Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Soil Physical Quality and Soybean Yield as Affected by Chiseling and Subsoiling of a No-Till Soil

Luis Alberto Lozano[1,3], Carlos Germán Soracco[1,3]*, Rafael Villarreal[1,3], Juan M. Ressia[2], Guillermo O. Sarli[1] and Roberto Raúl Filgueira[3]

[1] Universidad Nacional de La Plata, Facultad de Ciencias Agrarias y Forestales, La Plata, Argentina.
[2] Universidad Nacional del Centro, Facultad de Agronomía, Buenos Aires, Argentina.
[3] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), La Plata, Argentina.

ABSTRACT: The concept of soil physical quality (SPQ) is currently under discussion, and an agreement about which soil physical properties should be included in the SPQ characterization has not been reached. The objectives of this study were to evaluate the ability of SPQ indicators based on static and dynamic soil properties to assess the effects of two loosening treatments (chisel plowing to 0.20 m [ChT] and subsoiling to 0.35 m [DL]) on a soil under NT and to compare the performance of static- and dynamic-based SPQ indicators to define soil proper soil conditions for soybean yield. Soil sampling and field determinations were carried out after crop harvest. Soil water retention curve was determined using a tension table, and field infiltration was measured using a tension disc infiltrometer. Most dynamic SPQ indicators (field saturated hydraulic conductivity, K_0, effective macroporosity, ε_{ma}, total connectivity and macroporosity indexes [C_wTP and $C_w$mac]) were affected by the studied treatments, and were greater for DL compared to NT and ChT (K_0 values were 2.17, 2.55, and 4.37 cm h^{-1} for NT, ChT, and DL, respectively). However, static SPQ indicators (calculated from the water retention curve) were not capable of distinguishing effects among treatments. Crop yield was significantly lower for the DL treatment (NT: 2,400 kg ha^{-1}; ChT: 2,358 kg ha^{-1}; and DL: 2,105 kg ha^{1}), in agreement with significantly higher values of the dynamic SPQ indicators, K_0, ε_{ma}, C_wTP, and $C_w$mac, in this treatment. The results support the idea that SPQ indicators based on static properties are not capable of distinguishing tillage effects and predicting crop yield, whereas dynamic SPQ indicators are useful for distinguishing tillage effects and can explain differences in crop yield when used together with information on weather conditions. However, future studies, monitoring years with different weather conditions, would be useful for increasing knowledge on this topic.

Keywords: effective porosity, water retention curve, soil loosening, pore connectivity index.

*** Corresponding author:**
E-mail: gsoracco@agro.unlp.edu.ar

Received: June 19, 2015

Approved: August 27, 2015

How to cite: Lozano LA, Soracco CG, Villareal R, Ressia JM, Sarli GO, Filgueira RR. Soil Physical Quality and Soybean Yield as Affected by Chiseling and Subsoiling of a No-till Soil. Rev Bras Cienc Solo. 2016;v40:e0150160.

INTRODUCTION

The area under no tillage (NT) has been increasing continuously throughout the world in recent years. In 1999, NT was adopted on about 450,000 km^2 worldwide, increasing to 720,000 km^2 in 2003, and to 1,050,000 km^2 in 2009. The fastest rates of adoption have been experienced in South America (Kassam et al., 2009). Argentina is among the countries with a large area under NT, 280,000 km^2, which constitutes about 70 % of the whole cultivated area of the country (AAPRESID, 2014).

Economics, time savings, and soil conservation are the main factors responsible for widespread adoption of NT in Argentina since the 1990s (Álvarez et al., 2009a). Some authors have found that the replacement of Conventional Tillage (CT) by NT farming, in Argentina and in other temperate regions of the world, has resulted in improved erosion control, water conservation, and nutrient cycling; time savings; reduction in the use of fossil fuels; and increased soil C sequestration (Lal et al., 2007; Thomas et al., 2007; Strudley et al., 2008).

However, the effect of adoption of NT on soil physical properties has not always been consistent across locations, soils, and experimental designs (Green et al., 2003; Strudley et al., 2008). Some researchers in Argentina found a decrease in total porosity and greater bulk density (BD) under NT compared to CT in Typic Argiudolls (Elissondo et al., 2001; Fabrizzi et al., 2005; Sasal et al., 2006). Compaction associated with NT affects soil porosity, producing a reconfiguration of the soil pore system (Horton et al., 1994; Strudley et al., 2008). Several studies have investigated infiltration rates in soils under NT, with contradictory results. Some of them concluded that Mollisols from the Pampas region under NT have higher infiltration rates than under CT (Quiroga et al., 1998; Sanzano et al., 2005; Steinbach and Álvarez, 2007). Other studies reported lower infiltration rates under NT than under CT in similar soils (Álvarez et al., 2006; 2009a). In all cases, the soils were under NT for at least 5 years, the minimum period cited as necessary for stabilization of several soil properties (Álvarez et al., 2009a).

