Received: 28 October 2021 | Accepted: 1 January 2022 | Published online: 17 March 2022

DOI: 10.1002/saj2.20373

Soil Science Society of America Journal

SPECIAL SECTION: MOLLISOLS DEGRADATION AND EVOLUTION UNDER DIFFERENT MANAGEMENT PRACTICES AND CLIMATE CHANGE

Cover crops effects on soil hydraulic properties in two contrasting Mollisols of the Argentinean Pampas region

Rafael Villarreal[1,2] | **Luis Alberto Lozano**[1,2] | **Nicolas Polich**[1] | **María Paz Salazar**[2] | **Miriam Barraco**[3] | **C. German Soracco**[1,2]

[1]Centro de Investigación de Suelos para la Sustentabilidad Agrícola y Forestal (CISSAF), Facultad de Ciencias Agrarias y Forestales, UNLP. Calles 60 y 119, CC 31. 1900, La Plata, Argentina

[2]Consejo Nacional de Investigaciones Científicas y Técnicas, La Plata, Argentina

[3]Instituto Nacional de Tecnología Agropecuaria, General Villegas, Argentina

Correspondence
Luis Alberto Lozano, Centro de Investigación de Suelos para la Sustentabilidad Agrícola y Forestal (CISSAF), Facultad de Ciencias Agrarias y Forestales, UNLP. Calles 60 y 119, CC 31. 1900, La Plata, Argentina.
Email: luislozanoarg@gmail.com

Assigned to Associate Editor Hailong He.

Abstract

Decreasing physical quality of Mollisols in the Argentinean Pampas region is observed due to simplified crop rotations. The main objective of this work was to evaluate the effects of cover cropping management on soil water capture, transport, and storage as compared with different crop rotations with bare fallow in two different and representative Mollisols of the Argentinean Pampas region (one Typic Argiudoll [TA] and one Typic Hapludoll [TH]). Water capture, transport, and storage processes were assessed through soil sorptivity, infiltration tests at different pressures heads, and soil water retention curve determination. In addition, aggregate stability and soil organic carbon (SOC) were determined and the relationship between studied variables and processes was evaluated. It was observed that soybean [*Glycine max* (L.) Merr.] monocultures jeopardize Mollisols conservation, decreasing water capture and transport and SOC content. The inclusion of cover cropping management increased the soil water transport in the TA and water capture in the TH, as compared with bare fallow rotations. In this sense, our results show that cover cropping could be a suitable management in order to recover degraded soils due to simplified crop rotations in Mollisols from the Argentina Pampas region.

1 | INTRODUCTION

In Argentina, Mollisols are extended over 8.9×10^7 ha and have a high natural chemical fertility, with the Pampas region being one of the most productive areas in the world (Aparicio et al., 2018). However, these soils have a great natural susceptibility to compaction due to the little or null aggregation by the shrinkage and swelling process, related to their high contents of silt and fine sand (Taboada et al., 2008). In the last years, several authors have mentioned a decrease of soil physical quality in the Pampas region related to simplified crop rotations, including soybean [*Glycine max* (L.) Merr.] monoculture, with long bare fallow periods during winter and low supply of harvest residues (C. R. Alvarez et al., 2009; Ferreras et al., 2000; Lozano et al., 2013; Sasal et al., 2006; Soracco et al., 2010, 2019)

In general, diversifying the crop sequences and increasing the time with living crops have shown positive effects in soil quality, increasing aggregate stability (Behrends Kraemer et al., 2021; Novelli et al., 2013) and organic carbon content (Duval et al., 2016). However, there are contrasting results about the effects of crop diversification on

Abbreviations: BD, bulk density; FC, field capacity; M, monoculture; MCC, monoculture with winter cover crops; MWD, mean weight diameter; NT, no tillage; PAWC, plant available water content; Rot, crop rotation with bare fallow; RotCC, crop rotation with winter cover crops; SOC, soil organic C; SWRC, soil water retention curve; TA, Typic Argiudoll; TH, Typic Hapludoll.

soil hydraulic properties. Shaver et al. (2013) reported an improvement in soil water capture, reflected in higher values of soil sorptivity in more diverse crop rotations as compared with monocultures, due to a higher residue accumulation. In a silty clay loam Typic Argiudoll from Pampas region, Imhoff et al. (2010) found that the crop sequences under no tillage (NT), including graminaceous species during fallow, showed better structural quality and more hydraulically active pores. On the other hand, Sasal et al. (2010) evaluated soybean and maize (*Zea mays* L.) monocultures in comparison with different crop rotations (wheat [*Triticum aestivum* L.]/soybean and wheat/soybean–maize) in a silty loam soil from Argentinean Pampas Region. These authors reported no differences between rotations regarding infiltration rates (K_0) and pore size distribution. Głab et al. (2013) reported that crop rotation has no effects on soil water retention.

In the last years, cover cropping management has received increased attention as a soil conservation practice for soil quality improvement. Integration of winter cover crops could enhance NT performance by improving structural stability, soil porosity, and related soil water dynamics (Blanco-Canqui, 2018; Sasal et al., 2017). Blanco-Canqui et al. (2011) found that the inclusion of cover crops enhances NT performance, increasing soil water infiltration. In a meta-analysis performed by R. Alvarez et al. (2017) in the Argentinean Pampas Region, in 82% of the studied cases, infiltration increased under cover crops rotations. In addition, cover crops also could enhance soil water retention and transport, increasing plant available water content (PAWC) and K_0 (Basche et al., 2016; Bertollo et al., 2021). On the other hand, different authors mentioned the lack of effects of cover cropping management on soil water infiltration and water retention (Sindelar et al., 2019) and soil sorptivity (Ruis et al., 2020).

The effects of management practices on soil hydraulic properties is highly dependent on the soil type (Jirku et al., 2013). Villarreal et al. (2020) reported that Argiudolls and Hapludolls with high silt or fine sand content, respectively, under NT showed lower K_0 and porosity than clayey Argiudolls. Behrends Kraemer et al. (2017) found that the crop sequence intensification (i.e., increasing the time with living crops) could lead to more favorable structural features and higher porosity in clayey Argiudolls rather than in sandy Haplustolls. In contrast, Crespo et al. (2021), reported that the improvement of soil physical properties derived from intensification practices are more affected by the degradation degree than by soil texture. Blanco-Canqui et al. (2015) pointed out that there is scarce literature regarding the effects of cover cropping on soil physical properties with contrasting soil types. On the other hand, this kind of study determines, in general, soil hydraulic properties describing water capture, transport, or storage separately. Few studies have investigated the relationship within these processes under different managements and reported contrasting results (Kreiselmeier et al., 2019; Tarawally et al., 2004; Villamil et al., 2006). Moreover, studies on cover crops or crop rotation investigated s either hydraulic properties or aggregation and organic matter. Steele et al. (2012) pointed out this problem and found that after 13 yr, winter cover cropping consistently improved aggregate stability, but with an asynchronous relationship with soil water infiltration. In this sense, it has been reported that a more holistic approach is needed, integrating different soil physical properties (Ogilvie et al., 2021). For these reasons, the determination of different soil hydraulic properties describing water capture, transport, and storage (i.e., soil sorptivity, soil hydraulic conductivity function [$K(h)$], and soil water retention curve [SWRC], respectively), together with aggregate stability and soil organic C (SOC), in different soil types and crop sequences could help us to better understand the soil water dynamics, which is a key factor in dryland agroecosystems. Additionally, this kind of study will improve the knowledge of soil conservation of Mollisols, especially in the Argentinean Pampas region. Our hypotheses are that (a) the inclusion of cover cropping management under NT improves the soil capacity to capture, transport, and store water, as compared with different crop sequences with bare fallow in Mollisols from the Pampas region; and (b) changes in water capture, transport, and storage due to the inclusion of cover cropping management are related to topsoil SOC content and aggregate stability, depending on the soil type. The objectives of this work were (a) to evaluate the soil capacity to capture, transport, and store water under different crop sequences, including winter cover cropping management, in two different and representative Mollisols of Argentinean Pampas region (one Typic Argiudoll [TA] and one Typic Hapludoll [TH]); and (b) to determine the relationships between water capture, transport, and storage and the relationship of these processes with SOC and aggregate stability in two different and representative Mollisols of the Argentinean Pampas region.

Core Ideas

- Effects of cover crops on soil hydraulic properties depended on the soil type.
- Soybean monocultures decreased water capture and transport.
- Cover crops increased water transport in the Typic Argiudoll.
- Cover crops increased water capture in the Typic Hapludoll.

