watson & Luxmoore, 1986):

$$\varepsilon(ra,rb) = \frac{8\eta\Delta K(ra,rb)}{\rho g(ra)^2} \tag{2}$$

where ΔK (ra, rb) is the difference in K values in the pressure head interval corresponding to ra and rb, η is the dynamic viscosity of water [$M\ L^{-1}\ T^{-1}$], ρ is the density of water [$M\ L^{-3}$], and *g* is the acceleration due to gravity [$L\ T^{-2}$]). Since ra is the minimum equivalent pore radius in the range, ε (ra, rb) is an estimation of the maximum water-conducting porosity. Implicitly assumed in equation 2 is a unit hydraulic gradient, i.e. steady-state conditions during infiltration (Wahl et al., 2004).

According to equation 1, infiltration at water pressure heads of -3 and -6 cm will exclude pores with equivalent diameters >1 mm, and >0.5 mm, respectively. In our study we defined water-conducting macropores (ε_{ma}) as those pores draining at h > -3 cm (equivalent r > 0.5 mm), and water-conducting mesopores (ε_{me}) as those draining at h from -3 to -6 cm (0.5 mm > equivalent r > 0.25 mm).

Ry method

Watson & Luxmoore (1986) calculated the water-conducting porosities using the minimum equivalent pore radius, calculated using equation 1 in the range. This introduces an inconsistency, however, because K in equation 2 relates to the range of pore sizes participating in water transmission, whereas equivalent r, equation 1, relates to the maximum pore size for water storage (Bodhinayake et al., 2004). Reynolds et al. (1995) proposed using the flow-weighted mean pore radius R_0 (L), which represents an effective equivalent mean pore radius that is conducting water at a certain supply pressure head, and it has been used to characterize temporal and tillage-induced changes in water-conducting macropores (Messing & Jarvis, 1993; Reynolds et al., 1995; Sauer et al., 1990; Schwen et al., 2011). Following Reynolds et al. (1995), R_0 is defined by

$$R_0 = \frac{\sigma K_0}{\rho g M_0} \tag{3}$$

where, M_0 [$L^2\ T^{-1}$] is the matric flux potential of a soil, measured over the pore water pressure head range, where pores are considered to be water conducting, and can be calculated by:

$$M_0 = \int K(h)dh \tag{4}$$

As stated by the authors, R_0 as compared with storage-based r, better reûects the effects of pore restrictions, such as entrapped air bubbles or small unwetted zones.

Generally, R_0 indicates that with increasing h, larger pores become water conducting (Reynolds et al., 1995). Applying equation 1, we also calculated the maximum equivalent pore radius, C, that can be water conducting at a given supply pressure head (Reynolds et al., 1995; Moret & Arrúe, 2007).

Estimation of soil hydraulic parameters by inverse parameterization (IP) and by ROSETTA

To describe the unsaturated soil hydraulic properties, we used the van Genuchten-Mualem (VGM) model (Mualem, 1976; van Genuchten, 1980). The soil water retention $S_e(h)$ and hydraulic conductivity K(θ) functions are given by

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha_{VG} h|^n\right)^m} \tag{5}$$

$$K(\theta) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{6}$$

where, S_e is the effective water content, θ_r and θ_s denote the residual and saturated water contents, respectively [$L^3\ L^{-3}$], l is a pore-connectivity parameter, and α_{VG} [L^{-1}], n, and m (= 1 - 1/n) are empirical parameters. To reduce the number of unknown variables, for all parameter estimations, l was set constant at 0.5 (Schwen et al., 2011).

Inverse parameterization (IP) of the VGM model from WRC and K data was used in both sites, using the complete WRC data obtained in the lab in the second year of the crop sequence (see section 2.3), and the K *vs* h data was obtained using infiltration data in this year of the crop sequence (see section 2.2). RETC code (van Genuchten et al., 1991) was used in this analysis. The residual sum of squares and goodness of fit (r^2) were calculated.

The values of the VGM model parameters obtained by IP were compared with those obtained using the computer program ROSETTA 1.0 (Schaap et al., 2001), which uses hierarchical pedotransfer functions, and includes wide soil databases from North America and Europe. All possible input parameters (sand, silt, and clay content, BD, and water content at 33 and 1500 kPa) were included in the prediction.

