CIENCIA DEL SUELO

SOIL SHRINKAGE CURVES AND MICROMORPHOLOGY IN CONTRASTING MANAGEMENTS

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ABSTRACT

Compaction processes are generally described using methods that do not distinguish volume changes of different types and pore sizes. The adjustment of shrinkage curves (ShC) using the XP model allows elucidation of the effects of soil management on changes in pore volume. This method coupled with micromorphological and micromorphometric determinations in soil thin sections allows the characterization and quantification of important soil features included pore types. The aim of this work was to examine the potential of shrinkage analysis to describe soil physical degradation under the most common management (continuous cropping-CC), an alternative management (integrated crop/livestock-ICL), related to quasi-pristine (QP); in two soils of northern of the Pampean region of Argentina (Typic Hapludoll and Typic Argiudoll). We focused on the changes of soil structural porosity in both methods (ShC and micromorphological analyses) in silty soils with low shrinkage-swelling capacity. The QP had a higher volume (or lower bulk density) in both soils. The slope of the structural phase was QP<ICL<CC, indicating lower structural stability, as a consequence of macropore destruction due to management intensity. Micromorphological analyses were in concordance to shrinkage analysis. QP showed higher structural pores from shrinkage analyses; and from micromorphometric analyses: higher Pores>50 um, a good pore orientation (vertical angles), and crumb microstructure derived from an intense biological activity were observed. In Typic Hapludoll, structural porosity in CC and ICL presented similar values according to ShC determinations. In Typic Argiudoll CC it was presented a lower values of structural porosity than in ICL. Similar results were estimated from micromorphological analyses (Pores>50 μm = QP(20.0%)>ICL(17.7%)>CC(16.0%)). CC and ICL were characterized by the development of platy peds and horizontally oriented planes, whereas ICL presented more biological activity. ShC and micromorphology analyses improved the understanding of soil functioning in these non-expansive soils, allowing the comparison between cattle trampling and continuous cropping in different soil types.

Key words: compaction, XP model, soil porosity, thin section

CURVAS DE CONTRACCIÓN DEL SUELO Y MICROMORFOLOGÍA BAJO DIFERENTES MANEJOS

RESUMEN

El proceso de compactación en general es descripto usando métodos que no distinguen tipos y tamaños de poros que son afectados. El ajuste de las curvas de contracción (CC) usando el modelo XP permite diferenciar los manejos de suelos con relación a la porosidad. Este método está en consonancia con las determinaciones micromorfológicas y micromorfométricas de cortes delgados. El objetivo de este trabajo fue examinar el potencial del análisis de las CC de los suelos para describir la degradación física de los mismos bajo distintos manejos de la región pampeana de la Argentina: agricultura continua (AC), rotación agrícola-ganadera (AG), respecto de una situación cuasi-prístina (CP), en dos suelos: Hapludol Típico y Argiudol Típico. Desde dos aproximaciones

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de análisis de CC y análisis micromorfológico en suelos limosos de baja capacidad de expansión/contracción. El tratamiento CP presentó el volumen más alto (menor densidad aparente) para los dos suelos. Las pendientes de la fase estructural presentaron el siguiente orden: CP<AG<AC, mayor valor más destrucción de macroporos. El análisis micromorfológico estuvo en concordancia con el análisis de contracción. CP presentó los mayores valores de porosidad estructural hallándose por análisis micromorfológico poros >50um, buena orientación, y una microestructura migajosa derivada de la intensa actividad biológica. En el Hapludol Típico, la porosidad estructural fue similar en AC y en AG. En el Argiudol Típico, AG presentó valores mayores de porosidad estructural respecto de AC. Similares tendencias fueron halladas en los cortes delgados (Poros>50 μm = CP(20.0%)>GA(17.7%)>AC(16.0%)). AC and AG se caracterizaron por el desarrollo de estructuras laminares con poros orientados horizontalmente, sin embargo, GA presentó una mayor actividad biológica. La complementación de las CC y el análisis micromorfológico mejoró el entendimiento del funcionamiento de suelos no expandibles, permitiendo la comparación entre manejos agrícolas continuos y aquellos con pisoteo animal en diferentes tipos de suelo.

Palabras claves: compactación, modelo XP, porosidad del suelo, corte delgado

INTRODUCTION

Most of cropland in Argentina is managed under continuous cropping, which is based on the extensive use of no tillage system, extensive application of herbicides (*e.g.* glyphosate and atrazine), and prevalence of soybean (*Glycine max* L. Merrill) within the crop rotations. The Pampean region is the most productive and fertile region of Argentina. However, soil compaction is a common degradation process in this area due to intense machinery traffic, simplified crop sequences, reduction of crop–pasture rotation, low carbon inputs, between others. In addition, the absence of freeze-thaw processes and the clay type (mainly illite), with low shrinkage-swelling capacity, decrease the natural regeneration of soil structure in this region (Senigagliesi & Ferrari 1993; Kraemer, 2015). Therefore, soil compaction persists in the field, which could be reduced applying management practices that enhance biological aggregation mechanisms. Recently, the integration of crop and livestock production has been considered as an interesting alternative that allow soil alleviation when vegetation (*e.g.* weeds, pasture, etc.) was included in the scheme (Fernández *et al.,* 2015). However, this system can also present negative effects, including soil compaction by cattle trampling and machinery traffic (Hamza & Anderson, 2005). Thus, benefits of integration of crop and livestock compared to continuous cropping on soil quality are still on debate.

Compaction processes that develop as a result of livestock and machinery traffic cause a reduction in total porosity (Alakukku 1996a; Alakukku 1996b; Arvidsson & Hakansson 1996), alter pore morphology (Wiermann *et al.,* 2000; Kremer *et al.,* 2002) and change pore size distribution (Alakukku 1996a; Richard *et al.,* 2001). The change in pore distribution is due to the fact that macro- and micro-pores are not equally affected by compaction (Horn *et al.,* 1995; Richard *et al.,* 2001; Schäffer *et al.,* 2007b). Currently there is a predominance of studies that evaluate the presence of compaction by using bulk density (BD) and total porosity (Drewry *et al.,* 2000). Although both of these properties are readily assessable, they do not allow the identification of the type of pores that are affected or the structural changes that occur in a soil. The effect of compaction on soil quality depends not only on the reduction in total porosity, but also on the type of pores that are affected (Blackwell *et al.,* 1990). In this sense, both soil shrinkage curve and micromorphological and micromorphometric determinations could address a wider range of soil pore characteristics.