Deterioration of soil physical properties under NT produced a reduction in crop yields in Mollisols from the Pampas region (Álvarez et al., 2006; 2009b) due to a negative impact from compacted soil layers on root development and on water infiltration, resulting in less water available for the crop. This compacted layer is called as 'no-till pan' (Reichert et al., 2009), usually in depths from about 0.07 to 0.15-0.20 m, with high bulk density, low porosity, and high mechanical resistance, underlying an upper layer (0 to about 0.07 m) of reduced compaction due to rearrangement of soil particles and aggregates by biological processes and action of coulters and shanks of no-till seeders and planters coulters.

To improve soil physical properties and crop yield, some researchers have studied the effects of practices for loosening compacted NT soils. Elissondo et al. (2001) found a decrease in BD in Typic Argiudolls, and Álvarez et al. (2006) and Soracco (2009) found an increase in the infiltration rate due to the practice of loosening soil with a chisel plow in the same soil type, but this effect did not persist after harvest. Positive significant effects from subsoiling (DL) on crop yield in two Mollisols under NT were found by Álvarez et al. (2006).

Soil physical quality (SPQ) is a concept that refers primarily to soil strength and the storage and transmission of water and air (Iovino et al., 2013). This is a central concept for quantifying land degradation and developing "best management" land use practices (Reynolds et al., 2002; 2008). Assessing the SPQ of the top layer of the soil profile is of significant practical interest, given that it affects many basic agronomic and environmental processes, such as seed germination, root elongation, soil aggregation, impact of soil tillage, soil erosion, soil surface sealing/crusting, aeration, infiltration, and generation of runoff (Topp et al., 1997). Furthermore, SPQ is likely related to crop yield, as crop yield depends on several of the properties cited. Nevertheless, agreement on which soil physical properties should be included in the characterization of SPQ has not been reached. Reynolds et al.

(2009) suggested evaluating SPQ from the pore volume distribution function, which is derived from the water retention curve (WRC). However, Iovino et al. (2013) proposed adding dynamic indicators to this characterization, since water infiltration and movement depends on the existence of hydraulically active macroporosity, which is not detected by static measurements of the WRC. These dynamic indicators are consistent with the need of distinguishing between capacity and intensity soil properties, where the later include dynamic behavior over time and space and encompasses the functionality and the reaction or processes of systems within the given environmental conditions (Mentges et al., 2016; Reichert et al., 2016).

Measurement of hydraulic conductivity (K) at different soil water tensions and quantification of water-conducting macroporosity (θ_M) are 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 for quantifying macropore flow revealed that more than 70 % of water flux can move through macropores (Watson and Luxmoore, 1986). In general, 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). Macroporosity represents an important indicator of SPQ, particularly in relation to the site-specific water transmission properties, and can be used as a sensitive measure to assess soil structural degradation. The importance of soil macroporosity for water transport properties of the soil presents a challenging task for its quantitative assessment (Schwen et al., 2011).

A pore connectivity index based on water flux (Cw) that relates hydraulically active porosity and total porosity was recently by Lozano et al. (2013). This index was valuable for understanding the effects of the NT system on the connectivity of different pore size families and pore anisotropy.

Evaluation of the effects of different loosening practices on SPQ through the use of static and dynamic indicators, together with analysis of crop yield, can assist in understanding the modifications that these tillage systems produce on the soil. Furthermore, this can be a first step towards the choice of a set of useful indicators for evaluating SPQ in relation to crop yield. We hypothesized that soil physical quality indicators are good crop yield predictors, and that soil physical quality indicators based on dynamic properties are better predictors than those based on static properties.

The objectives of this study were to evaluate the ability of soil physical quality indicators based on static and dynamic properties to assess the effects of two loosening treatments in a soil under a long-term no-till system on crop yield; and to compare the performance of static- and dynamic-based soil physical quality indicators in relation to crop yield.

MATERIALS AND METHODS

Site and treatments

The experiment was carried out in the Pampas region, Argentina. The soil was classified as a fine, mixed, thermic Petrocalcic Paleudoll (Soil Survey Staff, 2006), Luvic Phaeozem (IUSS, 2007). The A horizon had a loam texture. The climate in the region is temperate (the temperature seldom goes below 0 °C), and approximate annual rainfall is 1,000 mm.

The plots studied were located at 36° 42' S and 59º 50' W. Initially, the plots were under NT with a crop rotation of wheat/short-season soybean for 20 years. In the year 2011, a complete randomized block experimental design with three treatments was applied: a) no tillage (NT), in which only a narrow (0.05 m) strip of the soil was drilled to deposit crop seeds; b) chisel plowing (ChT), in which the soil was chiseled to a depth of 0.20 m each year in November, just before soybean seeding (distance between shanks: 0.53 m);

and (c) deep loosening tillage (DL), in which the soil was subsoiled to a depth of 0.35 m each year in November, just before soybean seeding (distance between shanks: 0.57 m). There were three plots of 30 m width and 70 m length for each treatment.

At soybean crop maturity (which was reached on May 2013), soybean yields were measured using small quadrants (1 m^2, five replications per treatment and block). All plants in the quadrant were harvested by hand. Pods per plant, seeds per pod, and 1,000 grain weight were assessed. Crop yield was extrapolated to kg per hectare using the number of plants per hectare.

Soil sampling and infiltration runs were carried out in August 2013.