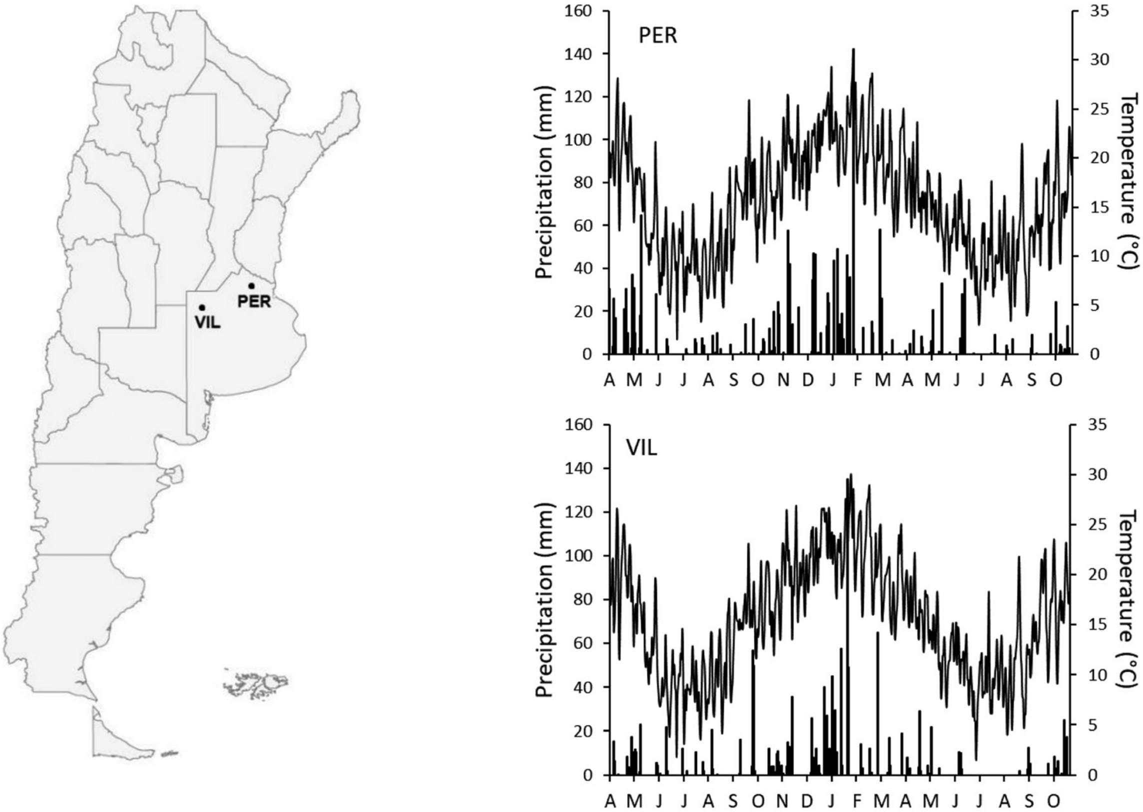

FIGURE 1 Location and climatic information (April 2018–October 2019) for the two studied sites (Pergamino [PER] and General Villegas [VIL])

2 | MATERIALS AND METHODS

2.1 | Experimental sites and treatments

The experiment was carried out at two different experimental stations with long-term field trials of the Instituto Nacional de Tecnología Agropecuaria (INTA), Argentina (Figure 1). Two different Mollisols, representative of the Argentinean Pampas region, were evaluated: a silty loam TA located near Pergamino City (33˚57′ S, 60˚33′ W); and a sandy loam TH, located near General Villegas City (34˚54′ S, 63˚44′ W). The horizon sequences and their depths in each soil type are as follows: for TA, A (0–0.25 m), BAt (0.25–0.34 m), Bt (0.34–0.95 m), BC (0.95–1.60 m), and Ck (1.60–2.00 m) horizons (Soil Survey Staff, 2014), Pergamino series (fine, illitic, thermic Typic Argiudoll; INTA-SAGyP, 1990); and for TH, A (0–0.30 m), Bw (0.30–0.70 m), BC (0.70–1.09 m) and Ck (1.09–1.30 m) horizons (Soil Survey Staff, 2014), Lincoln series (sandy, mixed, thermic Typic Hapludoll; INTA-SAGyP, 1990). The A horizon particle size distribution is 57.0% silt, 22.6% clay, and 20.4% sand for the TA and 22.4% silt, 14.3% clay, and 63.3% sand for the TH. At both sites, the climate is temperate humid without a dry season, with a mean annual temperature of 16.4 and 16.2 ˚C and a mean annual rainfall of 950 and 929 mm at Pergamino and General Villegas, respectively. Daily precipitation and air temperature are detailed in Figure 1.

For the TA, three crop sequences were evaluated: soybean monoculture (M) for the last 32 yr (since 1987); soybean monoculture with winter cover cropping (vetch [*Vicia villosa* L.] + barley [*Hordeum vulgare* L.]) (MCC) for the last 9 yr (before 2010, this treatment was under soybean monoculture for 23 yr); and maize–wheat/soybean (Rot) for the last 40 yr (since 1979). At the TH, four crop sequences were evaluated: soybean monoculture (M); soybean monoculture with winter cover cropping (rye [*Secale cereale* L.]) (MCC); maize–soybean (Rot); and maize–soybean with winter cover cropping (rye) (RotCC). All crop sequences in the TH had been under the same rotation for the last 15 yr. At both sites, cover crops seeding is carried out in April, whereas the termination (chemically dried with glyphosate) is carried out in September. Soybean seeding and harvest are carried out in November and April, respectively. Maize seeding and harvest are carried out in October and April, respectively. Wheat seeding and harvest (for the TA) are carried out in June and December, respectively. Soybean seeding and harvest in the Rot treatment for the TA are carried out in December and April, respectively.

The experiment at both sites consisted of a completely randomized design with 30-m × 10-m plots in the TA and 5-m × 20-m plots in the TH. Soil sampling was carried out at the end of October 2019 in both sites, after cover crop termination. Plots with the same relative position in the landscape from each crop sequence were selected. In each plot, a homogeneous and representative 5-m × 5-m area in the center was selected, avoiding visible wheel tracks. Within this area, sites were selected randomly in order to carry out soil sampling. Six undisturbed soil samples were collected (5-cm height, 5-cm diam., 98-cm^3 volume) from the first 5 cm (0–5 cm) in order to determine soil physical and hydraulic properties. Samples were air dried during 30 d at room temperature and stored at 4 ˚C until further processing.

Three undisturbed soil samples were taken from the topsoil (0–10 cm) in each treatment at both sites in order to determine aggregate stability. Six additional undisturbed soil samples were collected for bulk density (BD) determination. Disturbed soil samples were extracted from the direct surroundings of the intact cores in order to determine SOC content.

2.2 | Soil properties determination

2.2.1 | Aggregate stability, SOC content, and BD

For aggregate stability determination, Le Bissonnais methodology (Le Bissonnais, 1996) was used. Soil aggregates of ∼3- to ∼5-cm edge length were carefully detached from the undisturbed soil samples. Aggregates were dried at 40 ˚C for 24 h, and subsamples of ∼6 g were subjected to different stability tests: (a) fast wetting, MWD_{Fast} (where MWD stands for mean weight diameter); and (b) stirring in water after ethanol submersion, MWD_{Stirr}. These tests provide information about disaggregation mechanisms: (a) slaking (with the fast-wetting test), and (b) cohesion without slaking (stirring aggregates after ethanol submersion) (Behrends Kraemer et al., 2019). Aggregates were then sieved with a 0.05-mm-mesh sieve while immersed in ethanol with a shaker. The aggregates retained were dried at 40 ˚C for 48 h, and air sieved through a column of sieves to obtain the size distribution of dried aggregates. Results were expressed as mean weight diameter, according to Behrends Kraemer et al. (2019).

The SOC content, was measured by oxidation with chromic acid (Walkley & Black, 1934). For BD determination, the samples were dried at 105 ˚C until constant weight and the BD was determined according to Blake and Hartge (1986).

2.2.2 | Hydraulic conductivity and water-conducting porosity

A micro-infiltrometer (Soracco et al., 2019) was used in order to determine water infiltration under different water pressure heads in the air-dried undisturbed soil samples. The device consisted of a tube with a 1-cm-radius disc, with a membrane of the same material as the commercial tension disc infiltrometer (Perroux & White, 1988) attached to its base. This tube was connected to a water reservoir placed on an analytical balance (±0.001 g), connected to a computer. Each soil sample was placed on a scissor jack and brought into contact with the tension disc by raising the jack. Infiltration runs were performed at −0.6, −0.3, and 0 kPa water pressure head (h), applied in this order and in the same sample. Every determination at pressure head took approximately 5 min to reach the steady state and the mass of water that infiltrated the soil by capillarity was recorded as the mass variation in the analytical balance at every second. Cumulative infiltration was determined as the ratio between the infiltration volume and the disc area. The temperature during the experiments ranged between 20 and 24 ˚C. Hydraulic conductivity (K, cm h^{-1}) at the three pressure heads, namely, $K_{0.6}$, $K_{0.3}$, and K_0, was determined from the cumulative water infiltration using the multiple-head method (Ankeny et al., 1991) with the steady-state data.

Water-conducting macro- (ε_{ma}) and mesoporosities (ε_{me}) were determined, through the classical capillary rise equation, which approximates the maximum water-filled pore size, r [L], at a specific h [L]:

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

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}]. The equivalent pores with radii smaller than r derived from Equation 1 are full of water and are responsible for all the flux of water under a given water pressure head, and the equivalent pores with radii larger than the value calculated from Equation 1 are not contributing to the water flux. Then, according to Watson and Luxmoore (1986), the water-conducting porosity due to pores between two radii r_a and r_b ($r_a \le r_b$), θ (r_a,r_b), (assuming pore radius equals to the minimum pore radius), resulting in a difference in total soil water flux or hydraulic conductivity ΔK (r_a,r_b), is

$$\varepsilon(a, b) = \frac{8\eta\Delta K\left(r_a, r_b\right)}{\rho g\left(r_a\right)^2} \tag{2}$$

Because r_a is the minimum equivalent pore radius in the range, ε (r_a,r_b) is an estimation of the maximum water-conducting porosity, because pore radius (r_a) appears in the denominator of Equation 2. Steady-state conditions during infiltration are assumed. We defined ε_{ma} as those pores draining at $h > -0.3$ kPa (equivalent $r > 0.5$ mm) and ε_{me} as those draining at h from −0.3 and −0.6 kPa (0.5 mm > equivalent $r > 0.25$ mm).

