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Capacity and Intensity Indicators to evaluate the effect of different crop sequences and cover crops on soil physical quality of two different textured soils from Pampas Region

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ABSTRACT

Soil physical degradation is a current problem in Molisols of the Pampas Region under no-tillage (NT), that has been related to over-simplified agricultural systems with scarce or no rotations and long winter bare fallows. Soil physical quality (SPQ) is a key factor of soil health and productivity, as it controls root development and air and water fluxes and storage in the soil, which in turn affect nutrient uptake and plant growth. Cover crops have been proposed as a companion agricultural practice to improve NT performance and SPQ. The aim of this study was to evaluate the effect of the inclusion of winter cover crops in different cropping sequences on capacity and intensity indicators of SPQ in two soils of different texture under NT and to compare it with different traditional crop sequences, including non-agricultural plots. SPQ was evaluated at two different sites, one with a silty loam Argiudoll and the other with a sandy loam Hapludoll. Treatments included plots with and without cover crops, with different summer crop sequences (continuous soybean and corn – soybean rotations). Also, a corn – wheat/soybean rotation with and without pastures was evaluated. All treatments had more than 15 years under the same management. We measured soil organic carbon (SOC), and capacity SPQ indicators (bulk density, total porosity, pore size distribution, air capacity, plant available water, relative field capacity and S index). We also measured dynamic SPQ indicators derived from field infiltration tests (saturated and near saturation hydraulic conductivity, effective macro and mesoporosity, and porosity connectivity indexes for different pore families). On the silty loam Argiudoll, cover crops increased SOC but failed to improve SPQ. This was related to soil physical degradation and the low ability of these soils for structure regeneration. On the sandy loam Hapludoll, cover crops had mixed effects on SOC and pore size distribution, but increased near saturation hydraulic conductivity, in the case of the corn – soybean rotation with cover crops, reaching values similar to those of a natural grassland.

1. Introduction

Soil physical quality (SPQ) can be considered from an agronomical point of view as the sum on physical features that allow a soil to support plant growth. SPQ is a key factor of soil health and productivity, as it controls root development, and air and water fluxes and storage in the soil, which in turn affect nutrient uptake and plant growth (Topp et al., 1997; Reynolds et al., 2002). In the Argentinian Pampas, the main cropping area in the country, crop production has experienced a wide expansion over the last decades. This increase, achieved mostly by the adoption of continuous cropping under no-till (NT), has led to soil physical and chemical degradation (Sasal et al., 2006; Caride et al., 2012). Further simplification of agricultural systems by implementation of monoculture of low residue input crops, such as soybean, has

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worsened degradation problems (Duval et al., 2016; Sasal et al., 2017). Soil physical degradation is an issue of concern, as it affects crop yields, but also as it has severe implications on other environmental services such as carbon sequestration, water entry and flood regulation, and water purification (Wingeyer et al., 2015).

Currently, 33 million hectares are annually sown in Argentina under NT, from which around 16 million hectares are soybean (AAPRESID, 2020). The main agricultural area for extensive crops is the Humid Pampas region (which is a sub-region of the Pampas region), where the most frequent agricultural soils are Mollisols, loessic soils characterized by their high natural fertility (Durán et al., 2011). Though NT was expected to maintain and improve soil physical and chemical quality, many authors have reported processes of soil physical degradation in these soils under continuous cropping under NT. Increased bulk density (BD) and penetration resistance under NT has been reported by different authors (Díaz-Zorita et al., 2004; Fabrizzi et al., 2005; Alvarez and Steinbach, 2009). Schmidt et al. (2018) reported soil crusting and topsoil densification under NT, which restricted root growth in sandy loam, loam and clay-loam textured Mollisols. In silty soils of the Pampas Region, platy structure is often found within the top few cm of soil (Lozano, 2014; Sasal et al., 2009, 2017). This kind of structure can restrict root development in depth and is associated with low vertical pore connectivity, and thus can restrict water entry into the soil and favor surface runoff (Lozano, 2014; Sasal et al., 2017).

Many studies relate SPQ problems with simplified cropping sequences and with high frequency of soybean crops, mainly because of low residue input, long fallow periods, and relatively poor root development (Alvarez et al., 2014; Sasal et al., 2017; Behrends Kraemer et al., 2019, 2021; Wilson et al., 2020). Crop sequences with high soybean frequency can result in poorer aggregate stability, less macroporosity and pore connectivity and diminished organic carbon content compared to a more diverse cropping sequence (Novelli et al., 2013; Sasal et al., 2009; Behrends Kraemer, 2015). Platy structure occurrence is also enhanced in soils under soybean monoculture (Lozano et al., 2013; Novelli et al., 2017). Some authors suggest that diversifying the crop sequence, including double crops or including pastures can lead to better structural and functional features, even when they imply more machinery traffic or higher nutrient exportation (García-Préchac et al., 2004; Novelli et al., 2013; Behrends Kraemer and Morrás, 2018). García-Préchac et al. (2004) found that crop-pasture rotations in Mollisols under NT, compared to continuous cropping or conventional tillage, diminished soil erosion up to the levels observed in a natural grassland. Behrends Kraemer et al. (2021) observed that intensification of the cropping sequence in Mollisols of the Pampas region lead to higher aggregate stability as compared to more simplified cropping sequences (with higher frequency of soybean and winter bare fallow), though values observed were lower than in a natural environment. In order to achieve sustainability of agricultural systems, the use of companion management practices may be needed (Blanco-Canqui and Ruis, 2018; Basche and DeLonge, 2017, 2019; Blanco-Canqui, 2021).

Intensification through the implementation of cover crops has been proposed to maintain soil fertility and recover degraded soils (Recio-Vázquez et al., 2014; Poeplau and Don, 2015). Cover crops can protect soil from degradation as they imply cover from wind and rain, higher carbon inputs and more roots and biological activity in the soil (Mukherjee and Lal, 2015). Cover crops are considered to enhance aggregation and the formation of favorable soil structure (Duval et al., 2014, 2016; Blanco-Canqui et al., 2015; Behrends Kraemer et al., 2017). Sasal et al. (2017) found that a longer period of root activity in a year can favor the development of a fragmentary soil structure, reducing platy structure. However, there is limited information on how cover crops affect soil pore configuration. Some authors found that cover crops increased water-conducting porosity (Keisling et al., 1994; Blanco-Canqui et al., 2011). Calonego et al. (2017) found that some species with taproots were able to break through compacted layers increasing macroporosity. Villarreal et al. (2020) mentioned that biological activity increased macroporosity connectivity in loam and silty loam Argiudolls of the Humid Pampas region under NT. Regarding the effect of cover crops on hydraulic conductivity (K), different results have been reported. Blanco-Canqui et al. (2015) reported that cover crops can increase saturated hydraulic conductivity (K_0) in the long term (13–15 years), in silty loam soils under NT. Alvarez et al. (2017) found similar results in a review including different Molisolls of the Pampas Region. Other authors found no significant effect of cover crops or intensification of the rotation on hydraulic conductivity, in studies including Molisolls and other soil orders (Pikul et al., 2006; Villamil et al., 2006; Blanco-Canqui et al., 2011; Haruna et al., 2018). Bodner et al. (2008) found that the effect of cover crops on K was highly variable, recording increases, no effect or decreases depending on the time of the year and cover crop species. Carof et al. (2007), found similar results, highlighting that the increases in K observed during winter did not reflect an increase in total porosity (TP) nor size of functional pores, and thus were due to an increase in pore continuity.