Other measurements

Soil structure was assessed in the field at each sampling time. Bulk density (BD) was measured at each site and time period using the core method (Blake & Hartge, 1986). Ten replications for each treatment were considered. Additionally, particle size distribution using the pipette method, and the organic matter (OM) content (%) using the Walkley-Black method were determined for each site on the first sampling date.

Statistical analysis

In order to determine the factor effects, K_0, BD, and pore size fractions were analyzed for each site separately using ANOVA, with the crop as a factor (Sokal & Rohlf, 1995). The least significant difference

(LSD) multiple comparison test was used to compare the means of the different treatments. The Kolmogorov-Smirnov test was applied to determine if replicates of measured quantities within a treatment were normally or log-normally distributed. All statistical tests on K_0 were carried out using the log of the data, as the statistical frequency distribution of the K_0 data was log-normal, which is usual for this soil property (Bagarello et al., 2006). The BD and pore size fractions were normally distributed, and thus, no transformations were performed on these variables. For all analyses, significance was determined at p=0.05.

RESULTS AND DISCUSSION

General characteristics

The organic matter (OM) content of the A horizon was 51 g kg^{-1} for site 1 and 27 g kg^{-1} for site 2. The particle size distribution of the A horizon of site I exhibited 200 g kg^{-1} clay, 480 g kg^{-1} silt, and 320 g kg^{-1} sand, and was classified as loam. For site 2, particle size distribution exhibited 100 g kg^{-1} clay, 19 g kg^{-1} silt, and 71 g kg^{-1} sand, and was classified as sandy loam (USDA, 2006). The soil structure was laminar in the first few centimeters in site 1, while a surface subangular blocky structure was observed in site 2. These structural forms did not vary depending on the last crop. Surface laminar structure in silty loam soils under NT has been widely reported (Sasal et al., 2006, Álvarez et al., 2009, Soracco et al., 2010b). In our study, we found platy structure in a loam soil with 480 g kg^{-1} of silt content. This kind of structure has a negative impact on soil water infiltration (Sasal et al., 2006, Álvarez et al., 2009, Soracco et al., 2010b).

Last crop effects on soil hydraulic properties and on soil porosity

Bulk density, K_0, and pore size fractions corresponding to the treatments for both sites are shown in table 1.

For the loam soil (site 1), the different crops had a significant effect on ε_{maWL}, ε_{meWL}, ε_{maR}, ε_{meR}, R_{0ma}, R_{0ma}, R_{0me}, and θ_{ma}, while BD was not affected. Several authors found stabilization of BD after some years under NT (Blevins et al., 1983; Edwards et al., 1992; Díaz-Zorita et al., 2004), while others found the opposite (Moret & Arrúe, 2007). The results show that ε_{ma},, R_{0ma}, and θ_{ma} did not reach steady values after long-term NT treatment in this soil, but were dependent on the crop. The results are in agreement with the fact that crops mainly affect soil macroporosity (Wahl et al., 2004; Strudley et al., 2008). The results are in disagreement with Rhoton (2000), who concluded that changes in soil properties were independent of the crop. However, ε_{maWL} and R_{0ma} increased, and θ_{ma} decreased from the first to the second year of the crop sequence (Table 1). In site 1, a surface laminar structure was observed each year. Machine traffic can form an anisotropic soil pore system, with a platy structure in the upper few centimeters and elongated pores that are oriented parallel to the soil surface. These pores do not contribute to water entry into the soil (Pagliai et al., 2003; Soracco et al., 2010b). Small changes in the surface due to different crop root systems and soil cover can lead to an increase in macropore conductivity. Changes in the pore system due to different practices related to different crops lead to a decrease in θ_{ma} and to an increase in ε_{ma} if the root system generates vertical continuous macropores. A monocotyledonous root system, such as that of maize, is composed of numerous secondary roots which enhance the root system by increasing total root mass and the total area exploited by this root system. This system is strong and helps to create a continuous and vertically-oriented macroporosity (Fahad et al., 1982; Bathke & Blake, 1984). When these roots decay, these continuous macropores became hydraulically active. This explains the increase for site I in ε_{maWL} and R_{0ma} between the 1st and the 2nd year in the crop sequence. The creation of macropores in the soybean root system is more limited (Bathke & Blake, 1984). ε_{ma} decreased from the 2nd to the 3rd year of the crop rotation, but it reached a value higher than that of the first year of the crop sequence. The increase in R_{0ma} from the 1st to the 3rd year of the crop sequence indicates that the maize root system improved pore connectivity, possibly due to an enhanced soil structure (Schwen et al., 2011), and this may reflect a greater number of persistent cracks, worm holes, root channels, etc. (Reynolds et al., 1995). In contrast, the decrease in θ_{ma} from the 1st to the 3rd year of the crop sequence could be due to the cumulative effect of machine traffic since under NT with random traffic, 100 % of the soil area is being trafficked by wheels (Rasaily et al., 2011). The decrease in ε_{ma} from the second to the 3rd year of the crop sequence may be due to the cumulative effect of traffic since the 3rd year includes a double crop of wheat/soybean.