A shrinkage curve (ShC) is defined as the change in specific volume (V) in relation to its gravimetric water content (W), where V is the volume per gram of dry mass (Boivin *et al.*, 2006a; Boivin *et al.*, 2006b). It can also be interpreted as changes in pore volume as the soil dries (Braudeau *et al.*, 1999). ShC exhibits an “S” or sigmoid shape with three linear and two curvilinear zones, separated by 4 transition points (**Figure 1**) (Braudeau 1988a; Boivin, 1990; Braudeau *et al.*, 1999; Boivin *et al.*, 2006a; Boivin *et al.*, 2006b). Three sections, called residual shrinkage, basic shrinkage and structural shrinkage, can be identified. The parameters of the model include transitionspecific for each ShC (**Figure 1**). These transition points represent the soil characteristics

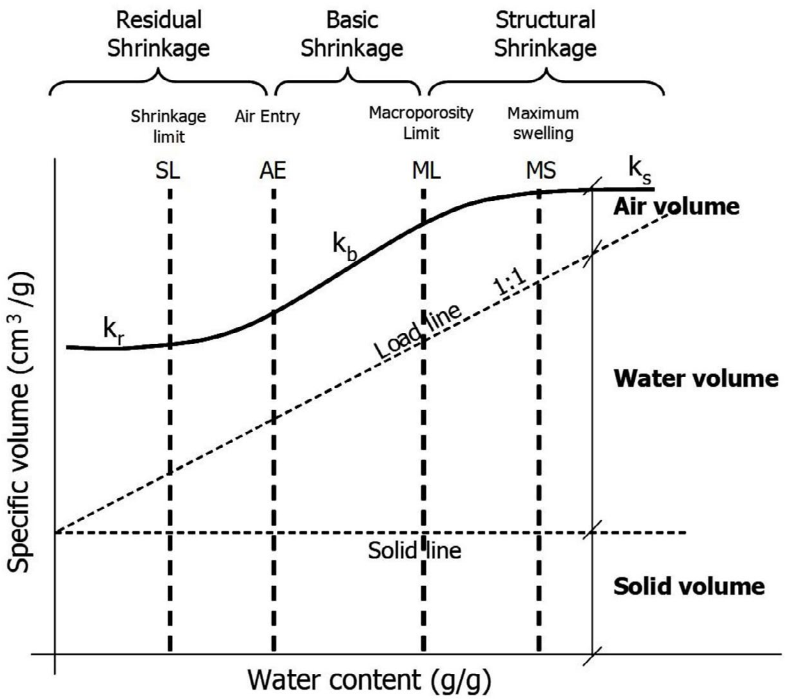

Figure 1. Theoretical shrinkage curve (ShC) of Specific Volume as a function of Soil Water Content, where volumes of solid, liquid and gas components are defined. Transition points of maximum swelling (MS), of macroporosity limit (ML), air entry (AE) and shrinkage limit (SL) are identified. Shrinkage phases: structural (ks), basic (kb) and residual (kr) shinkage slopes are shown (adapted from Braudeau *et al.*, 1999).

Figura 1. Curva de contracción teórica (ShC), volumen específico en función del contenido hídrico del suelo, en el cual se define los volúmenes de sólido, líquido y de aire. Los puntos de transición son de máxima expansión (MS), de maroporosidad límite (ML), entrada de aire (AE), y contracción límite (SL). Se presentan las pendientes de la fase estructural (ks), de la fase básica (kb) y de la fase residual (kr). (adaptado de Braudeau *et al.*, 1999).

that can be modified through management. In addition, several authors have found sound results using this approach in methodological trials even with low or no sample replications. Thus, ShC is a robust method suggesting a strong potential for standard laboratory routines.

Braudeau (1988a) proposed a conceptual model for soil shrinkage in which the shrinkage of soil aggregates is assumed to be similar to that of a "clay paste". In this model, the slope of the basic shrinkage is related to what is called aggregate "fabric" and to its stability. This means that the model assumes that soil shrinkage comprises shrinkage of two types of pore volumes, namely micropores and macropores. Braudeau *et al.*, (1999) proposed another model that provides general information and a better fit to data: the XP model (Boivin *et al.*, 2004), whose mathematical and the fit goodness properties have been compared with other models (Braudeau *et al.*, 1999). Braudeau & Bruand (1993) considered that the XP model can be used to calculate the volume of micropores or micromass directly from the ShC of undisturbed soil samples (Boivin *et al.*, 2004). Clods can be viewed as an assemblage of aggregates of micromass and coarse components, plus structural pores (Brewer, 1964). For Mollisols, the usual aggregation mechanism for micromass consists of domains of silt- and clay-size particles coated with organic matter and oxides, and its porosity is mostly small inter-particle pores with diameters smaller than 10–15 μm (Fiès & Bruand, 1998). The complementary porosity is called 'structural porosity'. Structural pores exceed 10–15 μm in diameter, but usually they are larger than 50 μm in diameter. They are of varied origin, shape and size; they include large cracks, biopores, and voids (Brewer, 1964), but also small lacunar pores (large pores inside the intraaggregate clay) between coarse components and micromass (Fiès & Bruand, 1998).

Although structural pores and plasma can be affected by mechanical stress (Horn *et al.,* 1995; Richard *et al.,* 2001; Schäffer *et al.,* 2007b), both are highly dynamic with respect to swelling and shrinkage by soil wetting and drying (Braudeau *et al.,* 2004). Richard *et al.* (2001) found that the most affected by compaction were the structural pores. The porosity of the plasma can be defined as the combination of silt- and clay-size particles independently of coarser fractions, and its porosity is composed of small interparticle voids with maximum pore diameters of 10-15 μm on oven dried (Fiès & Bruand, 1998) and it is generally considered less sensitive to soil mechanical stress. The XP model allows separation of the shrinkage of plasma pores from the shrinkage of macropores and thus evaluates the effect of soil management on porosity changes.