There are many SPQ indicators that quantify pore system configuration and function, and thus soil's strength and soil's ability to transfer and store water and air (Reynolds et al., 2002, 2009). However, which are the best SPQ indicators is still a matter of discussion. SPQ indicators can be classified in capacity and intensity parameters (Horn and Kutilek, 2009). Capacity SPQ indicators describe pore space and include BD, TP, and those indicators obtained from the soil water retention curve (SWRC), such as the volume of different pore classes, for instance macro, meso and microporosity (θma, θme, θmi), and S index, that is the slope of the SWRC at the inflection point (Dexter, 2004). Also, storage parameters derived from the SWRC such as air capacity (AC), plant available water (PAW), and relative field capacity (RFC) (Horn and Kutilek, 2009). Intensity SPQ indicators are those that include dynamic aspects, describing and quantifying the functionality and processes occurring in the soil (Horn and Kutilek, 2009). Intensity SPQ indicators include parameters derived from infiltration tests, such as K, water conducting macro and mesoporosity (ε_{ma} and ε_{me}), and connectivity indexes (total porosity connectivity, Cw_{TP}, and macro and meso porosity connectivity, Cw_{ma} and Cw_{me}) (Lozano et al., 2016). Lozano et al. (2016) observed that capacity SPQ indicators showed a low predictive value for crop yields and were not sensitive enough to detect differences between management practices. On the other hand, intensity SPQ indicators can be more sensitive, as they give information not only about pore composition in a given volume of soil, but also about its functionality (Soracco et al., 2018). However, the use of capacity parameters has some advantages, as they are easy to measure, values are easy to compare, and measures have lower variability than some intensity parameters such as K (Horn and Kutilek, 2009). Iovino et al. (2013) concluded that the use of both capacity and intensity SPQ indicators may give complementary information to describe the effect of land management on SPQ.

The soil structure and aggregate stability of Mollisols depend strongly on biological activity, as these soils have low capability of abiotic structuring (Behrends Kraemer et al., 2019). Within Mollisols, those soils with higher percentage of finer particles (clay and silt) retain more organic carbon and tend to have better physical properties than coarser soils (Taboada and Álvarez, 2008). However, soils with high silt content are more susceptible to suffer physical degradation (Chagas et al., 1994; Taboada et al., 1998) and to develop massive or platy structure (Sasal et al., 2006, 2017). Once compacted, Argiudolls have low ability for natural soil pore regeneration under NT (Sasal et al., 2006). This is due to the abundance of illite clay with low shrinkage-swelling capacity (Sasal et al., 2006), the prevalence of fine silts and bioliths within the silt fraction (Taboada and Álvarez, 2008) and the temperate climate, where there are few or none freeze–thaw processes (Sasal et al., 2006). Coarser soils have weaker structure but are also more dependent on the organic phase (Behrends Kraemer et al., 2019). Sandy loam soils frequently show a better response to NT than soils with finer texture, showing greater improvements on SPQ when this practice is adopted (Taboada et al., 1998; Díaz-Zorita et al., 2004;

Lozano et al., 2013; Basche and DeLonge, 2019), and thus may have better responses to cover crops inclusion than finer soils (Blanco-Canqui et al., 2015).

Cover crops can be useful to improve SPQ in soils degraded by years of agriculture under NT, mainly due to the effect of living roots and associated biota, and especially in soils with low capability of abiotic soil structure formation. The extent of the effects of cover crops on SPQ will depend on site specific factors such as climate, soil texture and cropping and tillage management (Blanco-Canqui et al., 2015). Valuable information may arise from studying the effect of cover crops on SPQ on soils of different texture and on different cropping sequences under NT. The aim of this study was to evaluate the effect of the inclusion of winter cover crops in different cropping sequences on capacity and intensity indicators of SPQ in two soils of different texture under NT and to compare it with different crop sequences, including non agricultural plots (pasture or natural grassland).

We hypothesized that i- winter cover crops improve SPQ to similar values observed in a pasture or a natural grassland, ii- more diverse crop rotations show improved SPQ, iii- changes on SPQ are broader in the sandy loam soil than in the silty loam soil, and iv- intensity SPQ indicators are more sensitive to the inclusion of cover crops than capacity SPQ indicators.

2. Materials and methods

2.1. Study sites

The study sites are located in the Argentinian Pampas, at Pergamino (33°51′ S, 60°40′ W) and General Villegas (34°54 ′S, 63°44 ′W), both experimental stations belonging to the Instituto Nacional de Tecnología Agropecuaria (INTA). The climate is temperate humid without a dry season, with mean annual temperature of 16.4 °C and mean annual rainfall of 950 mm at Pergamino, and 16.2 °C and 929 mm at General Villegas (Díaz-Zorita and Basanta, 1999; Restovich et al., 2012).

At Pergamino (PER), soil is a Typic Argiudoll (Soil Survey Staff, 2014), Pergamino series, deep, well-developed and well-drained. Soil texture is silty loam, with 57.0% silt and 22.6% clay in the A horizon. At General Villegas (VIL), soil is a Typic Hapludoll (Soil Survey Staff, 2014), Lincoln series. Soil texture is sandy loam, with 22.4% silt and 14.3% clay. Both at PER and VIL, soil texture showed no significant differences among treatments.

2.2. Treatments

At PER, four situations were evaluated:

(i) Soybean monoculture with winter bare fallow (S_{BF}).
(ii) Soybean crop with a winter cover crop (S_{CC}).
(iii) Corn – wheat/soybean rotation (R).
(iv) A 5-year pasture set on a plot that had been under a corn – wheat/soybean rotation (P).