Laboratory determinations

To determine the water retention curve (WRC), undisturbed soil samples (0.05 m height, 0.05 m diameter) were collected from the first 0.10 m of each plot, from places close to the infiltration runs, avoiding rows and trafficked zones. Ten replicates from each plot were collected. The samples were covered with plastic caps to protect the soil from mechanical disturbances and evaporation.

Soil bulk density (BD) was measured using the core method (Blake and Hartge, 1986). Total porosity (TP) was calculated from BD, assuming a particle density of 2.65 Mg m^{-3}, which is normal for mineral soils (Hillel, 1998) and close to values measured for similar soils in the Pampas region (Cosentino and Pecorari, 2002). Disturbed soil samples were taken from the same depth and placed in plastic bags to determine soil particle size distribution using the pipette method (Gee and Bauder, 1986) and to determine organic matter content using the Walkley-Black method (Walkley and Black, 1934). Water retention data in the range of pressure head values, h (L), from -1 to 0 m were determined on the undisturbed soil cores using a sand box apparatus. Volumetric water contents, θ (L^3 L^{-3}), corresponding to h ≤-3 m were estimated using the computer program ROSETTA 1.0 (Schaap et al., 2001), which uses hierarchical pedotransfer functions, with sand, silt, and clay content and bulk density (BD) as input parameters. The van Genuchten (1980) model was fitted to the water retention data obtained for each soil sample using the RETC code (van Genuchten et al., 1991).

In-situ infiltration test

A tension disc infiltrometer (Perroux and White, 1988) was used in order to determine the steady-state infiltration rate. Infiltration tests were carried out during the fallow period (August). The infiltrometer disc had a base radius of 0.0625 m. Infiltration measurements were conducted at four randomly selected sites in each plot, avoiding rows and trafficked areas. 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 soil water pressure head, h (namely, -0.06, -0.03, and 0.0 m, 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 and Messing, 1995). Flow monitoring continued until steady-state flow from the disc was attained. Cumulative infiltration was recorded every min up to 10 min, every 5 min up to 30 min, and every 10 min up to the end of the test. When the amount of water entering into the soil did not change 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.

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).

Soil Physical Quality (SPQ) indicators based on dynamic properties

Water-conducting macro- and mesoporosity

The classical capillary rise equation allows us to approximate the maximum water-filled pore size r [L] at a specific h [L]:

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

where σ is the surface tension of water [M T^{-2}], 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 assume that the equivalent pores with radii smaller than r calculated from equation 1 are full of water and are responsible for all the flux of water under a given water pressure head, and that the equivalent pores with radii larger than the value calculated from equation 1 are not contributing to the water flux.

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

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

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

From equation 1, infiltration at water pressure heads of -0.03 and -0.06 m 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>-0.03 m (equivalent r>0.5 mm), and water-conducting mesopores (ε_{me}) as those draining at h from 0.03 and -0.06 m (0.5 mm>equivalent r>0.25 mm).

Flow-weighted mean pore radius, R_0

Reynolds et al. (1995) proposed using the flow-weighted mean pore radius R_0 (L), which represents an effective equivalent mean pore radius conducting water at a certain supply pressure head and has been used to characterize temporal and tillage-induced changes in water-conducting macropores (Messing and Jarvis, 1993; Reynolds et al., 1995; Sauer et al., 1990; Schwen et al., 2011). Following Reynolds et al. (1995), R_0 is defined by:

$$R_0 = \frac{\sigma K_0}{\rho g M_0} \qquad \text{Eq. 3}$$

here, 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:

$$M_0 = \int K(h)dh \qquad \text{Eq. 4}$$

As stated by the authors, R_0, compared to storage-based r, better reflects 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). Iovino et al. (2013) proposed using R_0 as an integration of the traditional capacitive indices in evaluating the SPQ. In this paper, we calculated R_0 at the three water pressure heads measured (i.e., $R_{0\ 0.00\ m}$, $R_{0\ 0.03\ m}$, and $R_{0\ 0.06\ m}$).

Applying equation 1, we also calculated the maximum equivalent pore radius C that corresponds to pores can be water-conducting at a given supply pressure head (Reynolds et al., 1995; Moret and Arrúe, 2007).

Pore continuity index based on water flux

A pore continuity index (Cw) based on water flux (Lozano et al., 2013) was calculated for each pore size family with radii between r_a and r_b ($r_a > r_b$) as the ratio between $K(h_a)$ and $K(h_b)$ (cm h^1) (where h_a and h_b are the pressure heads at which pores with equivalent radii greater than r_a and r_b, respectively, drain) and the pore volume fraction occupied by this family ($m^3\ m^{-3}$) in this range, according to:

$$Cw_{ra\text{-}rb} = \frac{K(h_a) - K(h_b)}{\theta(h_a) - \theta(h_b)} \qquad \text{Eq. 5}$$

where $Cw_{ra\text{-}rb}$ (cm h^{-1}) is the pore continuity index for the pore size family with radii between r_a and r_b, $K(h_a)$ and $K(h_b)$ are the hydraulic conductivities at the pressure heads at which r_a and r_b, respectively, drain, and $\theta(h_a)$ and $\theta(h_b)$ are the pore volume fractions ($m^3\ m^{-3}$) with radii lower than r_a and r_b, respectively. In this study, we calculated Cw of TP, and Cw of macropores (diameter>1 mm) and mesopores (1 mm<diameter<0.5 mm). Pore volume fractions corresponding to TP, macropores, and mesopores were derived from the WRC for each treatment.