The XP model has been successfully applied in a wide range of soil types: Ferralsols, Vertisols, tropical and temperate Fluvisols and Cambisols, with a clay content range of 11-80 % (Boivin, 1990; Coquet *et al.,* 1998; Braudeau *et al.,* 1999; Boivin *et al.,* 2004, 2006a, 2006b) and different types of clay (Boivin, 2007). ShC was also proved in different managements subjected to soil compaction, as the effects of traffic agricultural machinery (Boivin *et al.,* 2006b; Schäffer *et al.,* 2008), natural situation with mechanical harvest and cattle grazing (Rasa *et al.,* 2009; Dörner *et al.,* 2009). However, ShC has been scarce evaluated in cattle trampling and grazing of crop residues after crop harvest. Moreover, the behaviour of ShC in silty soils with low swelling clay minerals (*e.g.* illite and kaolinite) and intense physical degradation as occurs in the Pampa region of Argentina has been not addressed.

In the other hand, micromorphological and micromorphometric determinations in soil thin sections are valuable to characterize and quantify different soil features. Type, size and pore orientation can be extracted from thin sections allowing comprehensive porosity descriptions. This methodology has been successfully used to assess the effects of different agricultural management on topsoil structures (Pagliai, 1987; VandenBygaart *et al.,* 1999; Rasa *et al.,* 2012). In the Pampa region, top soils under no-till management have shown a marked anisotropy and a high frequency of horizontal pores related to platy structures (Morrás & Bonel, 2005; Bonel *et al.,* 2005; Álvarez *et al.,* 2015). However, the link between micromorphometric/morphological data and ShC determinations is often overlooked and more studies are needed to couple both methodologies.

The aim of this work was to examine the potential of shrinkage analysis to describe the soil physical degradation under continuous cropping (maize and soybean) under no tillage, the most common soil management in North of the Pampean region of Argentina and under an alternative management (integrated crop livestock). In addition, the extent of the degradation was assessed by sampling the few remaining zones that were never cropped or trampled neighbouring to cultivated fields. We focused on the changes of soil structural porosity with shrinkage analysis coupled with micromorphological and micromorfometric analysis and we compared the shrinkage analysis results to the examination of the structural porosity on soil thin sections for the Typic Argiudoll.

MATERIALS AND METHODS

The samples were collected at two sites located in the northern Pampean Region of Argentina, in a Typic Argiudoll (33º18'23.3'S; 61º58'2.3'W) and in a Typic Hapludoll (34º03'45.6'S; 62º25'19.4'W). This region has a temperate (mean annual temperature of 17.3 ºC) and humid (mean annual precipitation of 1044 mm) climate. Soils have developed over aeolian sediments (loess) and with natural grassland vegetation (Soriano, 1991).

The Typic Hapludoll and Typic Argiudoll, are widespread soils in the region, and were selected for this study due to contrasting granulometric composition in the A horizon. While Typic Hapludoll are rich in fine sands, Typic Argiudoll present high silt and clay contents, suggesting different soil physical behaviour (**Table 1**).

Treatments and sampling

Samples were taken from three different management situations, namely quasi-pristine (QP), continuous cropping under no-till (CC) and integrated crop/livestock production under no-till (ICL). The QP treatment corresponds to samples taken in the park around the farm homestead, where it is assumed that the soil has not been tilled, trampled by cattle or subjected to farm machinery traffic for decades, and can be considered as positive control. The CC treatment, a sequence of maize followed by soybean with herbicide applications during the winter fallow, is the most common management system in the area. ICL consist of an 8-year cropping period alternating maize and soybean, followed by a 4-year period of a mixed grass-alfalfa pasture. In the

Table 1. Soil surface layer (0-5 cm) characteristics of studied soils under different management treatments: quasi pristine (QP), integrated crop/livestock production (ICL) and continuous cropping (CC). TOM: total soil organic matter. CEC: cation exchangeable capacity.

Tabla 1. Características del suelo bajo estudio del estrato superficial (0-5 cm) bajo diferentes tratamientos de manejos: cuasi-prístina (QP), integrada agrícola ganadera (ICL), y agrícola continua (CC). TOM: materia orgánica total del suelo. CEC: capacidad de intercambio catiónica.

	Typic Hapludoll			Typic Argiudoll		
	QP	ICL	CC	QP	ICL	CC
TOM (g kg-1)	35.5	32.9	20.6	38.1	37.1	26.8
Sand (g kg-1)	480	488	493	131	101	96
Silt (g kg-1)	407	395	376	694	681	689
Clay (g kg-1)	113	117	131	175	218	215
pH	6.05	6.26	6.33	6.15	6.33	6.65
CEC (cmolc kg-1)	16.1	14.9	12.5	16.8	19.9	17.2
Ca (cmolc kg-1)	7.7	7.9	7.1	10.3	11.1	9
Mg (cmolc kg-1)	2.0	2.3	2.0	1.8	2.3	1.9
Na (cmolc kg-1)	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
K (cmolc kg-1)	2.3	2.0	1.9	2.8	2.6	2.0

last case, soil samples were taken in the middle of cropping period. In these systems, crop residues and winter weeds (*Stellaria media,* Bowlesia incana) are grazed with an average stocking rate of 1.1 cow ha^{-1} (average weight 420 kg cow^{-1}, average pressure ca. 200 kPa) during the winter. Mixed pastures are under rotational management, with an average 30-40 cow ha^{-1} stocking rate. Samples in CC and ICL were taken during the fallow period. We selected a non-disturbed soil sample (0-5 cm depth) from a set of representative soil cores (5 cm of height, 5 cm of diameter).

The characteristics of each soil type under each management situation are presented in **Table 1**. Soil chemical analyses were realised from composites samples. Each one consisting of at least 20 subsamples, collected from the 0-5 cm soil depth at each treatment and soil. These composite samples were analysed in the laboratory. Total organic matter content (TOM) was determined by the Walkley and Black method (conversion factor: 1.72; Nelson & Sommers, 1996); soil pH (1:2.5, soil: water); particle size distribution (determined by the pipette method; Soil Conservation Service, 1972), and cation exchangeable capacity (CEC) was measured at pH 7 with ammonium acetate by extraction with potassium chloride.