All plots were under NT. S_{BF} had been under soybean monoculture for the last 32 years (since 1987). S_{CC} had been under soybean monoculture for 23 years (1987–2010), and then under soybean with winter cover crops for the last 9 years. Winter cover crop consisted of an oat (*Avena sativa* L.) and vetch (*Vicia sativa* L.) mixture with densities of 20 and 40 kg ha^{-1}, respectively. The plot without cover crops was chemically maintained without weeds during fallow. Cover crop was dried with glyphosate in spring (October), at the reproductive stage, in order to seed soybean. The plots under R had had a corn – wheat/soybean rotation under NT for the last 40 years (since 1979). The P treatment had also been under a corn – wheat/soybean rotation since 1979 but included pastures (*Festuca arundinacea, Trifolium repens* L. and *Medicago sativa* L.) for two periods (between 1998 and 2002 and 2014–2019).

At VIL, five situations were evaluated:

(i) Soybean monoculture with winter bare fallow (S_{BF})
(ii) Soybean crop with a winter cover crop (S_{CC}).
(iii) Corn-soybean rotation with winter bare fallow (R_{BF})
(iv) Corn-soybean rotation with a winter cover crop (R_{CC}).
(v) A plot that had had a natural grassland (NG) at least since the beginning of the trial.

At VIL, all agricultural plots had been under the same crop sequences under NT for 15 years. Cover crop was rye (*Secale cereale*), which was chemically dried in September.

The trials consisted of a completely randomized design with 30 m × 10 m plots in PER and 5 × 20 m plots in VIL. Soil sampling and infiltration runs were performed at the end of October 2019 in both sites (after cover crops were chemically dried and before summer crops seeding). At VIL, the rotation had had corn the previous summer.

2.3. Field infiltration

Infiltration was measured on site using a 6.25 cm radius tension infiltrometer (Perroux and White, 1988). For each treatment, four replicates were performed in randomly selected sites of each plot, avoiding visible wheel tracks. To ensure good hydraulic contact between the device and the soil, a dry sand layer was spread on the surface and flattened with a spatula. Infiltration runs were performed at three values of soil water pressure head, h (−6, −3 and 0 cm, applied in this order and in the same place). Flow monitoring continued every 5 min up to 30 min, and every 10 min until steady-state flow from the disc was attained, which occurred within 1 h.

From field infiltration data, intensity SPQ indicators were calculated: With the steady-state data of soil water infiltration curve, K_0 and field hydraulic conductivity at h = −3 (K_3) and at h = −6 (K_6) were calculated following Ankeny et al. (1991). Also, water-conducting macroporosity (ε_{ma}, r > 0.5 mm) and water-conducting mesoporosity (ε_{me}, r = [0.25–0.5 mm]) were calculated according to Watson and Luxmoore (1986) (Eqs. 1 and 2):

$$\varepsilon_{ma} = \frac{8\eta(K_0 - K_3)}{\rho g(r)^2} \tag{1}$$

$$\varepsilon_{me} = \frac{8\eta(K_3 - K_6)}{\rho g(r)^2} \tag{2}$$

where μ is viscosity of water, ρ is the density of water, g is acceleration due to gravity and r_a is the lower limit of the equivalent pore radius of each pore size family: $r_{a(ma)}$ = 0.5 mm and $r_{a(me)}$ = 0.25 mm.

2.4. Laboratory determinations

To determine SWRC, undisturbed soil samples (10 cm height, 7.5 cm diameter) were collected near the infiltration runs spots and avoiding wheel tracks, from the top 10 cm of soil. Six replicates were collected at each plot. The samples were covered with plastic caps to protect the soil from mechanical disturbances and evaporation. A sandbox apparatus was used to determine water retention data at h = 0, − 10, − 30, − 50, − 70 and − 100 cm. A pressure chamber was used to determine water retention data at h = −300 and − 5000 cm. BD was used to transform gravimetric to volumetric water contents. Water retention data from the SWRC was fitted with the van Genuchten (1980) model, employing the retention curve code (RETC) (van Genuchten et al., 1991) to calculate the following capacity SPQ indicators: macroporosity (θma), mesoporosity (θme) and microporosity (θmi), air capacity (AC), plant available water capacity (PAW) and relative field capacity (RFC) and Dexter's S (S_{index}) according to Lozano et al. (2016). Equivalent pore radii are > 30 μm for θma, [15–30] μm for θme, and < 15 μm for θmi.

In order to measure soil BD, four cores (10 cm height, 7.5 cm diameter) were collected at each treatment, in the places were infiltration runs had been made (Blake and Hartge, 1986). Total porosity was calculated from BD, assuming a particle density of 2.65 $Mg.m^{-3}$ (Hillel, 1998).

Additionally, total soil organic carbon (SOC) content at the 0–5 cm layer was measured according to Walkley and Black (1934).

2.5. Porosity connectivity indexes

Pore connectivity indexes of total porosity (Cw_{TP}), macroporosity (Cw_{ma}) and mesoporosity (Cw_{me}) were calculated based on field hydraulic conductivity and porosity of different size classes calculated from SWRC data. For each pore family with radii between r_a and r_b ($r_a > r_b$), the corresponding connectivity index (Cw) was calculated as:

$$Cw_{(r_a-r_b)} = \frac{K_{(h_a)} - K_{(h_b)}}{\theta_{(h_a)} - \theta_{(h_b)}}$$

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; $K(h_a)$ and $K(h_b)$ are hydraulic conductivities at h_a and h_b pressure heads; and $\theta(h_a)$ and $\theta(h_b)$ is volumetric water content at those pressure heads (Villarreal et al., 2020).

Reference values of the SPQ indicators were taken from Reynolds et al. (2009).

2.6. Statistical analysis

For each site, one way ANOVA was performed to determine the effect of treatment on the studied soil properties. The variables with a non-normal distribution were transformed to their logarithmic values to achieve normality (K_0, K_3, K_6, ε_{ma}, ε_{me}, Cw_{TP} and Cw_{ma}) before the statistical analysis. Fisher's (LSD) test was used to compare means (Sokal and Rohlf, 1995). For all the analysis the significance was determined at p-value < 0.05.

3. Results

3.1. Capacity soil physical quality (SPQ) indicators and soil organic carbon content (SOC)

Values of the capacity SPQ indicators (BD, TP, θma, θme, θmi, PAW, AC, RFC and S_{index}) are shown in Fig. 1 and Table 1. At PER, there was no treatment effect on any of the capacity SPQ indicators. At VIL, on the contrary, all capacity SPQ indicators were significantly affected by treatment at VIL.