2.2.3 | SWRC and pore size distribution

After the micro-infiltration test, SWRC determination was carried out. The soil cores were saturated with degassed water from the bottom for 48 h. Then, the samples were brought to different water pressure heads, h (0, −0.1, −0.3, −0.5, −0.7, −10, −30, and −500 kPa) using a sand box apparatus for h values between 0 and −10 kPa, and a pressure chamber for h values ≤−30 kPa. The retention curve code (RETC) (van Genuchten et al., 1991) was used to fit the van Genuchten (1980) model to the water retention data obtained for each soil sample. From the fitted data, PAWC and field capacity (FC) were determined as follows:

$$\text{PAWC} = \theta_{\text{FC}} - \theta_{\text{WP}} \tag{3}$$

$$\text{FC} = \theta_{\text{FC}} \tag{4}$$

where θ_{FC} [$L^3\ L^{-3}$] and θ_{WP} [$L^3\ L^{-3}$] are the volumetric water contents at h of −10 and −1,500 kPa, respectively (Lozano et al., 2016).

Additionally, transmission (diameter between 50 and 500 μm) and storage (diameter between 0.5 and 50 μm) pores were determined from the first derivative of the SWRC, using the fitted data and Equation 1 for pressure head transformation into equivalent pore size. These pore size reflect the main functions of those classes such as water movement (transmission pores) and retention (storage pores) (Kreiselmeier et al., 2019).

2.2.4 | Soil sorptivity

After the SWRC determination, the samples were air dried at room temperature for 30 d for soil sorptivity [$L\ T^{-1/2}$] determination, which reflects the soil's ability to rapidly capture water (Shaver et al., 2013). The used methodology corresponds to an improvement of the original Leeds-Harrison et al. (1994) method, proposed by Villarreal et al. (2017). The same device as the one for infiltration tests were used for sorptivity (S) determination. The tube with the membrane was changed for a small sponge (4-mm radius). Each soil sample was placed on a scissor jack and then put into contact with the sponge by raising the jack. Infiltrated water volume by capillarity was recorded as the mass variation in the balance at every second. Every determination took approximately 4 min. S was determined for each sample according to

$$S = \sqrt{\frac{Qf}{4br}} \tag{5}$$

where Q is the steady-state rate of flow from the circular pond of radius r, f is the difference between the final and initial volumetric soil water content, and b is a shape parameter taken as 0.55 (White & Sully, 1987). Volumetric water content difference was determined in each sample by removing very carefully the wet bulb at the end of each determination (the removed depth was approximate 2 cm, depending on the soil type) to determine the gravimetric water content (weighting before and after oven dried at 105 ˚C for 24 h), and later transformed in volumetric water content through the BD. The initial water content after air drying for all the samples was around 0.1 $m^3\ m^{-3}$, whereas the mean final water content was around 0.3 $m^3\ m^{-3}$. Villarreal et al. (2019) showed for similar soils that in this range of moisture, the influence of the initial water content on S determination can be neglected.

2.2.5 | Pore connectivity

Connectivity pore index (C_{w}) based on water flux (Lozano et al., 2013) was calculated for each pore size family with radii between r_{a} and r_{b} ($r_{\text{a}} > r_{\text{b}}$) as the ratio between $K(h_{\text{a}}) - K(h_{\text{b}})$ (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) and the pore volume fraction occupied by this family, according to

$$C_{\text{w},r_{\text{a}}-r_{\text{b}}} = \frac{K(h_{\text{b}}) - K(h_{\text{a}})}{\theta(h_{\text{b}}) - \theta(h_{\text{a}})} \tag{6}$$

The continuity of total porosity ($C_{\text{w}_{\text{TP}}}$) and large macropores (r > 0.5 mm, $C_{\text{w}_{\text{ma}}}$) and large mesopores was calculated according to Lozano et al. (2013). The volumes of large macroporosity and large mesoporosity were determined from the first derivative of the SWRC, using the fitted data and Equation 1 for pressure head transformation into equivalent pore size. This index allows comparison of different soils and managements in terms of connectivity of pore fractions (Lozano et al., 2013) and has been proven to be particularly useful as a soil physical quality indicator, because it integrates dynamic (hydraulic conductivity) and capacity (pore volume) information in a single value (Soracco et al., 2019).

2.3 | Statistical analysis

One-way ANOVA was carried out in order to determine if soil properties were influenced by crop sequences (three levels for the TA: M, MCC, and Rot; four levels for the TH: M, MCC, Rot, RotCC) as fixed effects. (Sokal & Rohlf, 1995). Each soil type was analyzed separately. Visual analysis in normal quantile–quantile (Q–Q) plots and Levene tests were performed to assess normality and homogeneity of variance, respectively. Because the statistical distribution of $K(h)$, ε_{ma}, and C_{w} data was skewed and non-normal, logarithmic values were used for the analysis. Fisher's LSD test (Sokal & Rohlf, 1995) was used to compare the means.

To investigate the relationships between the hydraulic properties describing the soil's capacity to capture, transport, and store water, Spearman's correlation coefficient was calculated between the studied variables. Correlation analyses were performed in each soil type separately. All analyses were carried out in STATISTICA software (Statsoft, 2004), using $p = .05$ for significance level.

To evaluate the effect of different crop sequences on soil quality, a Z score was determined, following Wulanningtyas et al. (2021) in each soil type separately. The Z score is how far and in what direction a determined item deviates from the mean of the distribution, expressed in units of standard deviation of the distribution (Rahman et al., 2009). The Z score allows us to determine the value of certain variables with a specific treatment factor and to compare it with the average value of certain variables in all treatments. Each Z score was calculated as follows:

$$Z_i = \frac{x_i - \bar{x}}{S} \quad (7)$$

where Z_i is the standardized value, x_i is the measured value of a certain variable with a specific treatment factor, $\bar{x}$ is the average value of a certain variable in all treatments, and S is the standard deviation of the variables in all treatments. Therefore, a score for each studied process (soil water capture, transmission, and storage) was calculated from the sum of a subtotal score for each variable that was measured [sorptivity for water capture; $K(h)$, water-conducting porosity, pore connectivity, and transmission porosity for water transmission; and PAWC, FC, and storage porosity for water storage] together with SOC and aggregate stability, based on the treatment factors (different crop sequences). In this way, the Z score allows us to make the results of the different studied processes more consistent and comparable.

3 | RESULTS AND DISCUSSION

3.1 | Soil water capture

Mean S values for the two studied Mollisols under different crop sequences are shown in Figure 2. Different effects were observed on S, depending on the soil type. In the TA, no differences between treatments were observed on S. In contrast, in the TH, MCC treatment showed higher values of S as compared with the other crop sequences, showing that the inclusion of cover cropping management in soybean monoculture improves the water capture in this soil type. Shaver et al. (2013) found a positive relationship between S and crop residues, mentioning that increasing cropping intensity increases S indirectly via improvements in soil physical properties that are conducive to water infiltration. On the other hand, Ruis et al. (2020), reported no effects of cover crop inclusion on S, as compared with bare fallow, in any of the studied soil types, including Hapludolls and Argiudolls. Furthermore, García-González et al. (2018) also reported no effects of cover crop inclusion on S, working in a Haplic Calcisol in a 10-yr experiment, disagreeing with our results. In the case of the TA, the lack of differences between treatments could be related to the presence of platy structure and its nonuniform distribution along the sample depth, leading to high spatial variation of the measured soil properties. This behavior is reflected in high values of CV in the TA; Villarreal et al. (2017) mentioned that the proposed methodology for S determination presents low CV values (around 15%) and higher precision as main advantages, because it is based on steady infiltration data. In the TA, CV values were around 50%, whereas in the TH, they were around 22%. It is important to remark that the results mentioned above from other authors were obtained from the transient flow data of field infiltration experiments. Villarreal et al. (2017) showed that the S values obtained from transient data could be overestimated because the gravity effect in the infiltration process cannot be neglected (Smettem et al., 1995; Vandervaere et al., 2000; Zhang, 1997) and the chosen time interval has strong influence (Bonell & Williams, 1986). For these reasons, comparison of the results obtained in our study and results obtained by previous work must be made with care.

Regarding the soil type, the TA showed higher values of S as compared with the TH. This lower ability to rapidly capture water by capillarity was reflected in volumetric water content differences during the S determination. Mean water content differences were 0.29 and 0.19 $m^3\ m^{-3}$ for the TA and the TH, respectively, showing that S is strongly dependent on the soil type (Stewart et al., 2013).

3.2 | Soil water transport

The values of the hydraulic properties describing the soil's ability to transport water are shown in Figure 3 (K_0, $K_{0.3}$, and $K_{0.6}$), Figure 4 (ε_{ma} and ε_{me}), and Table 1 ($C_{w_{TP}}$, $C_{w_{ma}}$, and transmission porosity [50–500 μm]). In both soil types, the same hydraulic properties were affected by the crop sequences ($p < .05$), but with different trends, showing that the effects of different crops sequences are complex because changes in soil pore configuration depend not only on the growing crop but on the soil type and climatic conditions (Jirku et al., 2013). In the TA, the inclusion of cover cropping management increased the soil water transport, because the treatment MCC showed higher values of K_0, $K_{0.6}$, ε_{ma}, $C_{w_{TP}}$, and transmission porosity as compared with Rot and M. This is in agreement with previous reports mentioning that cover cropping management increases soil K and infiltration (Haruna et al., 2018).