Sample preparation and shrinkage curve determination

We used a procedure descript by Boivin *et al.* (2004). Soil samples were saturated with deionized water, and it was measured. Samples were then placed on an electronic balance at 20 °C to record sample weight and height changes during soil drying. Changes in sample height were recorded using a calibrated displacement transducer with 1-micron accuracy and weight scale had a 0.01 g accuracy. Weight and height of soil samples were taken at 5 min intervals until the sample weight reached a constant value. At the end of ShC measurement samples were oven-dried at 40 °C during 24 h to determine their final dry weight and dry volume. Dry weight was used to calculate the water content W (g g^{-1}) and sample volumes were used to transform changes in sample height in changes in sample volume as follows.

Changes in sample height (L) were converted into changes in specific volume (V) applying Towner's equation (Towner, 1986):

$$V/V_f = (L/L_f)^n \qquad [1]$$

where,

V: volume of the sample during the experiment, L: height of the sample during the experiment, Vf and Lf : same variables at the end of the experiment, and n is the geometric factor, which was calculated using:

$$n = [\log (V_f/V_0)] / [\log (L_f/L_0)] \qquad [2]$$

where V0 is the volume of the sample at the beginning of the experiment, and L0 is the height of the sample at the beginning of the experiment. When n≈3 the shrinkage it is considered isotropic (Boivin, 2007). Our *n*-values were close to this threshold with a mean of 2.93. Considering that volume determinations errors are less than 1 % (Boivin 2007), this value suggest an isotropic behaviour of the samples.

Equations of the XP model

The equations of the XP model were developed by Braudeau *et al.* (1999) (**Tables 2 and 3**). The

Table 2. Equations of the XP model according Braudeau *et al.*, (1999) (from Boivin *et al.*, 2006).

Tabla 2. Ecuaciones del modelo XP propuesto por Braudeau *et al.*, (1999) (from Boivin *et al.*, 2006).

k_b	$k_b=[V_{AE}-V_{ML}]/[W_{AE}-W_{ML}]$ $k_b=[-k_s+(\exp(1)-1) \times (V_{ML}-V_{MS})/(W_{ML}-W_{MS})]/\exp(1)-2$
k_s	$k_s=[V_s-V_{MS}]/[W_s-W_{MS}]$; with V_s and W_s values of the structural phase. $k_s=[V_{ML}-V_{MS}] \times [\exp(1)-1]/[W_{ML}-W_{MS}] - k_b \times [\exp(1)-2)$
k_r	$k_r=[Vr-V_{SL}]/[W_r-W_{SL}]$; with V_r and W_r values of the residual phase. $k_r=[V_{AE}-V_{SL}] \times [\exp(1)-1]/[w_{AE}-W_{SL}] - k_b \times [\exp(1)-2]$
Range of W values	Applicable algorithms for calculation of values of V
$W>W_{MS}$	$V=V_{MS}-k_s \times (W_{MS}-W)$
$W_{ML}\leq W\leq W_{MS}$	$W_n=(W-W_{MS})/(W_{ML}-W_{MS})$ $V=V_{MS}+(V_{ML}-V_{MS}) \times [k_b \times (\exp(W_n)-W_n-1)+k_s \times (\exp(1) \times W_n - \exp(W_n)+1)] / (k_b \times (\exp(1)-2)+k_s)$
$W_{EA}<W<W_{ML}$	$V=V_{ML}-k_b \times (W_{ML}-W)$
$W_{SL}<W<W_{AE}$	$W_n=(W-W_{SL})/(W_{AE}-W_{SL})$ $V=V_{SL}+(V_{AE}-V_{SL}) \times [k_b \times (\exp(W_n)-W_n-1)+k_r \times (\exp(1)-W_n-\exp(W_n)+1)]/(k_b \times (\exp(1)-2)+k_r)$
$W<W_{SL}$	$V=V_{SL}-k_r-(W_{SL}-W)$

k_b = slope of basic shrinkage phase; k_s = slope of structural shrinkage phase; k_r = slope of residual shrinkage phase; V = volume; W = water content; AE = air entry; ML = macroporosity limit; MS = maximum swelling; SL = shrinkage limit

Table 3. Plasma porosity (Vp) and moisture content (Wp) calculated using the XP model according to Braudeau et al., (1999) (from Boivin et al., 2006).

Table 3. Porosidad de plasma (Vp) y contenido hídrico (Wp) calculada a través del modelo XP propuesto por Braudeau et al., (1999) (from Boivin et al., 2006).

Range of soil W values	Vp (cm^3/g)	Wp ($cm^3\ g^{-1}$)
$W<W_{SL}$	$(W_{AE}+0.718 \times W_{SL})/1.718$	W
$W_{SL}<W<W_{AE}$	$(1.718 \times W_{SL} + (W_{AE} - W_{SL}) \times (e^{\Theta}-\Theta))/1.718$ $\Theta=W-W_{SL}/W_{AE}-W_{SL}$	W
$W=W_{AE}$	W	Vp
$W_{AE}<W<W_{ML}$	W	Vp
$W=W_{ML}$	W	Vp
$W_{ML}<W<W_{MS}$	$(1.718 \times W_{MS} + (W_{ML} - W_{MS}) \times (e^{\Theta}-\Theta))/1.718$ $\Theta=W-W_{MS}/W_{ML}-W_{MS}$	Vp
$W=W_{MS}$	$(W_{ML}+0.718 \times W_{MS})/1.718$	Vp
$W_{MS}<W$	$(W_{ML}+0.718 \times W_{ME})/1.718$	Vp

V = volume; W = water content; AE = air entry; ML = macroporosity limit; MS = maximum swelling; SL = shrinkage limit
V= volume; W = contenido hídrico; AE= entrada de aire; ML = macroporosidad límite; MS = expansión máxima; SL = contracción límite

goodness of fit of the model allows the determination of the porosity, the air and water content of the macro-and micro-porosity in soil samples within a range of W values. Macropores are related to structural pores that generally exceed 10 to 15 μm in diameter and are mostly larger than 30 to 50 μm in diameter (Schäffer *et al.*, 2013). Although macro- and micro-porosity are derived from the behaviour of ShC, thus there is no predefined pore diameter to discriminate both porosity types. **Table 4** presents equations to calculate volume of the plasma air content (Ap), volume of macro-porosity (Vma), water content of macro-porosity (Wma), volume of air content of the macro-porosity (Ama)

The particle density (Pycnometer method, Blake & Hartge, 1986) of Typical Argiudoll was 2.14 g cm^{-3}, and for Typical Hapludoll was 2.21 g cm^{-3}. Finally, bulk density (BD) was calculated as the inverse of V. Data set from the device (height, weight, water tension, temperature, time) was modeled and fitted though the Hydre program, version 2 to obtain all parameters needed to calculate shrinkage curve´s parameters. This program adjusts equations of the XP model cited by Braudeau *et al.* (1999).