At VIL, TP was higher for the NG than for all the other treatments (NG > S_{BF}=S_{CC}=R_{BF}=R_{CC}), with no significant differences between the agricultural treatments (Fig. 1). Regarding pore size distribution, θma followed the order NG=S_{BF}=S_{CC} > R_{BF}=R_{CC}. Values of θme showed the following order: S_{BF} > S_{CC}=NG > R_{CC} > R_{BF}; and θmi followed the order NG > R_{BF}=R_{CC} > S_{BF}=S_{CC}. When comparing the effect of CC vs bare fallow for the same summer rotation, the presence of cover crops did not affect θma nor θmi. On the other hand, the presence of cover crops caused significant changes in θme both in the soybean treatment (S_{BF} > S_{CC}) and in the rotation (R_{CC} > R_{BF}).

Regarding soil air and water storage parameters at VIL, PAW was higher for the S_{BF} and for the R_{CC} treatments, and lower for S_{CC} (Table 1). The NG and R_{BF} treatments showed intermediate values, with no statistical differences with all the other treatments. When considering the same summer crop, the presence of CC decreased PAW on the soybean treatment (S_{BF} > S_{CC}), and caused no effect on the rotation (R_{BF}=R_{CC}). AC was significantly higher for S_{BF}, S_{CC} and NG, and lower for R_{CC} and R_{BF}. There were no significant differences on AC between treatments with and without cover crops when considering the same summer crop (R_{BF}=R_{CC} and S_{BF}=S_{CC}). Conversely, RFC was higher for R_{CC} and R_{BF}, and lower for S_{CC} and S_{BF}. The NG had higher RFC than S_{BF}, and lower than R_{CC} and R_{BF}. The presence of CC caused no effect on RFC (R_{BF}=R_{CC} and S_{BF}=S_{CC}).

The S_{BF} treatment showed the highest S_{index}. There was no significant difference between R_{BF}, R_{CC}, and the NG in the S_{index}. S_{index} was significantly higher for R_{CC} than for S_{CC} and was also higher for S_{BF} than for R_{BF}. For the same summer crop, the presence of CC caused a decrease on soybean (S_{BF} > S_{CC}) and no effect on the rotation (R_{BF}=R_{CC}). Despite significant differences, all S_{index} values felt within the optimal range suggested by Reynolds et al. (2009) ($S_{index} \geq 0.050$).

SOC values were affected by treatment factor at both sites. At PER, S_{CC} showed the highest SOC (Table 1). All the other treatments showed lower SOC than S_{CC}, with no statistical differences among treatments (S_{BF}=R=P). At VIL, SOC followed the order: R_{BF} > S_{CC} > S_{BF} =R_{CC} (Table 1). SOC at the NG was intermediate to that on the R_{BF} and S_{CC} treatments, with no statistical differences. When comparing CC with winter bare fallow for the same summer crop, CC caused an increase on SOC on soybean plots both at PER and VIL (S_{CC} > S_{BF}), while CC

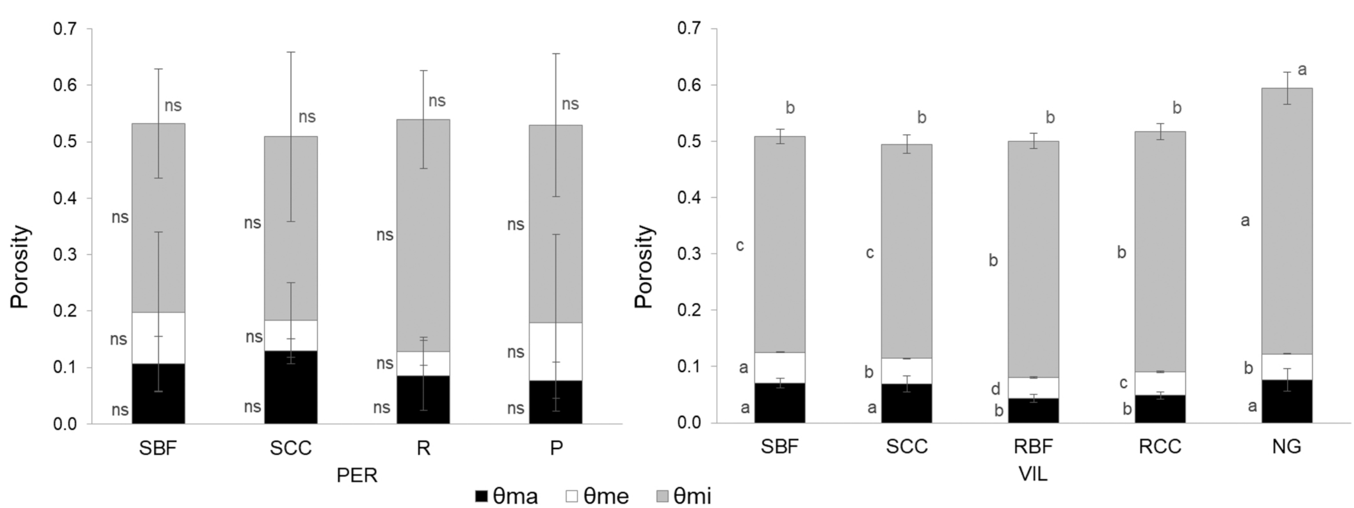

Fig. 1. Pore size distribution at Pergamino (PER) and Villegas (VIL). θma, θme, θmi: macro, meso and microporosity. The sum of the three bars (θma + θme + θmi) is the total porosity (TP). S_{BF}: soybean with winter bare fallow. S_{CC}: soybean with winter cover crops. R: corn-wheat/soybean rotation. P: pasture. R_{BF}: corn-soybean rotation with winter bare fallow. R_{CC}: corn-soybean rotation with winter cover crop. NG: natural grassland. For each pore family at each site, different letters indicate significant differences (LSD Fisher, p-value < 0.05) and ns stands for non-significant differences. Letters above the bars indicate statistical differences for TP. Samples were collected in October, after winter cover crop was ended, in randomly selected sites and avoiding borders and visible wheel tracks.

Table 1
Bulk density (BD), storage soil physical quality (SPQ) indicators and soil organic carbon content (SOC) at Pergamino (PER) and Villegas (VIL).