Soil Physical Quality indicators based on static properties

Soil Physical Quality indicators based on static properties were calculated from the soil WRC as follows (Reynolds et al., 2009; Iovino et al., 2013):

Macroporosity: $P_{mac} = \theta_s - \theta_m$ Eq. 6

Air capacity: $AC = \theta_s - \theta_{FC}$ Eq. 7

Plant available water capacity: $PAWC = \theta_{FC} - \theta_{PWP}$ Eq. 8

Relative field capacity: $RFC = \frac{\theta_{FC}}{\theta_S}$ Eq. 9

where θ_s [$L^3\ L^{-3}$], θ_m [$L^3\ L^{-3}$], θ_{FC} [$L^3\ L^{-3}$], and θ_{PWP} [$L^3\ L^{-3}$] are the volumetric water contents corresponding to pressure heads of 0, 0.1, 1, and 150 m, respectively.

The WRC data was also used to calculate the SPQ index S, following Dexter (2004):

$$S = -n\,(U_S - U_r)\left[1 + \frac{1}{m}\right]^{-(1+m)} \qquad \text{Eq. 10}$$

where U_s [$M\ M^{-1}$] and U_r [$M\ M^{-1}$] are the saturated and residual gravimetric water contents, respectively, and n and m are the fitting parameters, with $m = 1 - 1/n$. For each treatment, an average value for each SPQ indicator was calculated as the arithmetic mean of the values obtained in the 10 replicated samples.

The structural stability index (SSI) was calculated from texture and organic carbon content data, following Reynolds et al. (2009):

$$SSI = \frac{1.724OC}{(Silt + Clay)} \times 100; 0 \leq SSI < \infty \qquad \text{Eq. 11}$$

where OC is the soil organic carbon content (wt.%), and (Silt + Clay) (wt.%) is the combined silt and clay content of the soil.

Statistical analysis

To determine the effect of treatments, SPQ indicators and crop yields were analyzed separately (ANOVA with treatment as a factor) (Sokal and Rohlf, 1995). When a significant treatment effect was found, Fisher's least significant difference (LSD) test (Sokal and Rohlf, 1995) was used to compare the means of the different soil management practices.

Because the statistical distribution of K_0 data is skewed and non-normal, logarithmic values were used for analysis. The values of the SPQ indicators were compared with the range of optimal values suggested by Reynolds et al. (2009). For all analyses, significance was determined at p=0.05.

RESULTS AND DISCUSSION

Soil granulometry and organic matter

Mean particle size distribution of the A horizon did not differ significantly among treatments and exhibited 290 g kg^{-1} clay, 490 g kg^{-1} silt, and 220 g kg^{-1} sand, and was classified as clay loam. Soil organic matter content was different among treatments (NT: 40 g kg^{-1}, ChT: 50 g kg^{-1}, and DL: 56 g kg^{-1}). Organic matter contents were correlated with visual observation in the field of a greater amount of wheat crop residues in ChT and DL compared to NT. Greater wheat yield under tilled treatments than under reduced tillage treatments were found by Álvarez and Steinbach (2009), which supports the idea of higher production of wheat residues under ChT and DL compared to NT. In contrast, other studies did not find differences in organic matter content between NT and Minimum Tillage (Fabrizzi et al., 2005) or Conventional Tillage (García and Fabrizzi, 1998; Falótico et al., 1999). Thus, differences in organic matter content require further study.

K_0 and SPQ indicators based on dynamic properties

Field saturated hydraulic conductivity – K_0, ε_{ma}, C_wTP, and $C_w$mac were significantly higher for DL compared to NT and ChT (Table 1). These results are in agreement with the fact that K_0 depends mostly on ε_{ma}, which has already been reported (Capowiez et al., 2009; Soracco et al., 2011). The pore connectivity indexes for TP and for macroporosity (C_wTP and $C_w$mac, respectively) followed the same trend as K_0 and were higher for DL, which means that this practice increased the connectivity of macropores, and this change persisted until post-harvest. The results confirm the usefulness of C_w in detecting changes in pore configuration due to tillage practices.

The flow-based R_0 differed significantly among treatments only at a tension of 0.06 m of water column, and was highest for DL. The R_0 value, which includes the effects of pore constrictions on water transmission (Reynolds et al., 1995), describes an average pore size for the total soil tension range, including soil microporosity (Moret and Arrúe, 2007). A higher R_0 value can be considered indicative of poorer soil quality given that water flows at an excessive rate down the profile without being stored in the root zone (Iovino et al., 2013).