Based on Braudeau & Bruand's (1993) definition, soil swelling capacity (SC) was calculated as:

$$SC= [(VMS - VSL)/ VSL] \times 100 \qquad [3$$

where, VMS: specific volume at MS; VSL: specific volume at SLThe swelling capacity of the plasma (SC_p) can be calculated as:

$$SCp= [(VpMS - VpSL)/VpSL]\times 100 \qquad [4]$$

where, VpMS: specific volume of plasma porosity at MS; VpSL: specific volume of plasma porosity at SL

Thin sections

Thin sections from the Typic Argiudoll were obtained. Non-disturbed, vertically oriented topsoil samples under different management (QP, ICL, CC) were taken for the micromorphological study (Stoops, 2003). Samples were impregnated with a polyester resin and thin sections were prepared. Following the procedure described by Pastorelli *et al.* (2013) a portion of each thin section was selected, avoiding edges where disruption could have occurred. Oriented soil thin sections (7 x 6 cm; thickness: 30 μm) were analyzed by optical microscopy in transmitted and cross-polarized light (Leica Wild MZ8). Three subsets of the thin section were selected (n: 4, 2.25 cm^2 each) in order to avoid gray tones differences that could lower segmentation accuracy. Digital images were obtained from each sample with a Cannon Powershot S3IS 6MP, coupled with Image Capturec software and soil porosity parameters were assessed by image analysis with the JMicro-Vision v1.2 program. This study focused on the analysis of macropores, considered as such those greater than 50 μm (Pagliai, 1987; Pagliai & Kutilek, 2008), as they are responsible for the movement of air, water and radical growth (Vandenbygaard *et al.*, 1999). Porosity higher than 50 μm (Pores >50 μm) was obtained by dividing the total area of the selected cross-section of the pore space by the total sample area and it was expressed as a percentage (Pires *et al.*, 2008). Pore shape was assessed using a shape factor [perimeter2/ (4π area)] proposed by Bouma *et al.* (1977), where a factor <0.015 correspond to elongated pores, a factor between 0.015–0.04 is attributed to irregular pores and a factor >0.04 to rounded pores. Pore orientation considered angles close

Table 4. Plasma porosity (Vp) and moisture content (W) calculated using the XP model according to Bradudeau *et al.*, (1999) (from Boivin *et al.*, 2006).

Tabla 4. Porosidad del plasma (Vp) y contenido hídrico (W) calculado a través del modelo XP propuesto por Bradudeau *et al.*, (1999) (from Boivin *et al.*, 2006).

	Equations	
Volume of the plasma air porosity (A_p)	$A_p=V_p-W_p$	V: volume specific V_p: volume of plasma porosity W: gravimetric water content W_p: plasma water content ϱ: specific volume of solid phase
Volume of macro-porosity (V_{ma})	$V_{ma}=V-V_p-1/\varrho$	
Water content of macro-porosity (W_{ma})	$W_{ma}=W-W_p$	
Volume of air content of the macro-porosity (A_{ma})	$A_{ma}=V-V_p-1/\varrho-W_{ma}$	

to 0° and 180° as horizontal pores and those close to 90° as vertical pores.

RESULTS AND DISCUSSION

Shrinkage curves

Shrikage Curves were obtained in both soils even when both soils showed low contents of expansible clays. Average swelling capacity (SC) values were 2.58 % and 3.84 % for the Hapludoll and Argiudoll, respectively (**Table 5**). Stengel *et al.* (1984) found similar SC on silty-loamy soils. SC values were moderate (**Table 5**) when compared with those of Vertisols reported by Boivin (2007) (SC: 15 %). Clays in the surface horizon of the soils in this work are predominantly non-swelling illites (Liu *et al.*, 2012), so lower SC values than those of the Vertisols were expected. SC was higher in the QP Argiudoll, which had

Table 5. Values of parameters from the shrinkage curves for quasi pristine (QP), integrated crop/livestock (ICL) and continuous cropping (CC) treatments.

Tabla 5. Valores de los parámetros de las curvas de contracción para los tratamientos cuasi-prístino (QP), integrado agrícola-ganadera (ICL) y agricultura continua (CC)

			Typic Hapludoll			Typic Argiudoll		
			QP	ICL	CC	QP	ICL	CC
Parameters			Shrinkage properties					
Sc	Swelling capacity	%	2.31	1.77	3.67	4.26	3.79	3.48
k_r	slope of residual shrinkage phase	$cm^3\ g^{-1}$	0.136	0.011	0.000	0.036	0.051	0.054
k_b	slope of basic shrinkage phase	$cm^3\ g^{-1}$	0.116	0.069	0.067	0.174	0.099	0.112
k_s	slope of structural shrinkage phase	$cm^3\ g^{-1}$	0.094	0.123	0.219	0.094	0.190	0.265
W_{SL}	water content at shrinkage limit	$g\ kg^{-1}$	37	40	65	34	44	68
V_{SL}	Volume at shrinkage limit	$cm^3\ g^{-1}$	0.735	0.654	0.664	0.912	0.719	0.662
CH_{EA}	Water content at air entry	$g\ kg^{-1}$	48	72	94	89	69	79
V_{AE}	Volume at air entry	$cm^3\ g^{-1}$	0.737	0.655	0.665	0.917	0.721	0.663
W_{ML}	water content at macroporosity limit	$g\ kg^{-1}$	105	165	180	189	138	187
V_{ML}	Volume at macroporosity limit	$cm^3\ g^{-1}$	0.749	0.661	0.670	0.934	0.728	0.675
W_{MS}	water content at maximum swelling	$g\ kg^{-1}$	124	205	294	316	260	238
V_{MS}	Volume at maximum swelling	$cm^3\ g^{-1}$	0.752	0.665	0.688	0.950	0.747	0.686
BD_{SL}	Bulk density at shrinkage limit	$g\ cm^{-1}$	1.36	1.53	1.51	1.10	1.39	1.51
BD_{MS}	Bulk density at maximum swelling	$g\ cm^{-1}$	1.33	1.50	1.45	1.05	1.34	1.46
			Plasma porosity and Structural porosity					
SCp	Swelling capacity	%	162	211	177	267	225	178
Vp (SL)	Volume of plasma at shrinkage limit	$cm^3\ g^{-1}$	0.043	0.058	0.082	0.066	0.058	0.075
Vp (MS)	Volume of plasma at maximum swelling	$cm^3\ g^{-1}$	0.113	0.182	0.227	0.242	0.189	0.208
Vma (SL)	Volume of macroporosity at shrinkage limit	$cm^3\ g^{-1}$	0.247	0.090	0.068	0.316	0.165	0.085
Air-filled pore Vma (MS)	Air filled pore at maximum swelling	$cm^3\ g^{-1}$	0.236	0.070	0.002	0.242	0.094	0.055
Water-filled pore Vma (MS)	Water filled pore at maximum swelling	$cm^3\ g^{-1}$	0.011	0.020	0.067	0.029	0.074	0.071
Air-filled Vp (SL)	Air filled at shrinkage limit	$cm^3\ g^{-1}$	0.006	0.019	0.017	0.006	0.031	0.014