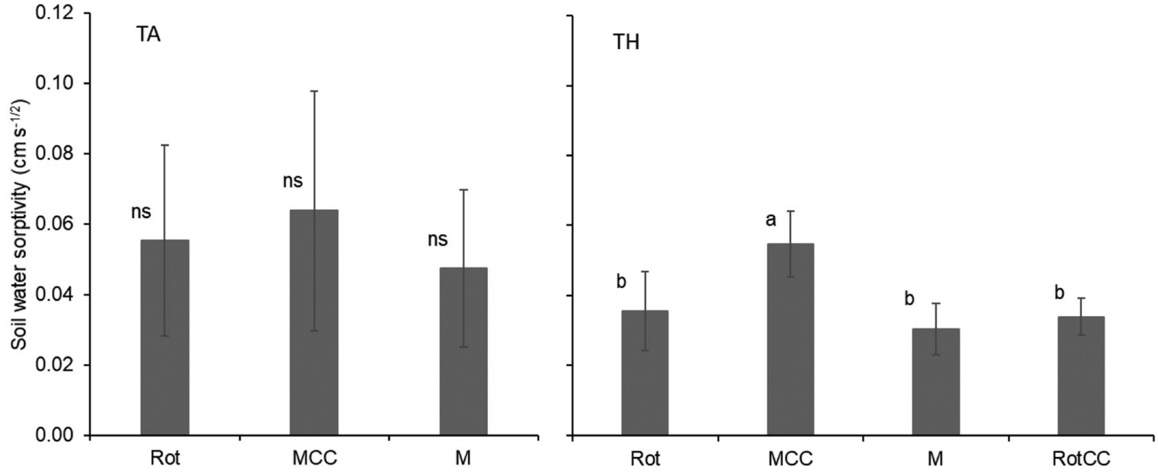

FIGURE 2 Mean values of S (soil water sorptivity) for different soils (Typic Argiudoll [TA] and Typic Hapludoll [TH]) and treatments (for the TA, soybean monoculture [M], soybean monoculture with winter cover cropping [vetch + barley] [MCC], and maize–wheat/soybean [Rot]; for the TH, soybean monoculture [M], soybean monoculture with winter cover cropping [rye] [MCC], maize–soybean [Rot], and maize–soybean with winter cover cropping [rye] [RotCC]). Different letters indicate significant differences among treatments (LSD test, $p < .05$). No significant differences among treatments are denoted by ns

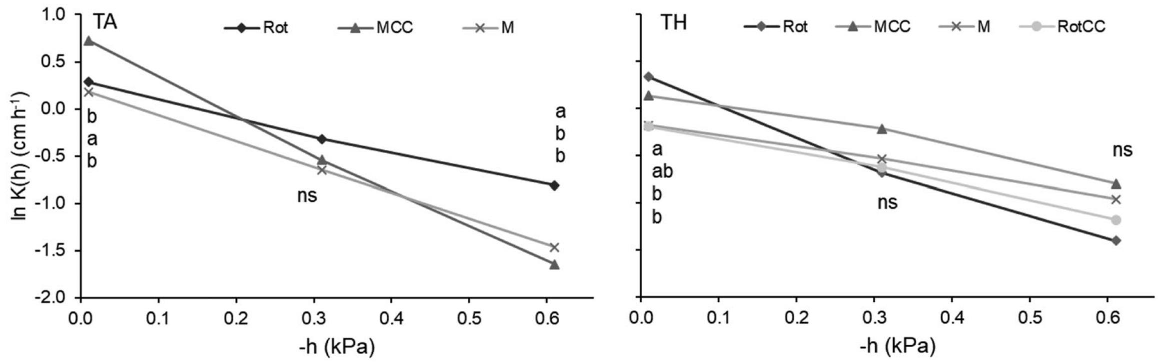

FIGURE 3 Mean K (hydraulic conductivity) values at different water pressure heads (h) for different soils (Typic Argiudoll [TA] and Typic Hapludoll [TH]) and treatments (for the TA, soybean monoculture [M], soybean monoculture with winter cover cropping [vetch + barley] [MCC], and maize–wheat/soybean [Rot]; for the TH, soybean monoculture [M], soybean monoculture with winter cover cropping [rye] [MCC], maize–soybean [Rot], and maize–soybean with winter cover cropping [rye] [RotCC]). Different letters indicate significant differences among treatments (LSD test, $p < .05$). The order of the letters, from top to bottom, is the same as the order of the legend from left to right. No significant differences ($p > .05$) among treatments are denoted by ns

Increasing K_0, ε_{ma}, and $C_{w_{TP}}$ could be attributed to root growth, creating stable and continuous biopores (Landl et al., 2019), which remain after the decomposition and contribute to the flow path of water (Yu et al., 2016). These results show that cover cropping could be a suitable management to counteract compaction processes in this soil type with high susceptibility to platy structure development. Sasal et al. (2017) mentioned that decreasing the frequency of platy structure could take up to 30 yr after the adoption of NT, and for this reason, living crops during the fallow period should be implemented.

On the other hand, in the TH, the Rot treatment showed higher values of K_0, ε_{ma}, $C_{w_{TP}}$, and $C_{w_{ma}}$, but not significantly different from the MCC treatment, whereas M and RotCC showed the lowest values of these variables. Moreover, in the TH, the Rot and RotCC treatments showed lower values of transmission porosity as compared with the M and MCC. Our findings suggest that the alternation of soybean with maize in the crop sequence could be enough to improve soil water movement in coarser soils. Imhoff et al. (2010) reported that the greater proportion of graminaceous species in the crop rotation has a positive effect on pore network by generating continuous pore, enhancing soil water infiltration. Bronick and Lal (2005) mentioned that the maize inclusion in the crop sequence improves soil structure due to

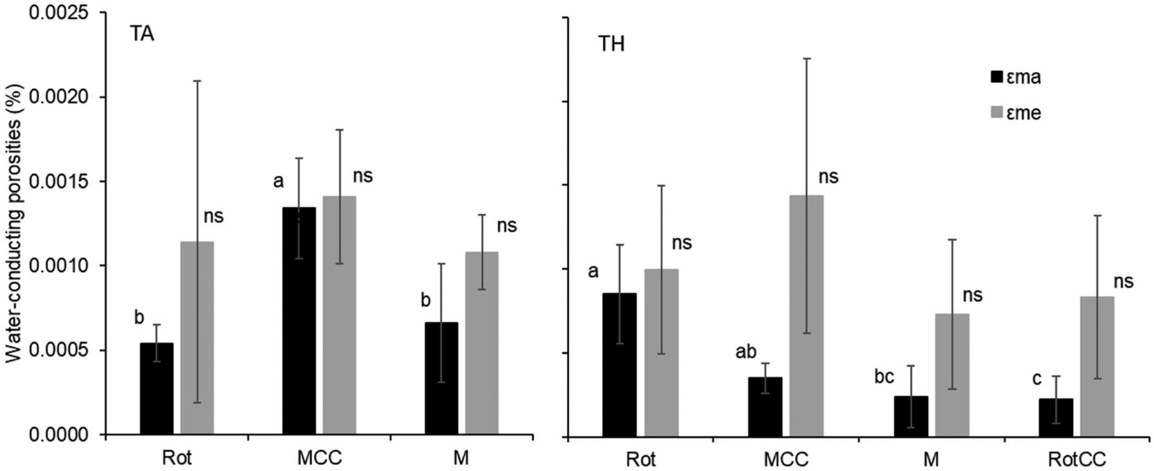

FIGURE 4 Mean values of ε_{ma} (water-conducting macroporosity) and ε_{me} (water-conducting mesoporosity) for different soils (Typic Argiudoll [TA] and Typic Hapludoll [TH]) and treatments (for the TA, soybean monoculture [M], soybean monoculture with winter cover cropping [vetch + barley] [MCC], and maize–wheat/soybean [Rot]; for the TH, soybean monoculture [M], soybean monoculture with winter cover cropping [rye] [MCC], maize–soybean [Rot], and maize–soybean with winter cover cropping [rye] [RotCC]). Different letters indicate significant differences among treatments (LSD test, $p < .05$). No significant differences among treatments are denoted by ns

TABLE 1 Mean values of natural log-transformed$C_{w_{TP}}$ (total porosity connectivity), $C_{w_{ma}}$ (macroporosity connectivity), and transmission pores (diameter between 50 and 500 μm) for different soils (Typic Argiudoll [TA] and Typic Hapludoll [TH]) and treatments ()

Site	Treatment[a]	$\ln(C_{w_{TP}})$	$\ln(C_{w_{ma}})$	Transmission pores
		cm h^{-1}		m^3 m^{-3}
TA	Rot	0.93 ± 0.26 b	4.70 ± 0.58 a	0.08 ± 0.03 b
	MCC	1.34 ± 0.21 a	4.03 ± 0.40 a	0.13 ± 0.02 a
	M	0.82 ± 0.37 b	3.93 ± 0.87 a	0.10 ± 0.01 ab
TH	Rot	1.03 ± 0.36 a	6.45 ± 0.45 a	0.04 ± 0.01 b
	MCC	0.84 ± 0.35 ab	4.55 ± 0.83 b	0.07 ± 0.01 a
	M	0.50 ± 0.30 b	4.55 ± 0.84 b	0.07 ± 0.01 a
	RotCC	0.47 ± 0.25 b	4.32 ± 1.57 b	0.05 ± 0.01 b

Note. Different letters indicate significant differences among treatments (LSD test, $P < .05$). ± denotes standard deviation.
[a]For the TA, soybean monoculture (M), soybean monoculture with winter cover cropping (vetch + barley) (MCC), and maize–wheat/soybean (Rot); for the TH, soybean monoculture (M), soybean monoculture with winter cover cropping (rye) (MCC), maize–soybean (Rot), and maize–soybean with winter cover cropping (rye) (RotCC).

the presence in their residues of important amounts of phenols, a high carbon/nitrogen ratio, and high organic carbon and carbohydrates. However, our results are in disagreement with previous results in similar soils under soybean–maize sequence with and without cover cropping management. Villamil et al. (2006) and Liesch et al. (2011), working in an Aquic Argiudoll and a Calcic Hapludoll, respectively, found that the inclusion of rye as winter cover crop in a maize–soybean rotation improved K_0, and general physical quality, as compared with the rotation with bare fallows. Additionally, Chalise et al. (2019) reported in two Hapludolls higher infiltration rates under cover cropping management as compared with bare fallow in a maize–soybean rotation, mentioning that this improvement was related to a better soil structure with more and continuous macro- and micropores, root channels, and less compaction. Another possible explanation for these discrepancies is the pore clogging caused by cover crop roots. Soil sampling was carried out immediately after the cover crop termination; Bodner et al. (2014) mentioned temporal pore clogging due to roots growing into preexisting pores, limiting water transport. However, this behavior was not observed in the TA, showing that pore clogging phenomena could depend on the soil type. At both soil types, no effects of crop sequence on ε_{me} were observed, showing that soil management mainly changes the macropores fraction (Imhoff et al., 2010).