The dynamic-based SPQ indicators show that, overall, the DL created persistent changes in effective macroporosity, increasing the connectivity of total- and macroporosity. These results are in agreement with Soracco et al. (2012) who, working in a similar soil, found no differences in K_0 and ε_{ma} between NT and ChT. found No differences in infiltration rate after harvest between NT and chisel plowing in silty loam and loam soils from the

Table 1. Values of field saturated hydraulic conductivity (K_0), water-conducting macro and mesoporosity (ε_{ma}, and ε_{me}, respectively), pore continuity indexes based on water flux for total porosity, macroporosity, and mesoporosity (C_wTP, $C_w$mac, and $C_w$mes, respectively), and flow-weighted mean pore radius corresponding to applied pressure heads of 0.00. 0.03, and 0.06 m ($R_{0\ 0.00\ m}$, $R_{0\ 0.03\ m}$, and $R_{0\ 0.06\ m}$, respectively) for the different treatments

Treatment	K_0 [(1)]	ε_{ma}	ε_{me}	C_wTP	$C_w$mac	$C_w$mes	$R_{0\ 0.0\ m}$	$R_{0\ 0.03\ m}$	$R_{0\ 0.06\ m}$
	cm h^{-1}	%		cm h^{-1}			mm		
NT	2.17 a	0.0011 a	0.0014 a	4.09 a	28.95 a	12.03 a	0.14 a	0.11 a	0.10 a
ChT	2.55 a	0.0018 a	0.0016 a	4.40 a	30.97 a	6.92 a	0.21 a	0.10 a	0.08 a
DL	4.37 b	0.0032 b	0.0017 a	7.81 b	47.90 b	11.57 a	0.19 a	0.06 a	0.22 b

Different letters in the same column indicate significant differences among treatments for the corresponding parameter (LSD test, p=0.05). [(1)] Statistical analysis on K_0 was performed on log-transformed values.

Pampas region were found by Sasal et al. (2006), Álvarez et al. (2006), and Soracco et al. (2010). Increased values of K_0 after subsoiling a previously no-tilled soil, compared to surface tillage, were found by Sojka et al. (1997). Higher values of water infiltration rates in soils from the Argentinean Pampas region under DL than under NT were found by Álvarez et al. (2009b). These studies show that the effects of soil loosening on soil hydraulic properties and its resilience depends on the implement used.

SPQ indicators based on static properties

There were no differences among treatments for most of the static SPQ indicators. Furthermore, most of these indicators fell in the optimal ranges proposed by Reynolds et al. (2009) (Table 2). According to static indicators, the ChT and DL treatments did not produce persistent changes in SPQ that remained until postharvest. Moreover, the NT treatment exhibited optimal/ideal values for all the SPQ indicators (except for SSI). These results are in agreement with several reports from the Pampas region (Sasal et al., 2006; Álvarez et al., 2006; Álvarez et al., 2009a,b; Soracco et al., 2010, 2012), which found that the effect of soil loosening before seeding on total porosity did not remain until harvest. In addition, the effects of soil tillage on macroporosity (Pmac) and air capacity (AC) did not remain until harvest. Macropores are the most affected by traffic, and the macropores created by the tillage treatments were likely destroyed by the harvest traffic.

Static-based SPQ indicators were not capable of distinguishing treatments.

Crop yields and SPQ relationships

Air temperature was high during emergence compared to the historical average, enabling rapid plant emergence but, as of January, the temperature was slightly lower than the historical average (Table 3). Very high rainfall was registered in November and December but, in January and February, a period with very high temperature and normally with water deficit, it was about half the historical average (Table 3). This produced a more pronounced water deficit in these two months.

Main crop yields for the treatments were as follows: NT: 2,400 kg ha^{-1}; ChT: 2,358 kg ha^{-1}; and DL: 2,105 kg ha^{-1}, the last treatment exhibiting significantly lower yield than the NT and ChT crops. This result is in disagreement with Botta et al. (2010), who found lower soybean yield under NT than under the chisel plowing treatment and subsoiling treatment. In contrast, Fabrizzi et al. (2005) found no differences in wheat yields between NT and ChT, in agreement with our results.

The DL treatment exhibited values of static SPQ indicators similar to those of NT and ChT (except for greater SSI). Thus, these static indicators were not useful for distinguishing treatments in terms of effects on crop yields.

The DL treatment exhibited significantly higher values of the dynamic SPQ indicators K_0, ε_{ma}, C_wTP, and C_wmac. However, the positive effect of this tillage treatment on pore connectivity and related water conductivity negatively influenced crop yield. This may

Table 2. Mean values and standard deviations of macroporosity (Pmac), air capacity (AC), plant available water capacity (PAWC), relative field capacity (RFC), bulk density (BD), Dexter´s index (S), and structural stability index (SSI) for the different treatments

Treatment	Pmac	AC	PAWC	RFC	BD	S	SSI
	m^3 m^{-3}				Mg m^{-3}		
NT	0.11 ± 0.01 a^{++}	0.23 ± 0.02 a^{++}	0.16 ± 0.01 a^{+}	0.54 ± 0.09 a^{-}	1.09 ± 0.05 a^{+}	0.059 a^{+}	5.07 $^{-}$
ChT	0.14 ± 0.05 a^{++}	0.25 ± 0.04 a^{++}	0.19 ± 0.03 b^{+}	0.53 ± 0.12 a^{-}	1.00 ± 0.06 a^{+}	0.061 a^{+}	6.13 $^{-}$
DL	0.12 ± 0.05 a^{++}	0.24 ± 0.06 a^{++}	0.17 ± 0.04 ab^{+}	0.55 ± 0.11 a^{-}	1.02 ± 0.12 a^{+}	0.056 a^{+}	7.11 $^{+}$

Different letters in the same column indicate significant differences among treatments for the corresponding parameter (LSD test, p=0.05). Values followed by a double plus sign ($^{++}$) are within the range of optimal/ideal values proposed by Reynolds et al. (2009); mean values followed by a plus sign ($^{+}$) are in the range of good values. A minus sign ($^{-}$) indicates that the value is outside the range of optimal and/or good values proposed by this author.