higher organic matter content than in the other treatments on both soils (**Table 1**). Rasa *et al.* (2009), in a clayey soil, also observed higher SC values under lower cropping intensity and higher organic matter content. This was not found in the Hapludoll. On the other hand, the Hapludoll SCp (average 183 %) was lower than the one of the Argiudoll (average 223 %, **Table 5**), something that was expected based on its lower clay content (**Table 1**), as shown by Braudeau & Mohtar (2004). Nonetheless, ShC parameters could be fitted with XP model. In both soils, QP treatment had the highest V value and, therefore, the highest porosity (**Table 5**; **Figure 2**). The CC and ICL treatments always showed smaller V (higher BD). In the Hapludoll, the ShC of CC and ICL treatments overlapped completely (**Figure 2B**). On the contrary in the Argiudoll, CC had a higher BD (or lower V) than the rest of the treatments (**Figure 2A**).

One of the most important parameter in the shrinkage analysis is the slope of the basic linear phase (k_b). Shrinkage at this phase is related to the plasma component, where type and proportion of clay in the soil determine V variations (Braudeau & Mohtar, 2006). The Argiudoll has higher clay content (mean 203 g clay kg^{-1} soil) than the Hapludoll (mean 120 g clay kg^{-1} soil) (**Table 1**), a feature linked to the k_b value, with the Hapludoll having a lower average k_b value (treatment mean= 0.084 cm^3 g^{-1}) than the Argiudoll (treatment mean = 0.128 cm^3 g^{-1}). The k_b values greater than 1 cm^3 g means great soil instability (Boivin *et al.,* 2006a), as has been found in sodic soils (Boivin, 1990). In adittion, Boivin *et al.* (2006b) noted that k_b values <0.200 cm^3 g^{-1}, correspond to rigid soils. However, k_b values <0.200 cm^3 g^{-1} may also correspond to compacted soils. Thus, in this study the QP treatments of each soil can be used as a reference for natural rigidity or compaction due to management history. As it is reported in **Table 5**, the k_b of the QP treatment was 0.116 cm^3 g^{-1} for the Hapludoll and 0.174 cm^3 g^{-1} for the Argiudoll, while the values for agricultural treatments were lower. These results suggest that the studied soils showed nearly rigid behavior, and thus those that have been cropped (ICL and CC) have

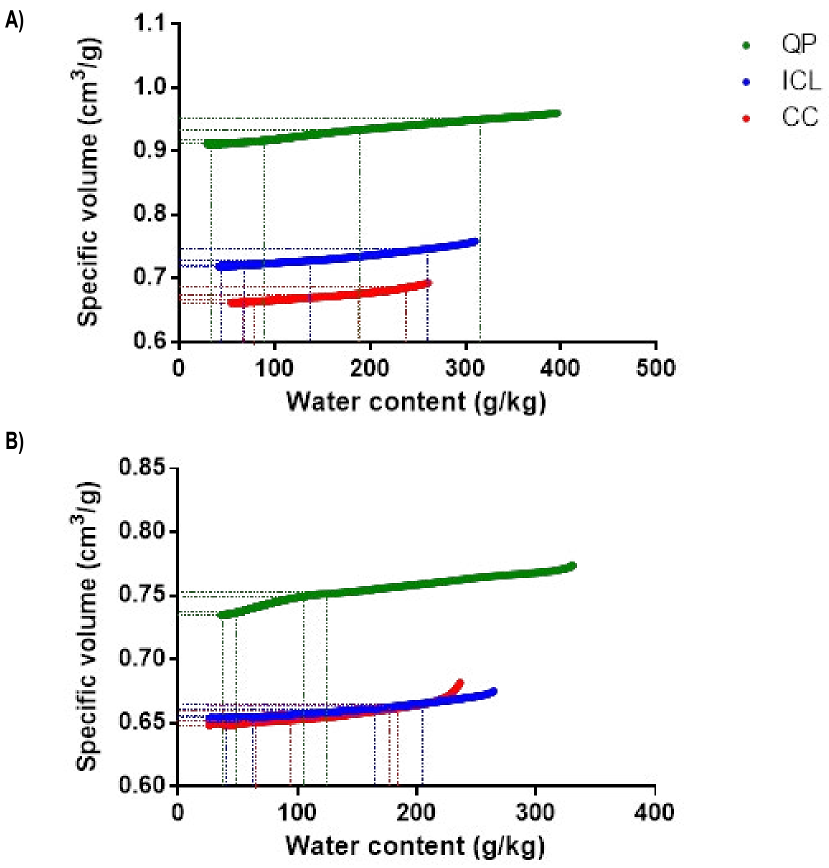

Figure 2. Specific volume as a function of soil water content for quasi pristine (QP), integrated crop/livestock (ICL) and continuous cropping (CC) treatments for two soil types: Argiudoll (A) and Hapludoll (B).

Figura 2. Volumen específico en función del contenido hídrico del suelo para los tratamientos cuasi-prístino (QP), agrícola ganadera (ICL) y agricultura continua (CC), para dos tipos de suelos: Argiudol (A) y Hapludol (B).

a higher compaction compared to QP. Having taking into consideration the effects of granulometric composition on k_b in the QP treatment, the organic matter content could also explain the lower compaction values in this treatment.