3.3 | Soil water storage

Mean values of FC, PAWC, and storage porosity for different crop sequences and soil types are shown in Table 2. The val-

TABLE 2 Mean values of FC (field capacity), PAWC (plant available water content), θ_{WP} (volumetric water content at −1,500 kPa), and storage pores (diameter between 0.5 and 50 μm) for different soils

Site	Treatment[a]	FC	PAWC	Storage pores	θ_{WP}
		$m^3\ m^{-3}$			
TA	Rot	0.40 ± 0.03 a	0.24 ± 0.03 a	0.31 ± 0.01 a	0.17 ± 0.003 c
	MCC	0.39 ± 0.02 a	0.16 ± 0.02 c	0.24 ± 0.01 c	0.23 ± 0.002 a
	M	0.39 ± 0.01 a	0.20 ± 0.01 b	0.28 ± 0.01 b	0.19 ± 0.004 b
TH	Rot	0.42 ± 0.01 a	0.30 ± 0.02 a	0.34 ± 0.01 c	0.12 ± 0.003 b
	MCC	0.38 ± 0.02 b	0.27 ± 0.02 b	0.34 ± 0.01 c	0.11 ± 0.002 b
	M	0.39 ± 0.01 b	0.31 ± 0.02 a	0.39 ± 0.01 a	0.07 ± 0.002 c
	RotCC	0.43 ± 0.01 a	0.32 ± 0.02 a	0.36 ± 0.01 b	0.11 ± 0.003 b

Note. TA, Typic Argiudoll; TH, Typic Hapludoll. Different letters indicate significant differences among treatments (LSD test, $P < .05$). ± denotes standard deviation.
[a]For the TA, soybean monoculture (M), soybean monoculture with winter cover cropping (vetch + barley) (MCC), and maize–wheat/soybean (Rot); for the TH, soybean monoculture (M), soybean monoculture with winter cover cropping (rye) (MCC), maize–soybean (Rot), and maize–soybean with winter cover cropping (rye) (RotCC).

ues of these variables were similar to the reported by other authors in the same region (Villarreal et al., 2020). In the TA, and PAWC and storage porosity were affected by the crop sequence ($p < .05$). The MCC treatment showed the lowest values of these variables, as compared with the M and Rot treatments. No effects of the crop sequence were observed on FC. These results are in disagreement with previous reports mentioning that crop sequences including winter cover crops increased the volume of water held at FC compared with bare fallow crop sequences (Villamil et al., 2006). In the TH, the values of FC were higher in Rot and RotCC treatments. The M and MCC treatments showed the lowest values of FC. Higher values of PAWC were observed under M and RotCC, whereas MCC treatment showed the lowest PAWC. Storage porosity was higher under M treatment, followed by RotCC, whereas Rot and MCC showed the lowest values of this variable. This is partially in agreement with Basche and DeLonge (2017), who showed in a meta-analysis study that continuous living cover significantly improved the water retained at FC, as compared with annual cropping systems. The MCC treatments showed in both studied Mollisols the lowest values of PAWC as compared with the other crop sequences. In the case of the TA, the decrease was due to higher values of θ_{WP}, whereas in the TH, it was due to reducing values of FC. Similar behavior was observed for storage porosities. R. Alvarez et al. (2017), in a meta-analysis of cover crops effects on soil properties in the Argentinean Pampas Region, reported that the cover crops produced a significant decrease in available water storage, being in agreement with our results. However, these authors mentioned that this reduction would not restrict water supply because of the large amount of rainfall in the region. Additionally, both FC and PAWC values were in the optimal ranges proposed by Reynolds et al. (2008). In this sense, our results show that the different crops involved in the rotation can affect the soil water retention differently, attributed to different root systems inducing different pores' networks of distinct characteristics and stability (Imhoff et al., 2010).

3.4 | SOC, aggregate stability, and BD

Mean values of SOC content, aggregate stability, and BD for each management treatment for both soils are shown in Table 3. Regarding the SOC values, two different trends were observed between the soil types. In the TA, the MCC treatment showed a strong SOC increment as compared with the other crop sequences. No differences between M and Rot treatments were observed. In the TH, Rot treatment showed the higher SOC values, followed by MCC, whereas M and RotCC treatments showed the lowest values of SOC. These results show that cover cropping management increases SOC content as compared with monocultures. This is in agreement with Duval et al. (2016), who reported an increment in SOC content after 4 yr of cover cropping management in a soybean monoculture, related to the amount of carbon supplied by the cover crops (oat and oat + vetch). In the TA, the SOC increment under MCC treatment was unexpectedly twofold higher than in the other crop sequences. This could be attributed not only to the input of fresh plant residues in the soil where plant biomass of the cover crops is not harvested, but also to the slow buildup of SOC (Six et al., 2004). Additionally, the presence of platy structure could help to the SOC increment. Strong fine laminar structure with abundant horizontal roots from 3 to 8 cm was observed in the M treatment. The presence of platy structure is widespread in these soils with high silt content under NT but also depends on the cropping system (Sasal et al., 2017). Before the cover cropping inclusion, MCC treatment was under soybean monoculture during 23 yr; this management led to the formation of platy structure and could produce an accumulation of root biomass of the cover crop in the topsoil, due to the impedance for root penetration, resulting in a high SOC stratification in the 0-to-5-cm depth. On the other hand, our results are in disagreement with Romaniuk et al. (2018). These authors reported in a TA in an 8-yr field experiment, no significant increments of SOC in the topsoil (0–5 cm) under cover cropping

TABLE 3 Mean values of SOC (soil organic carbon content), MWD_{Fast} (mean weight diameter for fast wetting), MWD_{Stirr} (mean weight diameter for stirring in water after ethanol submersion), and BD (bulk density) for different soils

Site	Treatment[a]	SOC	MWD_{Fast}	MWD_{Stirr}	BD
		%	mm		Mg m^{-3}
TA	Rot	1.73 ± 0.03 b	0.55 ± 0.14 a	2.39 ± 0.18 a	1.20 ± 0.02 a
	MCC	3.36 ± 0.36 a	0.63 ± 0.11 a	2.57 ± 0.21 a	1.17 ± 0.02 a
	M	1.68 ± 0.03 b	0.30 ± 0.05 b	1.75 ± 0.16 b	1.21 ± 0.01 a
TH	Rot	1.46 ± 0.20 a	0.44 ± 0.10 a	1.59 ± 0.12 a	1.36 ±0.02 a
	MCC	1.24 ± 0.01 b	0.66 ± 0.14 a	0.97 ± 0.12 a	1.35 ± 0.01 a
	M	1.00 ± 0.02 c	0.59 ± 0.20 a	1.50 ± 0.54 a	1.33 ± 0.03 a
	RotCC	0.96 ± 0.11 c	0.77 ± 0.22 a	1.44 ± 0.41 a	1.31 ± 0.03 a

Note. TA, Typic Argiudoll; TH, Typic Hapludoll. Different letters indicate significant differences among treatments (LSD test, $P < .05$). ± denotes standard deviation.
[a]For the TA, soybean monoculture (M), soybean monoculture with winter cover cropping (vetch + barley) (MCC), and maize–wheat/soybean (Rot); for the TH, soybean monoculture (M), soybean monoculture with winter cover cropping (rye) (MCC), maize–soybean (Rot), and maize–soybean with winter cover cropping (rye) (RotCC).

management in a soybean monoculture, as compared with soybean monoculture with bare fallow and no other crop sequences, including maize–soybean–wheat/soybean with and without cover crops. For the TH, the inclusion of cover cropping management under soybean monoculture had a positive effect on SOC, as was observed for the TA. The unexpected lower values of SOC under RotCC treatment in the TH could be related to the *priming* effect under the RotCC rotation. Poeplau and Don (2015) mentioned that the addition of rapidly decomposable plant material (low C/N ratio) leads to microbial community growth, producing the breakup of more stable compounds of old SOC as compared with the no-cover-crop treatments.