Table 3. Average air temperature and total rainfall received for the month during the soybean production season

Period[1]	Rainfall		Temperature	
	2012-2013	1961-1990	2012-2013	1961-1990
	mm		°C	
November	108.1	87.8	18.6	16.9
December	214.2	77.8	20.1	20.1
January	56.0	89.9	21.3	21.6
February	46.1	83.9	20.1	20.9
March	125.6	127.0	15.6	18.4
April	143.5	59.8	15.6	14.6
May	49.9	48.0	10.3	10.9
Total	743.4	574.2	17.4	17.6

[1] In Azul, Buenos Aires (National Weather Service, Azul Station: 36° 45′ S, 59° 50′ W).

be attributed to the exceptional dry period of January and February. Probably, the water available during December from very high rainfall during that month was rapidly conducted to deeper soil layers, due to the presence of more conductive macropores in that treatment. Therefore, in the subsequent dry period, the water was no longer available for the crop, while in the NT and ChT treatments, with lower K_0 and pore connectivity values, the water remained in the surface horizon. The soybean root system is characterized as shallow, and the creation of macropores by the soybean root system is more limited (Bathke and Blake, 1984).

For crop yield, the static SPQ indicators showed low predictive value. The dynamic SPQ indicators were capable of distinguishing treatments. In particular, the dynamic indicators related to pore connectivity (ε_{ma}, C_wTP, C_wmac, and R_0) were inversely related to crop yield. The DL treatment, with higher values of these indicators, exhibited lower crop yield. A possible interpretation of this result is that a soil with a high macropore connectivity value will likely transmit water quickly below the root zone, with a reduced ability to store it for crop use. Therefore, its soil quality can be considered poor, as previously indicated by Iovino et al. (2013). However, the impact of the treatments on crop yields may vary depending on weather conditions. In the year studied, the initial high rainfall and subsequent dry period, determined lower crop yields in the treatment with a greater amount of vertically connected macropores. Future studies, monitoring years with different weather conditions, would be useful for increasing knowledge on this topic.

CONCLUSION

Soil physical quality indicators based on static properties are not capable of distinguishing tillage treatments and have low efficiency as crop yield predictors, whereas those indicators based on dynamic properties are capable in distinguishing tillage effects and are useful as crop yield predictors.

REFERENCES

AAPRESID. Evolución de la superficie bajo SD en Argentina. 2014 [accessed at: July 2014]. Available at: http://www.aapresid.org.ar/wp-content/uploads/2013/02/aapresid.evolucion_superficie_sd_argentina.1977_a_2011.pdf.

Álvarez R, Steinbach HS. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil Till Res. 2009;104:1-15. doi:10.1016/j.still.2009.02.005

Álvarez CR, Taboada MA, Bustingorri C, Gutiérrez Boem FH. Descompactación de suelos en siembra directa: efectos sobre las propiedades físicas y el cultivo de maíz. Ci Suelo. 2006;24:1-10.

Álvarez CR, Taboada MA, Gutiérrez Boem FH, Bono A, Fernandez PL, Prystupa P. Topsoil properties as affected by tillage systems in the rolling pampa region of Argentina. Soil Sci Soc Am J. 2009a;73:1242-50. doi:10.2136/sssaj2008.0246

Álvarez CR, Torres Duggan M, Chamorro ER, D'ambrosio D, Taboada MA. Descompactación de suelos Franco Limosos en siembra directa: efectos sobre las propiedades edáficas y los cultivos. Ci Suelo. 2009b;27:159-69.

Ankeny MD, Ahmed M, Kaspar TC, Horton R. Simple field method for determining unsaturated hydraulic conductivity. Soil Sci Soc Am J. 1991;55:467-70. doi:10.2136/sssaj1991.03615995005500020028x

Bathke GR, Blake GR. Effects of soybeans on soil properties related to soil erodibility. Soil Sci Soc Am J. 1984;48:1398-401. doi:10.2136/sssaj1984.03615995004800060040x

Blake GR, Hartge KH. Bulk density. In: Klute A, editor. Methods of soil analysis; physical and mineralogical methods. 2nd ed. Madison: American Society of Agronomy; 1986. Pt 1. p.363-76.