		BD ($g.cm^{-3}$)	AC	PAW	RFC	S_{index}	SOC ($g.100^{-1}g^{-1}$)
PER	S_{BF}	1.17 ± 0.05 a (++)	0.15 ± 0.04 a (++)	0.3 ± 0.2 a (++)	0.60 ± 0.3 a (++)	0.1 ± 0.2 a (++)	1.68 ± 0.03 b
	S_{CC}	1.212 ± 0.003 a (+)	0.18 ± 0.07 a (++)	0.17 ± 0.03 a (+)	0.6 ± 0.2 a (++)	0.1 ± 0.2 a (++)	3.4 ± 0.4 a
	R	1.20 ± 0.04 a (++)	0.13 ± 0.09 a (+)	0.25 ± 0.05 a (++)	0.8 ± 0.2 a (-)	0.08 ± 0.03 a (++)	1.73 ± 0.03 b
	P	1.17 ± 0.06 a (++)	0.13 ± 0.03 a (+)	0.3 ± 0.2 a (++)	0.6 ± 0.3 a (++)	0.1 ± 0.2 a (++)	1.5 ± 0.2 b
VIL	S_{BF}	1.33 ± 0.03 a (-)	0.13 ± 0.01 a (+)	0.31 ± 0.02 a (++)	0.75 ± 0.02 c (++)	0.095 ± 0.006 a (++)	1.00 ± 0.02 c
	S_{CC}	1.35 ± 0.04 a (-)	0.11 ± 0.01 a (+)	0.27 ± 0.02 b (++)	0.77 ± 0.03 bc (++)	0.076 ± 0.006 c (++)	1.24 ± 0.02 b
	R_{BF}	1.36 ± 0.06 a (-)	0.081 ± 0.008 b (-)	0.30 ± 0.02 ab (++)	0.84 ± 0.02 a (-)	0.079 ± 0.006 bc (++)	1.46 ± 0.2 a
	R_{CC}	1.31 ± 0.07 a (-)	0.091 ± 0.007 b (-)	0.32 ± 0.02 a (++)	0.82 ± 0.02 a (-)	0.084 ± 0.006 b (++)	0.96 ± 0.1 c
	NG	1.11 ± 0.05 b (++)	0.12 ± 0.02 a (+)	0.30 ± 0.04 ab (++)	0.79 ± 0.04 b (-)	0.078 ± 0.01 bc (++)	1.42 ± 0.09 ab

AC: air capacity. PAW: plant available water. RFC: relative field capacity. SBF: soybean with winter bare fallow. SCC: soybean with winter cover crops. R: corn-wheat/soybean rotation. P: pasture. RBF: corn-soybean rotation with winter bare fallow. RCC: corn-soybean rotation with winter cover crop. NG: natural grassland. For each indicator, different letters indicate significant differences between treatments (LSD Fisher, p-value < 0.05). A double plus sign (++) indicates values are within the range of optimal values, a plus sign (+) indicates they are in the range of good values, and a minus sign (-) indicates that the value is outside the range of good or optimal values, considering reference values proposed by Reynolds et al. (2009). Samples were collected in October, after winter cover crop was ended, in randomly selected sites and avoiding borders and visible wheel tracks.

decreased SOC in the rotation at VIL ($R_{CC} < R_{BF}$).

3.2. *Intensity soil physical quality (SPQ) indicators derived from field infiltration measurements*

At PER, K at different water pressure heads was not affected by treatment (Fig. 2). On the other hand, ε_{ma} was affected by treatment, showing the highest values for S_{CC} and P (Fig. 3). R showed lower ε_{ma} values than S_{CC} and P. S_{BF} had intermediate ε_{ma}, that was not significantly different from all the other treatments (S_{BF}=R and S_{BF}=S_{CC}=P). There was no effect of treatment on ε_{me}. Regarding porosity connectivity indexes, there was no effect of treatment factor on Cw_{TP} (Table 2). Cw_{ma} was higher for P and R, and lower for S_{BF}. S_{CC} showed intermediate values, with no statistical differences with the other treatments. Values of Cw_{me} followed the order: R > S_{BF} > S_{CC}. The P treatment showed values of Cw_{me} that were intermediate (and not statistically different) to those of the R and S_{BF} treatments.

At VIL, K_0 was not significantly affected by treatment (Fig. 2). K_3 values followed the order NG=R_{CC} > R_{BF} =S_{BF}=S_{CC}. K_6 values followed the order NG=R_{CC} > R_{BF}=S_{CC} > S_{BF}. There was no treatment effect on ε_{ma} and ε_{me} (Fig. 3). Regarding pore connectivity indexes, there was no treatment effect on Cw_{TP} and Cw_{ma} (Table 2). Cw_{me} was affected by treatment, being higher for R_{BF}, R_{CC} and S_{BF} (with no statistical differences between these three treatments) and lower for S_{CC} (R_{BF}=R_{CC}=S_{BF} > S_{CC}). The NG showed intermediate values that were lower than those of the R_{CC} treatment, and not significantly different from S_{CC}, R_{BF} nor S_{BF}.

4. Discussion

Both at PER and VIL locations (silty loam and sandy loam soils), BD and TP failed to distinguish between management practices, indicating