For the sandy loam soil (site 2), the time period in the crop sequence significantly affected BD, and also affected ε_{maWL}, ε_{maR}, ε_{meR}, R_{0ma}, and R_{0me}, while θ_{ma} was not affected by the last crop. Bulk density was significantly greater after maize harvest than after soybean harvest. This result indicates that, for this sandy loam soil, BD did not reach a steady value after a long period under NT, which is in agreement with the previous report by Fernández (2011). ε_{maWL} and R_{0ma} increased from maize harvest to full-season soybean harvest, and decreased after short-season soybean harvest, reaching the same values of those of the 3rd year. The increase in ε_{maWL} and R_{0ma} from the 1st to the 2nd year in the crop sequence may be due to the decay of maize roots, which are strong and create continuous macropores (Fahad et al., 1982; Bathke

Table 1. Values of bulk density (BD), saturated hydraulic conductivity (K_0), total macroporosity (θ_{ma}), water-conducting macro- and mesoporosity (ε_{ma} and ε_{me}) calculated by two methods (WL and R), and flow-weighted mean pore radius in the macropore and in the mesopore range (R_{0ma} and R_{0me}, mm) depending on the year in the crop rotation for each site

Site	Year	BD	K_0	θ_{ma}	ε_{maWL} (1)	ε_{meWL}	R_{0ma} (2)	ε_{maR}	R_{0me}	ε_{meR}
		kg dm^{-3}	cm h^{-1}	m^3 m^{-3} × 100			mm	m^3 m^{-3} × 100	mm	
1	1st (Mz)	1.33 a	0.74 a	14.8 b	0.0004 a	0.0006 a	0.07 a	0.019 b	0.04 a	0.025 c
	2nd (Fssb)	1.31 a	3.88 c	12.9 ab	0.0094 c	0.0012 b	0.18 b	0.025 b	0.06 a	0.018 b
	3rd (Sssb)	1.26 a	2.38 b	10.8 a	0.0017 b	0.0009 a	0.26 c	0.006 a	0.14 b	0.002 a
2	1st (Mz)	1.44 a	1.55 a	13.9 a	0.0010 a	0.0010 a	0.13 a	0.015 b	0.06 a	0.018 b
	2nd (Fssb)	1.33 b	2.54 b	14.4 a	0.0044 b	0.0013 a	0.23 b	0.008 a	0.14 b	0.004 a
	3rd (Sssb)	1.33 b	1.28 a	15.2 a	0.0007 a	0.0008 a	0.17 a	0.006 a	0.12 b	0.003 a

(1) Watson & Luxmoore (1986) method; (2) Reynolds et al. (1995) method. Values followed by the same letter in each column, for each site, are not significantly different (LSD test; p=0.05). Mz: after maize harvest; Fssb: after full-season soybean harvest; Sssb: after short-season soybean harvest. Statistical analysis on K_0 was performed on log-transformed values.