Aggregate stability was only affected by the crop sequences in the TA. The M treatment showed the lowest aggregate stability (both MWD_{Fast} and MWD_{Stirr}), whereas under MCC, these two variables increased with similar values as compared with the Rot treatment, showing the susceptibility to disaggregation of soil under soybean monoculture in this type of Mollisol. In this sense, higher values of MWD_{Fast} observed in MCC treatment are in agreement with previous reports from the same studied region, mentioning that the addition of fresh residues on Mollisols decrease slaking and microcraking (Cosentino et al., 2006). Behrends Kraemer et al. (2021) showed that the presence of living roots in Mollisols from the Pampas Region decreases the sudden rupture of aggregates, increasing aggregate stability. On the other hand, in TH, the lack of differences between crop sequences showed the fragility of this soils to the aggregate disruption by fast wetting, probably related to the low clay content, which is one of the main variables for soil aggregation in Mollisols. These results are in agreement with Behrends Kraemer et al. (2019) who found no differences in MWD_{Fast} between good and poor agricultural practices under NT in an Entic Haplustoll, while in a TA the differences were more evident. Both soil types increased soil aggregate stability for the stirring test, showing that cohesion is one of the main stabilization mechanisms of soil structure in the Pampas region (Novelli et al., 2013). The TA showed higher values of MWD_{Stirr} as compared to the TH, probably related to the higher clay content (Behrends Kraemer et al., 2021). This test reflects the aggregates' cohesion, which is related to intrinsic soil characteristics (Kay & Angers, 2000).

Regarding the BD, no significant differences between treatments were observed in none of the studied soil types ($p > .05$). Several authors mentioned that BD is not a sensitive soil physical quality indicator in order to evaluate the effects of rotation and cover crops (R. Alvarez et al., 2017; Calonego et al., 2017). This is related to the fact that management practices could improve soil aggregation, changing the pore size distribution and configuration rather than the total porosity and BD (Soracco et al., 2015).

3.5 | Correlation analysis between soil water capture, transport, and storage and Z-score analysis

Through the correlation analysis, it was possible to elucidate the relationship between the water capture, transport and storage processes affected by different crops sequences. Spearman's correlation coefficients between the studied soil properties for each soil type are shown in Figure 5.

Different behaviors in the relationship between the hydraulic properties describing the water capture, transport and storage were observed, depending on the soil type. In the TA, a negative relationship was observed between storage and water transport. PAWC and storage porosity showed a negative correlation with K_0, ε_{ma}, C_{WTP}, and transmission porosity. Additionally, in this soil, FC was negatively correlated to the transmission porosity. For the TH, PAWC and FC were only negatively correlated with transmission porosity. This is in agreement with Kreiselmeier et al. (2019) who analyzed the evolution of soil structural porosity, and found that soils under

TA

	K0	K0.3	K0.6	εma	εme	Cw_{TP}	Cw_{ma}	Tr Pores	PAWC	FC	St Pores	S	BD	SOC	MWD Fast	MWD Stirr
K0	1															
K0.3		1														
K0.6		0.81	1													
εma	0.90			1												
εme	0.58	0.61			1											
Cw_{TP}	1.00			0.90	0.58	1										
Cw_{ma}							1									
Tr Pores	0.48			0.53			-0.71	1								
PAWC	-0.58			-0.69		-0.56	0.56	-0.95	1							
FC							0.75	-0.90	0.79	1						
St Pores	-0.69		0.47	-0.80		-0.67		-0.85	0.95	0.59	1					
S	0.55					0.55						1				
BD													1			
SOC	0.66			0.70		0.64		0.62	-0.70				-0.50	1		
MWD Fast	0.55			0.47		0.54								0.72	1	
MWD Stirr	0.53					0.52									0.69	1

TH

	K0	K0.3	K0.6	εma	εme	Cw_{TP}	Cw_{ma}	Tr Pores	PAWC	FC	St Pores	S	BD	SOC	MWD Fast	MWD Stirr
K0	1															
K0.3	0.49	1														
K0.6		0.78	1													
εma	0.47		-0.41	1												
εme	0.48	0.59			1											
Cw_{TP}	1.00	0.48		0.48	0.48	1										
Cw_{ma}	0.54		-0.46	0.88		0.54	1									
Tr Pores							-0.50	1								
PAWC								-0.68	1							
FC								-0.96	0.08	1						
St Pores									0.60		1					
S		0.43							-0.41			1				
BD													1			
SOC	0.60			0.66		0.62	0.60				-0.67			1		
MWD Fast	-0.45			-0.59		-0.46	-0.61	-0.54						-0.80	1	
MWD Stirr		-0.42							0.60	0.54		-0.72			-0.43	1

FIGURE 5 Correlation matrix (expressed in Spearman's rank correlation coefficient) for natural log-transformed K_0, $K_{0.3}$, and $K_{0.6}$ (hydraulic conductivity at 0, −0.3 and −0.6 kPa water pressure head, respectively), natural log-transformed ε_{ma} (water-conducting macroporosity), ε_{me} (water-conducting mesoporosity), natural log-transformed $C_{w_{TP}}$ (total porosity connectivity), $C_{w_{ma}}$ (macroporosity connectivity), Tr pores (transmission pores, diameter between 50 and 500 μm), PAWC (plant available water content), FC (field capacity), St pores (storage pores, diameter between 0.5 and 50 μm), S (soil water sorptivity), BD (bulk density), SOC (soil organic carbon content), MWD_{Fast} (mean weight diameter for fast wetting), and MWD_{Stir} (mean weight diameter for stirring in water after ethanol submersion) for different studied soils (Typic Argiudoll [TA] and Typic Hapludoll [TH]). Only correlations with $p < .05$ are shown

NT showed lower transmission pores but higher storage pores, as compared with different tillage. Tarawally et al. (2004) found that when soil compaction occurs, the storage pores increases at the detriment of the water transmission porosities. In contrast, Imhoff et al. (2010) mentioned that soils with better structural quality in NT systems due to a greater proportion of graminaceous in the rotation, present higher hydraulic active big pores, with similar water storage pore in comparison with simplified crop rotations. On the other hand, our results are in disagreement with Villamil et al. (2006),

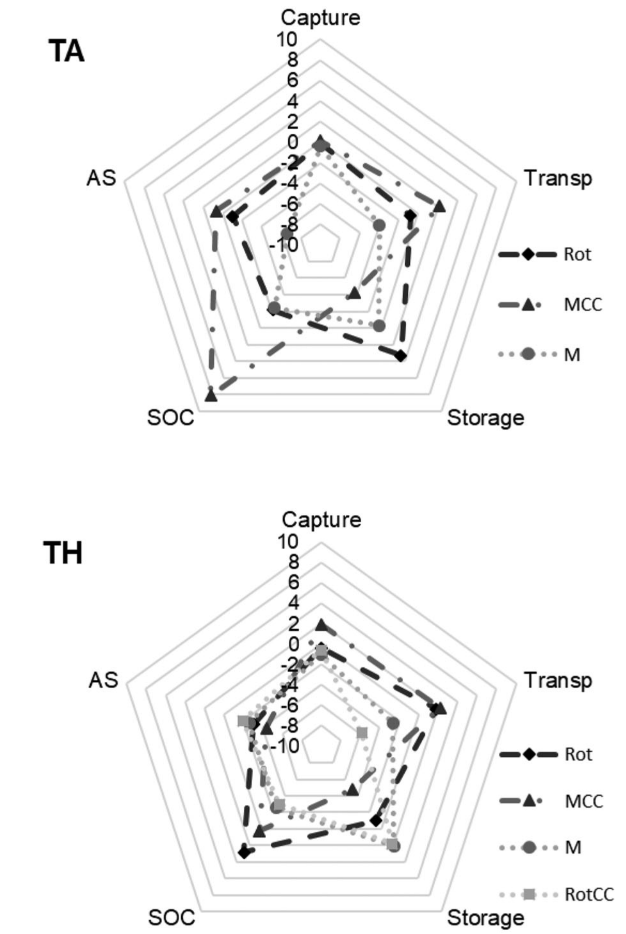

FIGURE 6 *Z* score representation of the soil water capture, transport (transp), and storage; SOC (soil organic carbon) content; and aggregate stability (AS) for different soils (Typic Argiudoll [TA] and Typic Hapludoll [TH]) and treatments (for the TA, soybean monoculture [M], soybean monoculture with winter cover cropping [vetch + barley] [MCC], and maize–wheat/soybean [Rot]; for the TH, soybean monoculture [M], soybean monoculture with winter cover cropping [rye] [MCC], maize–soybean [Rot], and maize–soybean with winter cover cropping [rye] [RotCC])

who reported that the use of winter cover crops increases the percentages of transmission pores and aeration and also is effective in increasing storage porosity.

In the case of soil's ability to rapidly capture water, in both soil types a positive relationship between S and transmission properties was observed. In the TA, S was related to K_0, and $C_{w_{TP}}$ Cw_{TP}, while in the TH, S was only related to $K_{0.3}$. Additionally, water capture was negatively correlated to the storage only in the TH, where a negative relationship between S and PAWC was observed. These results indicate that the water capture process is related to specific pore fractions. This is partially in agreement with Shaver et al. (2013) who found increasing S values with increasing total porosity and macroaggregation. These authors mentioned that increasing crop residue accumulation produces higher water capture via improvement in soil physical properties that are conducive to higher water infiltration. In addition, S is a measure of the soil wettability. It has been stated that organic coatings on soil particles increases soil water repellency (Tillman et al., 1989). In this sense, it is expected that SOC affects soil S. However, from our results, no correlation between S and SOC was observed. Similar results were found by Behrends Kraemer et al. (2019), who reported no significant correlation between S and SOC or aggregate stability.