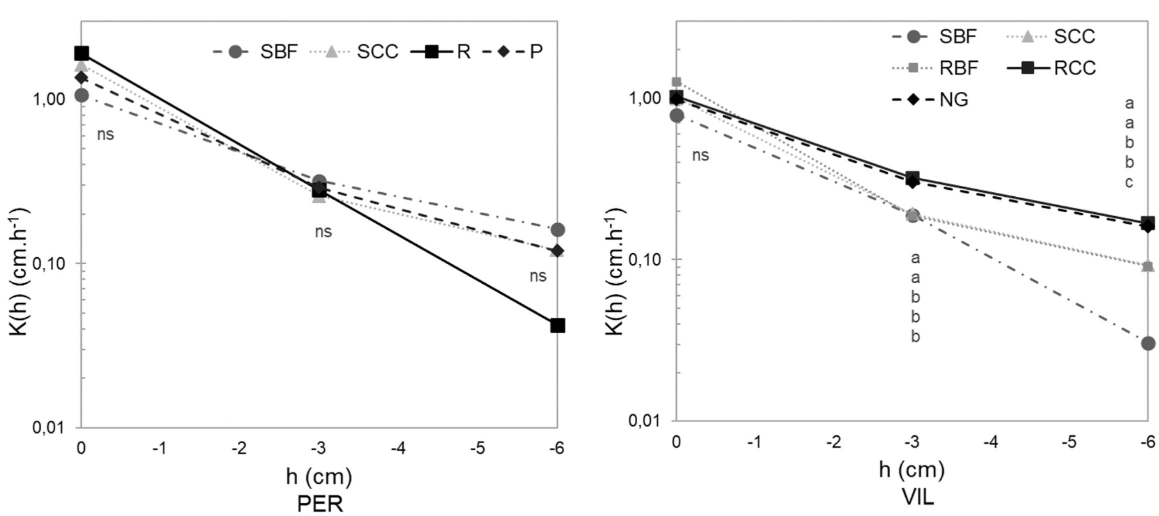

Fig. 2. Hydraulic conductivity at 0, − 3 and − 6 cm pressure heads (K_0, K_3 and K_6, respectively) at Pergamino (PER) and Villegas (VIL). K(h) is plotted in a logarithmic scale. S_{BF}: soybean with winter bare fallow. S_{CC}: soybean with winter cover crops. R: corn-wheat/soybean rotation. P: pasture. R_{BF}: corn-soybean rotation with winter bare fallow. R_{CC}: corn-soybean rotation with winter cover crop. NG: natural grassland. For each pressure head and site, different letters (from top to bottom) indicate significant differences between treatments (from left to right) (LSD Fisher, p-value < 0.05). ns: non-significant differences. Infiltration runs were performed in October, after winter cover crop was ended, in randomly selected sites and avoiding borders and visible wheel tracks.

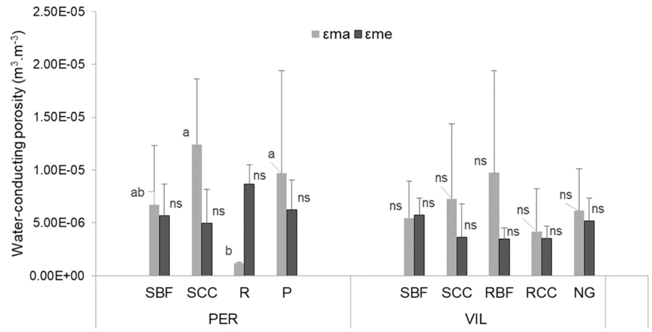

Fig. 3. Water-conducting macro and mesoporosity (ε_{ma} and ε_{me}, respectively) at Pergamino (PER) and Villegas (VIL). S_{BF}: soybean with winter bare fallow. S_{CC}: soybean with winter cover crops. R: corn-wheat/soybean rotation. P: pasture. R_{BF}: corn-soybean rotation with winter bare fallow. R_{CC}: corn-soybean rotation with winter cover crop. NG: natural grassland. For each indicator and site, different letters indicate significant differences between treatments (LSD Fisher, p-value < 0.05). ns: non-significant differences. Infiltration runs were performed in October, after winter cover crop was ended, in randomly selected sites and avoiding borders and visible wheel tracks.

Table 2
Porosity connectivity indexes at Pergamino (PER) and Villegas (VIL).

		Cw_{TP} (cm.h^{-1})	Cw_{ma} (cm.h^{-1})	Cw_{me} (cm.h^{-1})
PER	**SBF**	2.0 ± 1.5 a	37 ± 31 b	15 ± 8 b
	SCC	3.1 ± 1.4 a	69 ± 35 ab	2 ± 1c
	R	3.7 ± 2.1 a	238 ± 167 a	39 ± 8 a
	P	2.5 ± 2.2 a	204 ± 204 a	27 ± 12 ab
VIL	**SBF**	1.6 ± 0.7 a	263 ± 171 a	46 ± 13 ab
	SCC	2.0 ± 1.5 a	252 ± 244 a	24 ± 21c
	RBF	2.5 ± 2.2 a	693 ± 686 a	45 ± 13 ab
	RCC	2.0 ± 1.5 a	403 ± 405 a	63 ± 22 a
	NG	1.7 ± 0.8 a	149 ± 96 a	26 ± 11 bc

CwTP, Cwma and Cwme: total, macro and meso-porosity connectivity. SBF: soybean with winter bare fallow. SCC: soybean with winter cover crops. R: corn-wheat/soybean rotation. P: pasture. RBF: corn-soybean rotation with winter bare fallow. RCC: corn-soybean rotation with winter cover crop. NG: natural grassland. For each indicator and site, different letters indicate significant differences (LSD Fisher, p-value < 0.05).

these are not sensitive SPQ indicators to rotation and cover crops (Alvarez et al., 2017; Calonego et al., 2017). At VIL, BD was lower, and TP was higher in the NG, which is expected as it is known that agricultural use causes soil compaction (Reynolds et al., 2002). Furthermore, BD values for the agricultural treatments in VIL were outside the range proposed by Reynolds et al. (2009), indicating poor quality. According to this author, [0.9–1.2] g.cm^{-3} is the optimal range for BD, while values greater than 1.25–1.30 g.cm^{-3} indicate compacted soils. For plots under agricultural use, BD values were higher at VIL (sandy loam) than at PER (silty loam), as was expected for coarser soils (Díaz-Zorita and Grosso, 2000). It is important to mention that real particle density was not measured. However, it has been reported that a value of 2.65 g.cm^{-3} is a suitable estimative for these soils (Cosentino and Pecorari, 2002; Villarreal, 2018).

At PER, S_{CC} had the highest SOC content, with values that doubled those of the other treatments. This can be the result of higher annual organic matter inputs in plots with cover crops, where plant biomass is not harvested (Blanco-Canqui et al., 2015; Jian et al., 2020). The wide difference between SOC at S_{CC} and the other treatments can be attributed to a higher stratification, as SOC was measured in the 0–5 cm layer where plant residues accumulate under NT (Franzluebbers, 2002). SOC content at S_{CC} was also higher than SOC at P. The P treatment consisted on 5 years pastures within an intensified cropping sequence (corn – wheat/soybean rotation). Thus, including cover crops can be more effective at increasing SOC than including occasional pastures within an intensified cropping sequence.

At VIL, rye cover crops increased SOC in plots under soybean (S_{CC} vs S_{BF}). On the other hand, in plots under corn-soybean rotation the presence of rye cover crops caused a decrease on SOC (R_{CC} vs R_{BF}). The R_{CC} treatment, which had a higher frequency of gramineous crops (and where the last crop in the summer rotation had been corn), showed also increased mesoporosity and mesopore connectivity. This could have enhanced soil aeration and SOC mineralization over SOC humification (Jensen et al., 1996a, 1996b; Zech et al., 1997). In plots under soybean, on the contrary, cover crops decreased mesoporosity, and a balanced rotation (including gramineous and leguminous crops every year) may have helped SOC build-up (Blanco-Canqui et al., 2015). Similarly, (Romaniuk et al., 2018) found that including a wheat cover crop increased SOC in a soybean crop, but caused no changes in a rotation already including gramineous crops. Several authors highlight that, though gramineous residues have a higher quality and tend to increase SOC, an adequate source of nitrogen is needed to enhance microbial activity, and residue to SOC transformation (Villamil et al., 2006; Duval et al., 2016; Beltran et al., 2018). These results also show that cover crops can have mixed effects on SOC, depending on soil type and crop rotation.