& Blake, 1984). The reduction in ε_{maWL} and R_{0ma} from the 2nd to the 3rd year of the crop sequence was attributed to the cumulative traffic associated with the double crop of wheat/short-season soybean in the 3rd year of the crop sequence. Furthermore, the results show that the water-conducting porosity created by maize roots in the sandy loam soil were less stable than the water-conducting porosity in the loam soil. The OM content of this sandy loam soil was about one half that of the loam soil (2.7 and 5.1 %, see section 3.1). Soils with lower OM content are more susceptible to compaction (Aragón et al., 2000). θ_{ma} was not affected by the crop. The results show that in this soil only the connectivity and conductivity of macropores were affected, while the total volume did not change over time and with the crop, which is in agreement with the fact that soil compaction affects not only pore volume but also soil pore configuration (Green et al., 2003; Horn et al., 2003). The complex behavior of ε_{maR} and ε_{meR} can be explained by the fact that K depends on water-conducting porosity and on R_0 (Reynolds et al., 1995). Thus, for a given K, a "small" R_{0ma} value is compensated by a "large" ε_{maR} value, and *vice versa*.

Field saturated hydraulic conductivity, K_0, was significantly affected by the last crop at both sites (p=0.05), following a tendency similar to ε_{maWL}, R_{0ma}, and R_{0me}. This result is in agreement with the fact that K_0 depends mainly on macroporosity (Cameira et al., 2003; Moret & Arrúe, 2007). The ε_{maWL}, R_{0ma}, and R_{0me} values were in agreement with previous reports (Reynolds et al., 1995; Schwen et al., 2011).

The BD and K_0 values did not follow the same tendency at either site (Table 1). Alaoui et al. (2011) emphasized that BD, as an indicator of soil compaction, integrates information about total change in the volume of voids, but it cannot account for changes in the volume distribution of these voids, their connectivity, or the changes in this connectivity.

Moreover, θ_{ma} and K_0 did not follow the same tendency. At site 1, θ_{ma} decreased while K_0 increased from maize to soybean. In site 2, θ_{ma} did not vary significantly among the years, while K_0 did. These results show that changes in θ_{ma} do not necessarily affect infiltration. The connectivity of macropores must be considered (Horn et al., 2003; Wahl et al., 2004; Alaoui et al., 2011).

Nevertheless, measured K_0 values were low, showing that these soils, after a long period under NT, did not reach a good physical condition. The same can be said about pore size fractions. This is in agreement with Álvarez et al. (2009), who concluded that physical properties of soils from the Pampas region showed deterioration in cropped soils and manifested little or no recovery from CT to NT.

Overall, in these two soils of different texture from the Pampas region, soil pore configuration and hydraulic properties were not stable and changed over the crop sequence, depending on the last crop, even when both soils had been under NT for 20 years, showing that in future studies of soil properties under NT, the time period in the crop sequence should not be excluded from analysis.

Water-conducting porosities and flow-weighted mean pore radius

Water-conducting porosities calculated by the WL method were one to two orders of magnitude lower compared with those calculated using the Ry method. The difference is due to the radius considered in equation 2. Watson & Luxmoore (1986) calculated the water-conducting porosities using the minimum equivalent pore radius r in the range (Equation 1). However, this introduces an inconsistency because K in equation 2 relates to the range of pore sizes participating in water transmission, whereas the equivalent r relates to the maximum pore size for water storage (Bodhinayake et al., 2004). As stated by Reynolds et al. (1995), R_0, compared to storage-based C, better reflects the effects of pore restrictions, such as entrapped air bubbles or small unwetted zones. C defines a "maximum" equivalent pore radius for water storage, whereas R_0 defines an "average" equivalent pore radius for water transmission. In other words, the flow-based R_0 value includes the effects of pore constrictions (e.g., entrapped air bubbles, small unwetted zones, etc.) to a much greater extent than the storage-based C value.