Finally, through the *Z* score analysis, it was possible to determine that the inclusion of cover cropping management in soybean monocultures in both studied Mollisols improves the soil capacity to capture and transport water, but decreases the storage capacity, as compared with different crop rotations, partially supporting our hypothesis (Figure 6). The MCC treatments in both soil types showed positive *Z* score values for all studied characteristics, except for water storage in the TA and water storage and aggregate stability in the TH. In contrast, M treatments in both soil types presented lower and negative values of *Z* score for the studied characteristics, showing clearly that soybean monoculture jeopardizes Mollisols conservation. This is in agreement with several studies from the Argentinean Pampas region mentioning that soil physical conditions are negatively affected in soybean monocultures systems (Novelli et al., 2017; Sasal et al., 2010, 2017), which contributes to soil degradation (Wilson et al., 2020).

Agricultural management must adapt in response to climate change, which is causing more droughts, less water availability, and more extreme climatic events (IPCC, 2013). Our study evaluates robustly three key process in soil water dynamics (i.e., water capture, transport, and storage), because their determination was carried out in the same soil sample using different approaches, providing reliable information. In this sense, our results show that soil cover cropping inclusion during fallow periods in soybean monocultures could be a suitable management in order to recover degraded soil due to over simplified crop rotations in Mollisols, improving their ability to capture and transport water.

4 | CONCLUSIONS

The effects of cover crops inclusion on soil hydraulic properties in Mollisols from the Pampas region will be different, depending on the soil type. Cover cropping management in soybean monocultures, as compared with crop rotations, increases the soil water capture only in TH and improves the soil capacity of transport water in the TA. Additionally, soybean monocultures reduce the soil's ability to capture, transport, and store water in Mollisols from the Pampas region, threating their conservation. Changes in soil water transport are directly related to aggregate stability and SOC content only in the TA. Increasing transport capacity in Mollisols from Pampas region reduces soil water storage. The inclusion of cover cropping management during the fallow period in soybean monocultures could be an appropriate agricultural management in order to improve water capture and transport in Mollisols of the Argentinean Pampas region, especially in typic Argiudolls.

ACKNOWLEDGMENTS

This research was founded by grants PICT-2017-0202 of Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT), PIP 0345 of Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), and PI+D 11A315 of Universidad Nacional de la Plata (UNLP). The authors acknowledge with thanks the staff of Instituto Nacional de Tecnología Agropecuaria (INTA), Estación Experimental Agropecuaria (EEA) Pergamino, and EEA Villegas, for the use of the experiment facility.

AUTHOR CONTRIBUTIONS

Rafael Villarreal: Conceptualization; Data curation; Formal analysis; Methodology; Writing – original draft. Luis Alberto Lozano: Investigation; Methodology; Supervision; Writing – review & editing. Nicolas Polich: Methodology; Visualization. María Paz Salazar: Methodology; Visualization. Miriam Barraco: Methodology. C. German Soracco: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Luis Alberto Lozano https://orcid.org/0000-0002-7892-0320

REFERENCES

Alvarez, C. R., Taboada, M. A., Gutierrez Boem, F. H., Bono, A., Fernández, P. L., & Prystupa, P. (2009). Topsoil properties as affected by tillage systems in the rolling Pampa Region of Argentina. *Soil Science Society of America Journal*, *73*, 1242–1250. https://doi.org/10.2136/sssaj2008.0246

Alvarez, R., Steinbach, H. S., & De Paepe, J. L. (2017). Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. *Soil and Tillage Research*, *170*, 53–65. https://doi.org/10.1016/j.still.2017.03.005

Ankeny, M. D., Ahmed, M., Kaspar, T. C., & Horton, R. (1991). Simple field method for determining unsaturated hydraulic conductivity. *Soil Science Society of America Journal*, *55*(2), 467–470.

Aparicio, V., Zamora, M., Barbera, A., Castro-Franco, M., Domenech, M., de Gerónimo, E., & Costa, J. L. (2018). Industrial agriculture and agroecological transition systems: A comparative analysis of productivity results, organic matter and glyphosate in soil. *Agricultural Systems*, *167*, 103–112. https://doi.org/10.1016/J.AGSY.2018.09.005

Basche, A., & DeLonge, M. (2017). The impact of continuous living cover on soil hydrologic properties: A meta-analysis. *Soil Science Society of America Journal*, *81*(5), 1179–1190. https://doi.org/10.2136/sssaj2017.03.0077

Basche, A. D., Kaspar, T. C., Archontoulis, S. V., Jaynes, D. B., Sauer, T. J., Parki, T. B., & Miguez, F. E. (2016). Soil water improvements with the long-term use of a winter rye cover crop. *Agricultural Water Management*, *172*, 40–50. https://doi.org/10.1016/j.agwat.2016.04.006

Behrends Kraemer, F., Hallett, P. D., Morrás, H., Garibaldi, L., Cosentino, D., Duval, M., & Galantini, J. (2019). Soil stabilisation by water repellency under no-till management for soils with contrasting mineralogy and carbon quality. *Geoderma*, *355*, 113902. https://doi.org/10.1016/j.geoderma.2019.113902

Behrends Kraemer, F., Morrás, H., Fernández, P. L., Duval, M., Galantini, J., & Garibaldi, L. (2021). Influence of edaphic and management factors on soils aggregates stability under no-tillage in Mollisols and Vertisols of the Pampa Region, Argentina. *Soil and Tillage Research*, *209*, 104901. https://doi.org/10.1016/j.still.2020.104901

Behrends Kraemer, F., Soria, M. A., Castiglioni, M. G., Duval, M., Galantini, J., & Morrás, H. (2017). Morpho-structural evaluation of various soils subjected to different use intensity under no-tillage. *Soil and Tillage Research*, *169*, 124–137. https://doi.org/10.1016/j.still.2017.01.013

Bertollo, A. M., de Moraes, M. T., Franchini, J. C., Soltangheisi, A., Junior, A. A. B., Levien, R., & Debiasi, H. (2021). Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil. *Soil and Tillage Research*, *206*, 104820. https://doi.org/10.1016/j.still.2020.104820

Blake, G. R., & Hartage, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis: Part 1. Physical and mineralogical methods* (2nd ed., pp. 363–375). ASA and SSSA. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Blanco-Canqui, H. (2018). Cover crops and water quality. *Agronomy Journal*, *110*(5), 1633–1647. https://doi.org/10.2134/agronj2018.02.0077

Blanco-Canqui, H., Mikha, M. M., Presley, D. R., & Claassen, M. M. (2011). Addition of cover crops enhances no-till potential for improving soil physical properties. *Soil Science Society of America Journal*, *75*(4), 1471–1482. https://doi.org/10.2136/sssaj2010.0430

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal*, *107*(6), 2449–2474. https://doi.org/10.2134/agronj15.0086

Bodner, G., Leitner, D., & Kaul, H. P. (2014). Coarse and fine root plants affect pore size distributions differently. *Plant and Soil*, *380*(1), 133–151. https://doi.org/10.1007/s11104-014-2079-8

Bonell, M., & Williams, J. (1986). The two parameters of the Philip infiltration equation: Their properties and spatial and temporal heterogeneity in a red earth of tropical semi-arid Queensland. *Journal of Hydrology*, *87*(1–2), 9–31. https://doi.org/10.1016/0022-1694(86)90112-5

Bronick, C. J., & Lal, R. (2005). Soil structure and management: A review. *Geoderma*, *124*, 3–22. https://doi.org/10.1016/j.geoderma.2004.03.005

Calonego, J. C., Raphael, J. P., Rigon, J. P., de Oliveira Neto, L., & Rosolem, C. A. (2017). Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. *European Journal of Agronomy*, *85*, 31–37. https://doi.org/10.1016/j.eja.2017.02.001

Chalise, K. S., Singh, S., Wegner, B. R., Kumar, S., Pérez-Gutiérrez, J. D., Osborne, S. L., Nleya, T., Guzman, J., & Rohila, J. S. (2019). Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. *Agronomy Journal*, *111*(1), 99–108. https://doi.org/10.2134/agronj2018.03.0213

Cosentino, D., Chenu, C., & Le Bissonnais, Y. (2006). Aggregate stability and microbial community dynamics under drying-wetting cycles in a silt loam soil. *Soil Biology & Biochemistry*, *38*, 2053–2062. https://doi.org/10.1016/j.soilbio.2005.12.022

Crespo, C., Wyngaard, N., Rozas, H. S., Studdert, G. A., Barraco, M., Gudelj, V. P., Barbagelata, P., & Barbieri, P. (2021). Effect of intensified cropping sequences on soil physical properties in contrasting environments. *Catena*, *207*, 105690. https://doi.org/10.1016/j.catena.2021.105690

Duval, M. E., Galantini, J. A., Capurro, J. E., & Martinez, J. M. (2016). Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions. *Soil and Tillage Research*, *161*, 95–105. https://doi.org/10.1016/j.still.2016.04.006

Ferreras, L. A., Costa, J. L., Garcia, F. O., & Pecorari, C. (2000). Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern "Pampa" of Argentina. *Soil and Tillage Research*, *54*(1–2), 31–39. https://doi.org/10.1016/S0167-1987(99)00102-6

García-González, I., Hontoria, C., Gabriel, J. L., Alonso-Ayuso, M., & Quemada, M. (2018). Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. *Geoderma*, *322*, 81–88. https://doi.org/10.1016/j.geoderma.2018.02.024

Głąb, T., Ścigalska, B., & Łabuz, B. (2013). Effect of crop rotations with triticale (× *Triticosecale* Wittm.) on soil pore characteristics. *Geoderma*, *202*, 1–7. https://doi.org/10.1016/j.geoderma.2013.03.002

Haruna, S. I., Nkongolo, N. V., Anderson, S. H., Eivazi, F., & Zaibon, S. (2018). In situ infiltration as influenced by cover crop and tillage management. *Journal of Soil and Water Conservation*, *73*(2), 164–172. https://doi.org/10.2489/jswc.73.2.164

Imhoff, S., Ghiberto, P. J., Grioni, A., & Gay, J. P. (2010). Porosity characterization of Argiudolls under different management systems in the Argentine Flat Pampa. *Geoderma*, *158*(3–4), 268–274. https://doi.org/10.1016/j.geoderma.2010.05.005

Instituto Nacional de Tecnología Agropecuaria – Secretaría de Agricultura, Ganadería y Pesca (INTA-SAGyP). (1990). *Atlas de suelos de la República Argentina*. INTA-SAGyP.