The slope of the structural linear phase (k_s) is another important parameter, which is closely related to structural pore stability. The two studied soils showed the lowest k_s values in the QP treatments, intermediate in ICL and highest values in CC (i.e. QP <ICL <CC). Boivin *et al.* (2006b) observed that in permanent pastures the k_s value was low, indicating good structural pore stability. High k_s values indicate that as a soil dries, contraction occurs due to the collapse of macropores up to the W at MS (W_{MS} >10 μm, Boivin *et al.*, 2004). The structural pore volume (V_{ma}) at transition point MS, was highest in the QP treatment (Hapludoll: 0.247 cm^3 g^{-1}; Argiudoll: 0.316 cm^3 g^{-1}) followed by ICL and finally by CC (QP> ICL> CC) (**Table 5**). Richard *et al.*, (2001) also found that macropore volume was higher in the absence of machinery traffic, as pores reduce their volume when affected by machinery traffic (Schäffer *et al.*, 2007a; Schäffer *et al.*, 2007b; Schäffer *et al.*, 2008).

The differences on soil densification between both agricultural treatments evaluated (CC>ICL), could be firstly related to different organic matter content in their surface horizons (**Table 1**). The organic matter content in both soils under CC is lower than in the ICL treatments, which should facilitate the re-arrangement and consolidation of inorganic particles, particularly those integrating the predominant silt fraction. Secondly, more compaction and a greater deterioration of soil structure can be expected in the CC treatments due to a higher intensity and frequency of machinery traffic along time, simplify crop sequences (*i.e.* soybean monoculture), low residues input, long periods without living roots (Studdert & Echeverría, 2000; Kraemer *et al.*, 2018). This deterioration is magnified due to the high silt content of this soil together with the high percentage of phytoliths and volcanic glasses (Durán *et al.*, 2011; Kraemer 2015).

Thin sections

Micromorphological observations provide additional information supporting these interpretations. In the QP treatments, inclusions of faeces of edaphic macro and meso fauna can be seen,

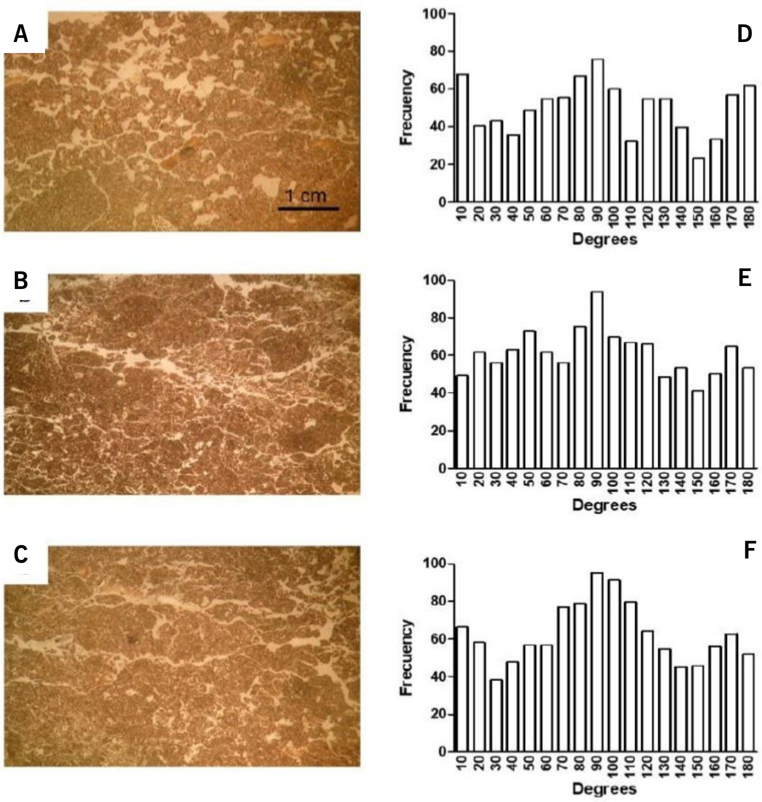

Figure 3. Thin sections and pore-angle frequency distribution of quasi pristine (A, D), integrated crop/livestock (B, E) and continuous cropping (C, F); for the Argiudoll.

Figura 3. Cortes delgados y distribución de frecuencia de los ángulos de poros para cuasi-prístina (A, D), integrado agrícola-ganadero (B, E) y agricultura continua (C, F); para el Argiudol.

a result of biological activity (**Figure 3A**). Thin sections of the ICL (**Figure 3B**) and CC (**Figure 3C**) treatments, although showing alteration of the structure by soil fauna, show a predominance of laminar aggregates, structures associated to machinery traffic (Bonel *et al.*, 2005; Morrás *et al.*, 2012). The laminar structure is evident in the thin sections of **Figure 3**, which are consistent with the pore angle frequency distributions (**Figures 3D,E,F**), indicating that the QP treatment showed the most uniform distribution, something that is congruent with the low densification exhibited through the ShC.

Micromorphological observations of the Argiudoll revealed an anisotropic organisation of the first centimetres, as well as a lateral heterogeneity appearing in the three treatments, also at the scale of single thin sections. Nevertheless, some microstructural features clearly differentiate the QP condition from the cultivated soils. In the first one, the topsoil is characterized by an intense fauna activity represented by tubular voids and infillings and a granular to crumb microstructure given by spheroidal microaggregates mainly of biological origin (excrements), partly welded, separated by compound packing voids. Therefore, microstructure spatial variability is less marked than in the agricultural treatments. CC and ICL show higher anistropic microstructure derived from management as found by Bonel *et al.* (2005) and Morrás *et al.* (2012). Besides, plant residues in different stages of humification are more abundant in the QP condition than in the cultivated plots, particularly at the soil surface. The colour of the groundmass, where the silt fraction is dominant, is slightly darker in the QP and in the ICL than in the CC treatment.