Generally, R_0 indicates that with increasing h, larger pores become water conducting (Reynolds et al., 1995). Compared to the maximum equivalent pore radius C, R_0 was smaller for all measurements (Figure 1). Thus, differences between C and R_0 indicate a reduction of pore connectivity, leaving a certain fraction of pore space disconnected from the water-conducting pores. This difference was greatest close to saturation, where flow is controlled by macropores. Connectivity was greatest in the mesopore range, in agreement with previous reports (Ehlers et al., 1995; Schwen et al., 2011). The smallest difference over the measured pressure head range was observed for both sites in the 2nd year of the crop sequence, indicating better connectivity of the pores after maize, possibly due to better soil structure, well-established biological activity (e.g., earthworm burrows), and the presence of root channels (Schwen et al., 2011).

The complex relationships among K_0, θ_{ma}, ε_{ma}, ε_{me}, R_0, and C_0 for both sites suggest that the water transmission properties of near-saturated field soils are determined by intricate, nonlinear, and often compensating interactions among the size, number, and morphology of the water-conducting macropores (Reynolds et al., 1995).

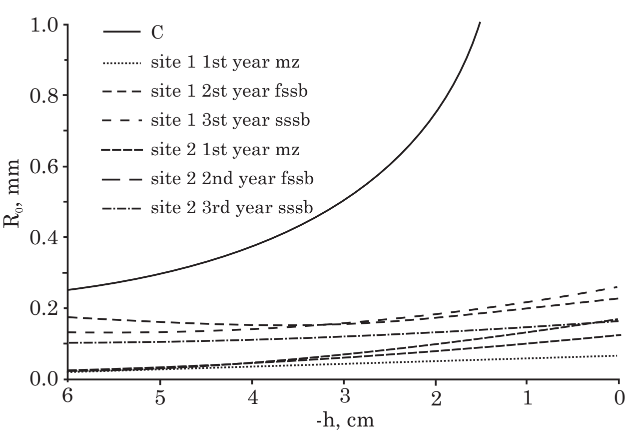

Figure 1. Flow-weighted mean pore radius R_0 *versus* pressure head h in the range of the tension inûltrometer measurements. The solid line denotes the maximum equivalent pore radius C. R_0 was calculated using the approach of Reynolds et al. (1995). Representative mean curves for the treatments at both sites are shown.

Efficiency of ROSETTA on estimation of water retention and conductivity

Inverse parameterization (IP) of the VGM model from WRC and K data was used at both sites from data of the 2nd year of the crop sequence. The values of these parameters were compared with those obtained using ROSETTA (Schaap et al., 2001), with all possible input parameters (sand, silt. and clay content, BD, and water content at 33 and 1500 kPa). Table 2 shows the parameters of the VGM model obtained by IP and those predicted by ROSETTA. ROSETTA gave poor estimations of the WRC and the K *vs* h curve (Figures 2 and 3). ROSETTA failed particularly in the wet zone of the WRC, which is expected as this part depends mainly on soil structure, and the input parameters of ROSETTA do not include structure-related parameters. Our findings are in agreement with Minasny et al. (1999), who stated that PTFs should

Table 2. Parameters of the van Genuchten-Mualem model obtained by inverse parameterization (IP) and predicted by ROSETTA for both sites

Parameter(1)	Site 1		Site 2	
	IP	ROSETTA	IP	ROSETTA
ThetaS (%)	0.55	0.43	0.54	0.4214
ThetaR (%)	0.002	0.05	0.004	0.0288
Alpha (cm^{-1})	0.0026	0.0074	0.0016	0.0181
n	1.17	1.44	1.19	1.36
K_0	3.51	1.17	2.26	2.89
RSS	0.157		0.109	
r^2	0.91		0.92	

(1) ThetaS: water content at saturation; ThetaR: residual water content; Alpha: curve shape parameter; n: curve shape parameter, dimensionless; K_0: saturated hydraulic conductivity; RSS: residual sum of square; and r^2: goodness of fit.