Botta GF, Tolon-Becerra A, Lastra-Bravo X, Tourn M. Tillage and traffic effects (planters and tractors) on soil compaction and soybean (*Glycine max* L.) yields in Argentinean pampas. Soil Till Res. 2010;110:167-74. doi:10.1016/j.still.2010.07.001

Cameira MR, Fernando RM, Pereira LS. Soil macropore dynamics affected by tillage and irrigation for a silty loam alluvial soil in southern Portugal. Soil Till Res. 2003;70:131-40. doi:10.1016/S0167-1987(02)00154-X

Capowiez Y, Caodux S, Bouchant P, Ruy S, Roger-Estrade J, Richard G, Boizard H. The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. Soil Till Res. 2009;105:209-16. doi:10.1016/j.still.2009.09.002

Cosentino DJ, Pecorari C. Limos de baja densidad: impacto sobre el comportamiento físico de los suelos de la región pampeana. Ci Suelo 2002;20:9-16.

Dexter AR. Soil physical quality. Part I: theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma. 2004;120:201-14. doi:10.1016/j.geoderma.2003.09.004

Elissondo E, Costa JL, Suero E, Fabrizzi KP, García F. Evaluación de algunas propiedades físicas de suelos luego de la introducción de labranzas verticales en un suelo bajo siembra directa. Ci Suelo 2001;19:11-9.

Fabrizzi KP, García FO, Costa JL, Picote LI. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. Soil Till Res. 2005;81:57-69. doi:10.1016/j.still.2004.05.001

Falótico JL, Studdert GA, Echeverría HE. Nutrición nitrogenada del trigo bajo siembra directa y labranza convencional. Ci Suelo. 1999;17:9-20.

García FO, Fabrizzi KP. Wheat and corn fertilization under no-till in the southeast of Buenos Aires. Balcarce, Argentina: EEA/INTA; 1998. (Boletín técnico, 150).

Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis; physical and minerological methods. 2nd ed. Madison: American Society of Agronomy; 1986. Pt 1. p.383-411.

Green TR, Ahuja LR, Benjamin JG. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 2003;116:3-27. doi:10.1016/S0016-7061(03)00091-0

Hillel D. Environmental soil physics. San Diego: Academic Press; 1998. p.173-201.

Horton R, Ankeny MD, Allmaras RR. Effects of compaction on soil hydraulic properties. In: Soane BD, van Ouwerkerk C, editors. Soil compaction in crop production. Amsterdam: Elsevier; 1994. p.141-65.

Iovino M, Castellini M, Bagarello V, Giordano G. Using static and dynamic indicators to evaluate soil physical quality in a Sicilian area. Land Degrad Develop. [online]. 2013. doi:10.1002/ldr.2263

IUSS Working Group WRB. World Reference Base for Soil Resources 2006, first update 2007. Rome: FAO. 2007. (World Soil Resources Reports, 103).

Jarvis NJ, Messing I. Near-saturated hydraulic conductivity in soils of contrasting texture measured by tension infiltrometers. Soil Sci Soc Am J. 1995;59:27-34. doi:10.2136/sssaj1995.03615995005900010004x

Kassam A, Friedrich T, Shaxson F, Pretty J. The spread of conservation agriculture: justification, sustainability and uptake. Inter J Agric Sustain. 2009;7:292-320. doi:10.3763/ijas.2009.0477

Lal R, Reicosky DC, Hanson JD. Evolution of the plow over 10000 years and the rationale for no-till farming. Soil Till Res. 2007;93:1-12. doi:10.1016/j.still.2006.11.004

Lozano LA, Soracco CG, Cornelis WM, Gabriels D, Sarli GO, Villarreal R. Anisotropy of pore size classes' connectivity related to soil structure under no tillage. Soil Sci. 2013;178:612-7. doi:10.1097/SS.0000000000000027

Mentges MI, Reichert JM, Rodrigues MF, Awe GO, Mentges LR. Capacity and intensity soil aeration properties affected by granulometry, moisture, and structure in no-tillage soils. Geoderma. 2016;263:47-59. doi:10.1016/j.geoderma.2015.08.042

Messing I, Jarvis NJ. Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. J Soil Sci. 1993;44:11-24. doi:10.1111/j.1365-2389.1993.tb00430.x

Moret D, Arrúe JL. Dynamics of soil hydraulic properties during fallow as affected by tillage. Soil Till Res. 2007;96:103-13. doi:10.1016/j.still.2007.04.003

Perroux KM, White I. Designs for disc permeameters. Soil Sci Soc Am J. 1988;52:1205-15. doi:10.2136/sssaj1988.03615995005200050001x

Quiroga A, Ormeño O, Peinemann N. Efectos de la siembra directa sobre las propiedades físicas de los suelos. In: Panigatti J, Marelli H, Buschiazzo D, Gil R, editors. Siembra directa. Buenos Aires: Hemisferio Sur; 1998. p.237-43.