Both the presence of cover crops and the summer crop rotation caused changes on pore size distribution at VIL. Cover crops affected θme values, having different effects on the corn-soybean rotation (where θme increased) than in the soybean treatment (where θme decreased). Treatments with soybean as main crop (S_{BF} and S_{CC}) showed a higher proportion of θma and a lower proportion of θmi than the other treatments, which included more gramineous crops in the summer rotation. This indicates that, besides the presence of the cover crop, long term crop rotation caused a change on pore size distribution, towards lower proportion of θmi and greater θma and θme, in systems where the main crop was soybean as compared to rotations with gramineous crops. Calonego et al. (2017) found that, although gramineous crops were better at increasing aggregation, legume species with their taproot systems can increase θma. Temporal clogging of macropores by gramineous roots (which are more resistant to degradation) should also be considered (Bodner et al., 2008). This suggests the need of studying the temporal variation of pore size distribution within the crop cycle.

At VIL, summer crop rotations had higher RFC than soybean systems, regardless of the presence of cover crops. This is related to greater θmi values, which may be a consequence of corn fibrous roots, which enhance micro and mesoporosity (Basche et al., 2016; Calonego et al., 2017). However, when comparing to values proposed by Reynolds et al. (2009), RFC values indicate poor quality for the R_{BF} and R_{CC} treatments, indicating limited areation (Soracco et al., 2018). Values of RFC, on the other hand, fall within the optimal values for S_{BF} and S_{CC} (Reynolds et al., 2009). R_{CC} showed higher PAW than $S_{CC.}$ Plant growth is enhanced in soil with higher PAW contents, making a difference in yields especially in dry years (Dexter and Czyż, 2007). However, the presence of cover crops caused no changes on RFC nor PAW in the corn-soybean rotation and caused a decrease in PAW in S_{CC} when compared to S_{BF}. This disagrees with other authors that found winter cover crops increased RFC and PAW in Mollisols under NT both in the short term (4 years) (Villamil et al., 2006) and in a longer period of time (13 years) (Basche et al., 2016). AC values, on the other hand, were higher for the soybean treatments and the NG than for R_{CC} and R_{BF}. Values of AC in the corn-soybean rotations indicate limited aeration, as was observed for RFC values (Reynolds et al., 2009).

At VIL, S_{index} was higher for the S_{BF} than for all the other agricultural treatments. S_{index} was not affected by cover crops but was higher for R_{CC} than for S_{CC}. Greater S_{index} values can indicate improved SPQ (Dexter and Czyż, 2007). However, in this study S_{index} calculated for all treatments and at both sites correspond to very good SPQ according to Dexter and Czyż (2007). Values of AC and RFC, on the other hand, indicated poor aeration at VIL (Soracco et al., 2018). In view of this, the issue of whether different reference values for S_{index} may be more suitable remains open for discussion. Other authors observed inconsistencies between S_{index} and other SPQ indicators. Reynolds et al. (2009) observed S_{index} failed to assess SPQ in coarser soils, concluding that S_{index} should be accompanied with other SPQ indicators. Pulido-Moncada et al. (2015) observed that S_{index} threshold values proposed in the literature did not apply for all soils and conditions, especially in the case of soils with moderate SPQ and in process of degradation. Aparicio and Costa (2007) found that, for sandy clay loam, clay sandy loam and loam soils of the Argentinean Pampas, S_{index} ranged between 0.60 and 0.82, both for soils under continuous cropping and on a reference environment (more than 30 years under pastures). These values are one order of magnitude greater than the reference value of $S_{index} \geq 0.050$ for optimal SPQ suggested by Reynolds et al. (2009). In view of this, although Dexter and Czyż (2007) stated that S_{index} was valid over a wide range of soils, reference values should be assessed for each soil type (Pulido-Moncada et al., 2015).

Saturated hydraulic conductivity (K_0) was not affected by crop rotation nor cover crops, both at PER and VIL. This disagrees with most studies that report that K increases after winter cover cropping in the long term (Keisling et al., 1994; Alvarez et al., 2017; Chalise et al., 2019). Blanco-Canqui et al. (2011), however, found no significant effect of cover cropping on K_0 measured by the constant head method, after 15 years. These authors also found that a sunn hemp cover crop increased water infiltration rates and cumulative infiltration by three times relative to bare fallow, while a late maturing soybean cover crop caused no effect. Saturated hydraulic conductivity measures tend to have high variation coefficients, which can mask the effect of management practices (Blanco-Canqui et al., 2011). Similarly, in a long-term experiment, Irmak et al. (2018) found that K_0 values showed interannual variation for the same treatments, but there was no difference when comparing plots with and without cover crops, for the same year. In the present study, variation coefficients ranged between 45% and 87% for K_0 values. Values of K_3 and K_6 (where significant differences between treatments were observed at VIL) had lower variation coefficients (24–44% and 5–38%, respectively).

The inclusion of cover crops was effective increasing unsaturated K (K_3 and K_6), both in the soybean crop and in the corn-soybean rotation at VIL. This can be attributed to improved soil structure and a more functional pore system (Mukherjee and Lal, 2015), though aggregate stability and structure were not measured directly. Cover crops increased K_6 by 3 times in S_{CC} in relation to S_{BF}, and doubled K_6 in R_{CC} in relation to R_{BF}, increasing it up to the NG levels. Cover crops also increased K_3 in R_{CC} in relation to R_{BF} (almost to double). However, the S_{CC} treatment had significantly lower Cw_{me} than the S_{BF} treatment, which disagrees with Carof et al. (2007), who reported that increases on K caused by cover crops were due to increases in pore connectivity. K_3, K_6 and Cw_{me} were the only intensity SPQ parameters affected by the presence or absence of cover crops in a same summer crop sequence at VIL.