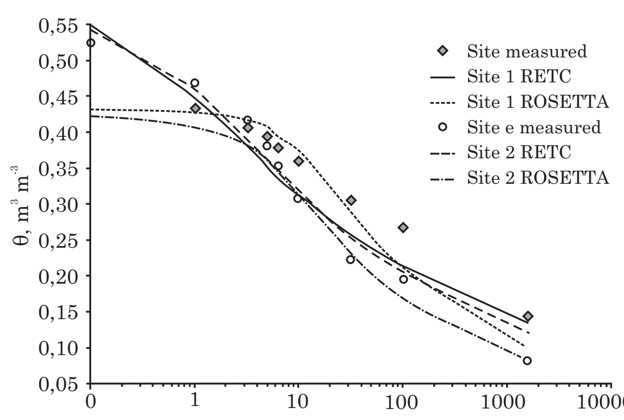

Figure 2. Measured points of water content (θ), the water retention curve (WRC) fitted to the van Genuchten-Mualem model (VGM) using the RETC program (RETC), and the WRC predicted using ROSETTA, for loam soil (Site 1) and sandy loam soil (Site 2).

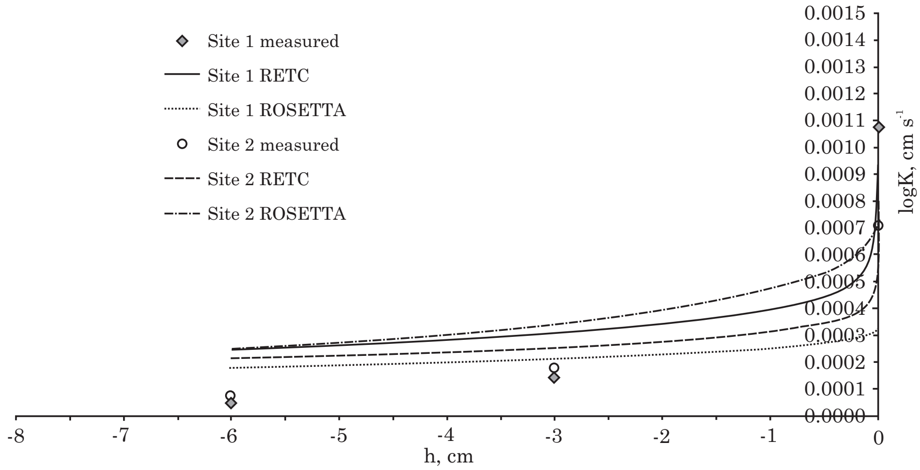

Figure 3. Measured points of hydraulic conductivity K, K(h) curve fitted to the van Genuchten-Mualem model (VGM) using the RETC program (RETC), and the K(h) curve predicted using ROSETTA, for loam soil (Site 1) and sandy loam soil (Site 2).

not be extrapolated beyond their geographical training area without first assessing their general validity because the performance of published PTFs varied according to the pedological origin of the soil on which they were developed (Soracco et al., 2010a). ROSETTA was developed using soils from North America and Europe as datasets. It gives also uncertainty estimates of the parameters, but, in general, the parameters obtained by IP were outside the range of the parameters estimated by ROSETTA±uncertainty estimates (data not shown). Thus, use of this program is not recommended in the Pampas region without a previous study of its performance, showing the need for development of similar tools for this important agricultural region. Use of ROSETTA to estimate the VGM parameters from basic soil data has been used by some authors (Kutlu & Ersahin, 2008; Schwen et al., 2011). Kutlu & Ersahin (2008) found the same problems for near-saturated conditions. Schwen et al. (2011) evaluated the performance of IP of the VGM model from the K *vs* h data, comparing the values with those obtained from ROSETTA. Our results suggest that this procedure is risky, as the WRC obtained by IP was closer to measured values than the WRC predicted by ROSETTA. The VGM model did not adequately describe the K(h) curve (Figure 3), overestimating unsaturated K and underestimating K_0.

CONCLUSIONS

1. After a long period under NT, the soil porous system configuration and saturated hydraulic conductivity, K_0, do not reach steady values independent of the specific time in the crop sequence for the soils under study. Field saturated hydraulic conductivity, K_0, and water-conducting macroporosity, ε_{ma}, are particularly affected by the last crop in the crop sequence. In future studies involving soil physical properties under NT, the crop effect should not be neglected.

2. The VGM model adequately describes the WRC for these soils, but not the K(h) curve. ROSETTA fails in estimation of these parameters, and the predicted WRC is particularly different from the measured values in the wet zone.

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