In the CC treatment micromorphological analysis also reveals platy microstructure in the topsoil with laminar peds separated by horizontal planar voids. The microstructure in the CC has a high lateral variability, from spots with separated microaggregates, passing by the closely packed pellets, to denser areas where biological microaggregates are no longer recognised and the main voids are horizontal planes. In the ICL treatment the microstructure is quite similar to the precedent, with a predominance of compacted biological microaggregates occurring as platy peds. Difference observed between both agricultural treatments is a slightly higher content of plant debris in the ICL (mainly from weeds) accounted by visual inspection at the field comparatively to the CC management and thus higher organic carbon contents.

Image analyses from thin sections were different between treatments regarding porosity and type and pore orientation (**Figure 4**). Porosity higher than 50 μm (Pores>50 μm) presented the following trend QP (20.0%) > ICL (17.7%)> CC (16.0%). According to Pagliai *et al.,* (1988), all treatments are classified as moderately porous (10-25%). Several authors have observed a reduction in macroporosity under non tillage compared to natural situations using micromorphometric analyses (Pagliai *et al.,* 1983; VandenBygaart *et al.,* 1999). In Argentina, the decline in macroporosity in plot under no till are related to platy structure occurrence and heavy machinery traffic (Alvarez *et al.,* 2015; Sasal *et al.,* 2016), particle size distribution with high silt content (Durán *et al.*, 2011) and low organic matter content under cropping periods (Studdert *et al.*, 1997; Gentile *et al.*, 2005).

For all treatments, most of the Pores>50 μm correspond to elongated pores (> 63%). Elongated porosity presented similar trends respect to Pores>50 μm where QP (12.6 %)> ICL (12.1%)> CC (10.5%). Elongated pores are of special interest as they are the most affects by management practices (Fernández *et al.*, 2012; Rasa *et al.*, 2012) and correlates with air and water movement through soils (Pagliai *et al.*, 2003, Castiglioni *et al.*, 2007). Morphologically, elongated pores correspond to fissures and channels. Fissures are related to weakness planes on aggregates surface related also with laminar structures. This was the case in CC and ICL. Furthermore, channels consisted in tubular pores, resulted from fauna activity and plant roots grown (Morrás, 2015). This last morphology (channels) corresponded to QP and some ICL pores. These results are in agreement with soil micromorphometry and organic matter contents discussed earlier.

In this work, only small differences were found regarding rounded pores (**Figure 4**). In terms of relative porosity, rounded pores and their number were higher in CC (14.0%, n=1018) and ICL (14.1%, n= 1601) compared to QP (13.1%, n=761). This pore type was found in small pore sizes (data not shown). Similar pore size was found in Castiglioni & Morrás (2007) were rounded pores present small diameters. Rounded pores could be related to vesicles originated by structural degradation process due to air entrapment or to cavities or packing voids due to mechanical compression (Morrás, 2015). Lima *et al.* (2006) found high frequency of this pore type in compacted soils.

In terms of pore orientations, a more equilibrated orientation was found in QP and ICL (**Figure 3D**, e). CC presented an increment of pore frequency in angles near 0 and 180 indicating the presence of horizontal pores (**Figure 3F**). As was evident in the micromorphological analyses, this treatment reveals common presence of platy structures. This structure is often related to continuous cropping under no-tillage in the Pampean region (Alvarez *et al.,* 2015; Kraemer 2015; Sasal *et al.,* 2016). Horizontal pores related to platy structures could lead to impaired drainage and therefore an increase of runoff (Sasal *et al.,* 2016) and high moisture contents which also increase soil compaction.

CONCLUSIONS

Shrinkage curves obtained suggest different compaction degrees in different treatments under the same soils. Thus, curves presented a gradient of k_s (QP<ICL<CC), indicated variations of soil structural stability. Also, in both soils, soil shrinkage curve suggests different degree of soil compaction due to management treatment. Micromorphological and micromorphometric analysis, showed different porosity (orientation and shapes), and biological activity. Most of the compaction features were found in CC whereas biological activity was evident in QP. Obtained results are a novel and promising, suggesting the benefits of coupling the quantification of structural porosity by ShC and micro-scale analyses in order to achieve better characterization and interpretations of porosity status.

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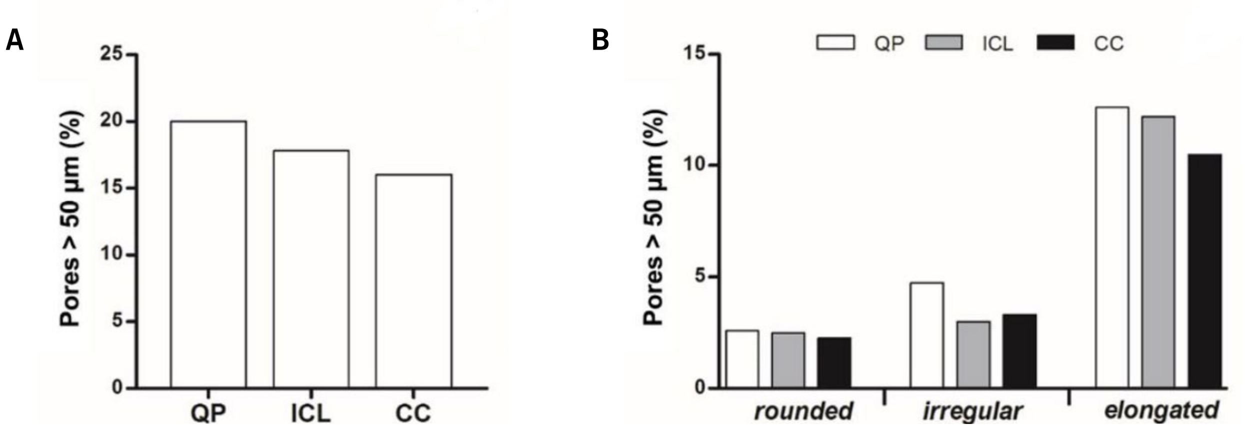

Figure 4. Porosity higher than 50 µm (Pores>50 µm) (a); and pore shape (rounded, irregular, elongated) (b) for managements evaluated: quasi-pristine (QP), integrated crop livestock (ICL) and continuous cropping (CC) in the Argiudoll.

Figura 4. Porosidad más grande que 50 µm (Poros>50 µm) (a); y formas de poros (redondeados, irregulares, elongados) (b) para los manejos evaluados: cuasi-prítino (QP), integrado agrícola-ganadero (ICL), y agricultura continua (CC) en el Argiudol.

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