When comparing the effect of the summer crop rotation, R_{CC} had higher K_3 and K_6 than S_{CC}, reaching similar values to those of the NG, indicating that a more diversified cropping sequence with winter cover crops can improve K when compared to continuous soybean cropping (with or without cover crop). These differences did not correlate with differences in effective porosity values but could be explained as R_{CC} had higher Cw_{me}, which might be related to a higher frequency of gramineous crops (Bodner et al., 2008). This is the result of soil fauna activity and root activity and decay that create an inter-connected pore system with vertical continuity (Jirků et al., 2013; Bodner et al., 2014). Lower values of Cw_{me} in the NG than in R_{CC} can be explained as the presence of constant roots, that often follow existing pore networks, can cause the clogging of these pore spaces (Reynolds et al., 2002; Bodner et al., 2008).

At PER, the presence of cover crops (when comparing S_{BF} and S_{CC} treatments) had no effect on most SPQ indicators, except for Cw_{me}, where S_{CC} had lower Cw_{me} than S_{BF}. These plots had a history of 23 years of soybean monoculture. It is possible that this soil could not be improved by 8 years of cover crops, as it was highly degraded, and as Argiudolls have a low ability for pore regeneration (Sasal et al., 2006). Similar results were found by other authors in degraded soils. Irmak et al. (2018) found that 13 years of cover crops on a corn-soybean rotation had no effect on SPQ in silt loam soils that had been under the same summer crop rotation with winter bare fallow for decades. Other authors found that cover crops failed to alleviate compacted sandy loam soils after 1–4 years of cover crop implementation (Pulido-Moncada et al., 2020a, 2020b). However, these authors observed a tendency to the formation of continuous bio-pores in cover crops treatments. On the other hand, Villamil et al. (2006) found that cover crops were able to increase TP, θma, θme, PAW and RFC after 4 years on a soybean-corn rotation under NT in a silty loam Argiudoll. However, in this study no long-term continuous cropping nor previous SPQ deterioration were reported. Other studies also show improvements on some SPQ indicators in shorter periods of time, though these studies were performed on different soil types, and under different conditions (Carof et al., 2007; Calonego et al., 2017; Haruna et al., 2018; Nascente and Stone, 2018). In the same way, at PER there were no differences between the R and P treatments in most SPQ indicators (where R represents a 40 years corn - wheat/soybean rotation, and P the same rotation with the inclusion of pastures over two periods). Differences between these treatments could only be observed in ε_{ma}, where P showed significantly higher values. This supports the idea that SPQ recovery is a slow process in degraded Argiudolls (Sasal et al., 2006).

When comparing all treatments at PER, differences in ε_{ma}, Cw_{ma} and Cw_{me} arise. S_{CC} and P showed higher ε_{ma} values than R, and S_{BF} showed intermediate (not statistically different) values. Though statistically not different, S_{CC} showed higher (double fold) ε_{ma} than S_{BF} at PER. This suggests cover crops may also improve water conducting macroporosity as compared to soybean monoculture or a corn-wheat/soybean rotation. As compared to S_{BF} and R, both S_{CC} and P imply a longer period of crop cover and root activity in the year and a higher proportion of gramineous crops, that have a well-developed radical system. This may help build effective macroporosity and protect structure from physical degradation (Carof et al., 2007; Blanco-Canqui et al., 2015). Furthermore, these differences in ε_{ma} were measured at the end of the cover crop cycle, while wider differences may be found during the subsequent summer crop, when cover crop roots decay (Villarreal et al., 2020).

The P and R treatments showed a more interconnected pore system than plots under soybean (reflected in higher Cw_{ma} and Cw_{me}). Both P and R had a cropping history with a more diversified crop rotation. S_{BF} and S_{CC} treatments had been under soybean monoculture under NT for 20 and 12 years respectively. Field observation of morphological features of the epipedon exposed poor structural features (presence of platy structure and no visible biopores) in plots under soybean. These structural features showed differences between the S_{CC} and S_{BF} treatments. Platy structure was strong and clearly restricted roots downward development in the S_{BF} treatment. In the S_{CC} treatment, platy structure was weaker, with roots surpassing it. These observations agree with other authors that observed that a long crop cover in a year, could favor fragmentary soil structure, mainly due to the effect of active roots (Calonego et al., 2017; Sasal et al., 2017). However, these changes did not result in significant differences on pore connectivity indexes or hydraulic conductivity. According to Villarreal et al. (2020), greater differences between treatments in the pore system may be observed during the following summer crop (and not at the end of the winter period Thus, studying the temporal variation of these properties throughout the crop period may be necessary (Jirků et al., 2013). At PER, differences on ε_{ma}, Cw_{ma} and Cw_{me} did not correlate with differences on K values, indicating that porosity connectivity and effective porosity indexes may provide additional information to K values. The treatments that showed better structural features with higher water conducting porosity and a more interconnected pore system (S_{CC}, R and P), include gramineous crops that enhance soil aggregation and porosity. However, the R treatment (that consisted of a corn-wheat/soybean rotation) had lower ε_{ma} than S_{CC} and P. This treatment represents a more intensified crop sequence with higher machine traffic and nutrient extraction (when compared to S_{CC} or P) and a lower frequency of winter cover and gramineous crops per year. This may explain lower values of ε_{ma}.

In this study, the sandy loam Hapludoll (VIL) seemed to have a better response to management practices than the loam Argiudoll (PER). This was observed on an improvement in SPQ indicators in the summer crop rotation in relation to continuous soybean, and especially when a winter cover crop was included to the corn-soybean rotation. Taboada et al. (1998) reported that a silty clay loam Argiudoll was more susceptible to compaction under NT than a sandy loam Hapludoll. Furthermore, many authors reported compaction with platy structure formation in Argiudolls under NT (Sasal et al., 2017). These soils have a low probability of recovering topsoil porosity after several years under NT. Coarser soils, on the other hand, might be more sensitive to management practices, which can improve their SPQ and water storage conditions (Díaz-Zorita et al., 2004).

5. Conclusions

Cover crops increase near saturation hydraulic conductivity on a sandy loam typic Hapludoll but have mixed effects on the volume of different pore families and on porosity connectivity indexes. Cover crops do not modify most SPQ indicators and hydraulic properties on a silty loam typic Argiudoll that had a history of decades of soybean monoculture. Thus, SPQ improvement is greater on the coarser textured soil, and intensity SPQ indicators (K_3 and K_6) are more sensitive to the inclusion of cover crops.

SPQ indicators improve when a more balanced summer crop rotation (with the inclusion of corn or pastures) is used, with better results when cover crops are included in these systems. For this reason, we conclude that winter cover crops may be a valuable tool to improve SPQ, when they are used along with other conservation practices such as crop rotation and alternation with pastures. However, further studies on the effect of different summer crop rotations, different cover crop species and the effect of intensified traffic, as well as soil aggregate stability determination, may help to reach more conclusive results.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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