Reichert JM, Suzuki LEAS, Reinert DJ, Horn R, Hakansson I. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Till Res. 2009;102:242-54. doi:10.1016/j.still.2008.07.002

Reichert JM, Da Rosa VT; Vogelmann ES; Da Rosa DP, Horn R, Reinert DJ, Sattler A, Denardin JE. Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. Soil Till Res. 2016;158:123-36. doi:10.1016/j.still.2015.11.010

Reynolds WD, Gregorich EG, Curnoe WE. Characterization of water transmission properties in tilled and untilled soils using tension infiltrometers. Soil Till Res. 1995;33:117-31. doi:10.1016/0167-1987(94)00437-J

Reynolds WD, Bowman BT, Drury CF, Tan CS, Lu X. Indicators of good soil physical quality: density and storage parameters. Geoderma. 2002;110:131-46. doi:10.1016/S0016-7061(02)00228-8

Reynolds WD, Drury CF, Yang XM, Tan CS. Optimal soil physical quality inferred through structural regression and parameter interactions. Geoderma. 2008;146:466-74. doi:10.1016/j.geoderma.2008.06.017

Reynolds WD, Drury CF, Tan CS, Fox CA, Yang XM. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma. 2009;152:252-63. doi:10.1016/j.geoderma.2009.06.009

Sanzano GA, Corbella RD, García JR, Fadda GS. Degradación física y química de un Haplustol típico bajo distintos sistemas de manejo de suelo. Ci Suelo. 2005;23:93-100.

Sauer TJ, Clothier BE, Daniel TC. Surface measurements of the hydraulic properties of a tilled and untilled soil. Soil Till Res. 1990;15:359-69. doi:10.1016/0167-1987(90)90109-Q

Sasal MC, Andriulo AE, Taboada MA. Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinean Pampas. Soil Till Res. 2006;87:9-18. doi:10.1016/j.still.2005.02.025

Schaap MG, Leij FJ, van Genuchten MTh. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J Hydrol. 2001;251:163-76. doi:10.1016/S0022-1694(01)00466-8

Schwen A, Bodner G, Scholl P, Buchan GD, Loiskandl W. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. Soil Till Res. 2011;113:89-98. doi:10.1016/j.still.2011.02.005

Soil Survey Staff. Keys to soil taxonomy. 10th ed. Washington, DC: USDA-Natural Resources Conservation Service; 2006.

Sojka RE, Home DJ, Ross CW, Baker CJ. Subsoiling and surface tillage effects on soil physical properties and forage oat stand and yield. Soil Till Res. 1997;40:125-44. doi:10.1016/S0167-1987(96)01075-6

Sokal RR, Rohlf FJ. Biometry. New York: Freeman; 1995.

Soracco CG. Efecto de la compactación sobre el sistema poroso del suelo en diferentes situaciones de labranza: modelización y realidad [tesis]. La Plata: Universidad Nacional de La Plata; 2009.

Soracco CG, Lozano LA, Sarli GO, Gelati PR, Filgueira RR. Anisotropy of Saturated Hydraulic Conductivity in a soil under conservation and no-till treatments. Soil Till Res. 2010;109:18-22. doi:10.1016/j.still.2010.03.013

Soracco CG, Lozano LA, Sarli GO, Gelati PR, Filgueira RR. Using tension disc infiltrometer to determine infiltration and water-conducting macroporosity and mesoporosity relationships in an agricultural silty loam soil. Soil Sci. 2011;176:459-63. doi:10.1097/SS.0b013e3182257d65

Soracco CG, Lozano LA, Balbuena R, Ressia JM, Filgueira RR. Contribution of macroporosity to water flux of a soil under different tillage systems. Rev Bras Cienc Solo. 2012;36:1149-55. doi:10.1590/S0100-06832012000400009

Steinbach HS, Álvarez R. ¿Afecta el sistema de labranza las propiedades físicas de los suelos de la región pampeana? Inf Agron Cono Sur. 2007;33:7-12.

Strudley MW, Green TR, Ascough II CA. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil Till Res. 2008;99:4-48. doi:10.1016/j.still.2008.01.007

Thomas GA, Titmarsh GW, Freebairn DM, Radford BJ. No-tillage and conservation farming practices in grain growing areas of Queensland: a review of 40 years of development. Aust J Exp Agron. 2007;47:897-98.

Topp GC, Reynolds WD, Cook FJ, Kirby JM, Carter MR. Physical attributes of soil quality. In: Gregorich EG, Carter MR, editors. Soil quality for crop production and ecosystem health; development in soil science. New York: Elsevier; 1997. v. 25. p.21-58.

van Genuchten MTh. A closed-form equation for predicting the hydraulic conductivity of unsaturated soil. Soil Sci Soc Am J. 1980;44:892-8. doi:10.2136/sssaj1980.03615995004400050002x

van Genuchten MTh, Leij FJ, Yates SR. The RETC code for quantifying the hydraulic functions of unsaturated soils, Version 1.0. EPA Report 600/2-91/065. Riverside: U.S. Salinity Laboratory, USDA, ARS; 1991.

Wahl NA, Bens O, Buczko U, Hangen E, Hüttl RF. Effects of conventional and conservation tillage on soil hydraulic properties of a silty-loamy soil. Phys Chem Earth. 2004;29:821-9. doi:10.1016/j.pce.2004.05.009

Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37:29-38.

Watson K, Luxmoore R. Estimating macroporosity in a forest watershed by use of a tension infiltrometer. Soil Sci Soc Am J. 1986;50:578-82. doi:10.2136/sssaj1986.03615995005000030007x