IPCC. (2013). *Climate change 2013: The physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel On Climate Change*. Cambridge Univ Press.

Jirku, V., Kode, R., Nikodem, A., Mühlhanselová, M., & Anna, Ž. (2013). Temporal variability of structure and hydraulic properties of topsoil of three soil types. *Geoderma*, *205*, 43–58. https://doi.org/10.1016/j.geoderma.2013.03.024

Kay, B. D., & Angers, D. A. (2000). Soil structure. In M. Sumner (Ed.), *Handbook of soil science* (pp. 229–276). CRC Press.

Kreiselmeier, J., Chandrasekhar, P., Weninger, T., Schwen, A., Julich, S., Feger, K. H., & Schwarzel, K. (2019). Quantification of soil pore dynamics during a winter wheat cropping cycle under different tillage regimes. *Soil and Tillage Research*, *192*, 222–232. https://doi.org/10.1016/j.still.2019.05.014

Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkons, U., Vereecken, H., & Vanderborght, J. (2019). Modeling the impact of biopores on root growth and root water uptake. *Vadose Zone Journal*, *18*. https://doi.org/10.2136/vzj2018.11.0196

Le Bissonnais, Y. (1996). Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science*, *47*, 425–437. https://doi.org/10.1111/j.1365-2389.1996.tb01843.x

Leeds-Harrison, P. B., Youngs, E. G., & Uddin, B. (1994). A device for determining the sorptivity of soil aggregates. *European Journal of Soil Science*, *45*(3), 269–272. https://doi.org/10.1111/j.1365-2389.1994.tb00509.x

Liesch, A. M., Krueger, E. S., & Ochsner, T. E. (2011). Soil structure and physical properties under rye-corn silage double-cropping systems. *Soil Science Society of America Journal*, *75*(4), 1307–1314. https://doi.org/10.2136/sssaj2010.0292

Lozano, L. A., Soracco, C. G., Cornelis, W. M., Gabriels, D., Sarli, G. O., & Villarreal, R. (2013). Anisotropy of pore size classes' connectivity related to soil structure under no tillage. *Soil Science*, *178*(11), 612–617. https://doi.org/10.1097/SS.0000000000000027

Lozano, L. A., Soracco, C. G., Villarreal, R., Ressia, J. M., Sarli, G. O., & Filgueira, R. R. (2016). Soil physical quality and soybean yield as affected by chiseling and subsoiling of a no-till soil. *Revista Brasileira de Ciência do Solo*, *40*. https://doi.org/10.1590/18069657rbcs20150160

Novelli, L. E., Caviglia, O. P., & Piñeiro, G. (2017). Increased cropping intensity improves crop residue inputs to the soil and aggregate-associated soil organic carbon stocks. *Soil and Tillage Research*, *165*, 128–136. https://doi.org/10.1016/j.still.2016.08.008

Novelli, L. E., Caviglia, O. P., Wilson, M. G., & Sasal, M. C. (2013). Land use intensity and cropping sequence effects on aggregate stability and C storage in a Vertisol and a Mollisol. *Geoderma*, *195–196*, 260–267. https://doi.org/10.1016/j.geoderma.2012.12.013

Ogilvie, C. M., Ashiq, W., Vasava, H. B., & Biswas, A. (2021). Quantifying root-soil interactions in cover crop systems: A review. *Agriculture*, *11*(3), 218. https://doi.org/10.3390/agriculture11030218

Perroux, K. M., & White, I. (1988). Designs for disc permeameters. *Soil Science Society of America Journal*, *52*(5), 1205–1215. https://doi.org/10.2136/sssaj1988.03615995005200050001x

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops: A meta-analysis. *Agriculture Ecosystems and Environment*, *200*, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

Rahman, R., Shi, Z. H., & Chongfa, C. (2009). Soil erosion hazard evaluation: An integrated use of remote sensing, GIS and statistical approaches with biophysical parameters towards management strategies. *Ecological Modelling*, *220*, 1724–1734. https://doi.org/10.1016/j.ecolmodel.2009.04.004

Reynolds, W. D., Drury, C. F., Yang, X. M., & Tan, C. S. (2008). Optimal soil physical quality inferred through structural regression and parameter interactions. *Geoderma*, *146*, 466–474. https://doi.org/10.1016/j.geoderma.2008.06.017

Romaniuk, R., Beltrán, M., Brutti, L., Costantini, A., Bacigaluppo, S., Sainz-Rozas, H., & Salvagiotti, F. (2018). Soil organic carbon, macro- and micronutrient changes in soil fractions with different lability in response to crop intensification. *Soil and Tillage Research*, *181*, 136–143. https://doi.org/10.1016/j.still.2018.04.014

Ruis, S. J., Blanco-Canqui, H., Elmore, R. W., Proctor, C., Koehler-Cole, K., Ferguson, R. B., Francis, C. A., & Shapiro, C. A. (2020). Impacts of cover crop planting dates on soils after four years. *Agronomy Journal*, *112*(3), 1649–1665. https://doi.org/10.1002/agj2.20143

Sasal, M. C., Andriulo, A. E., & Taboada, M. A. (2006). Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. *Soil and Tillage Research*, *87*(1), 9–18. https://doi.org/10.1016/j.still.2005.02.025

Sasal, M. C., Boizard, H., Andriulo, A. E., Wilson, M. G., & Léonard, J. (2017). Platy structure development under no-tillage in the northern humid Pampas of Argentina and its impact on runoff. *Soil and Tillage Research*, *173*, 33–41. https://doi.org/10.1016/j.still.2016.08.014

Sasal, M. C., Castiglioni, M. G., & Wilson, M. G. (2010). Effect of crop sequences on soil properties and runoff on natural-rainfall erosion plots under no tillage. *Soil and Tillage Research*, *108*(1–2), 24–29. https://doi.org/10.1016/j.still.2010.03.010

Shaver, T. M., Peterson, G. A., Ahuja, L. R., & Westfall, D. G. (2013). Soil sorptivity enhancement with crop residue accumulation in semiarid dryland no-till agroecosystems. *Geoderma*, *192*(1), 254–258. https://doi.org/10.1016/j.geoderma.2012.08.014

Sindelar, M., Blanco-Canqui, H., Jin, V. L., & Ferguson, R. (2019). Cover crops and corn residue removal: Impacts on soil hydraulic properties and their relationships with carbon. *Soil Science Society of America Journal*, *83*(1), 221–231. https://doi.org/10.2136/sssaj2018.06.0225

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*, 7–31. https://doi.org/10.1016/j.still.2004.03.008

Smettem, K. R. J., Ross, P. J., Haverkamp, R., & Parlange, J. Y. (1995). Three-dimensional analysis of infiltration from the disk infiltrometer: 3. Parameter estimation using a double-disk tension infiltrometer. *Water Resources Research*, *31*(10), 2491–2495. https://doi.org/10.1029/95WR01722

Soil Survey Staff. (2014). *Keys to soil taxonomy* (12th ed.). USDA Natural Resources Conservation Service.

Sokal, R. R., & Rohlf, F. J. (1995). *Biometry: The principles and practices of statistics in biological research* (3rd ed.). W.H. Freeman and Company.

Soracco, C. G., Lozano, L. A., Sarli, G. O., Gelati, P. R., & Filgueira, R. R. (2010). Anisotropy of saturated hydraulic conductivity in a soil under conservation and no-till treatments. *Soil and Tillage Research*, *109*(1), 18–22. https://doi.org/10.1016/j.still.2010.03.013

Soracco, C. G., Lozano, L. A., Villarreal, R., Palancar, T. C., Collazo, D. J., Sarli, G. O., & Filgueira, R. R. (2015). Effects of compaction due to machinery traffic on soil pore configuration. *Revista Brasileira de Ciência do Solo*, *39*, 408–415. https://doi.org/10.1590/01000683rbcs20140359

Soracco, C. G., Villarreal, R., Melani, E. M., Oderiz, J. A., Salazar, M. P., Otero, M. F., Irizar, A. B., & Lozano, L. A. (2019). Hydraulic conductivity and pore connectivity. Effects of conventional and no-till systems determined using a simple laboratory device. *Geoderma*, *337*, 1236–1244. https://doi.org/10.1016/j.geoderma.2018.10.045

Statsoft. (2004). *STATISTICA (Version 7)*. Statsoft.

Steele, M. K., Coale, F. J., & Hil, R. L. (2012). Winter annual cover crop impacts on no-till soil physical properties and organic matter. *Soil Science Society of America Journal*, *76*(6), 2164–2173. https://doi.org/10.2136/sssaj2012.0008

Stewart, R. D., Rupp, D. E., Najm, M. R. A., & Selker, J. S. (2013). Modeling effect of initial soil moisture on sorptivity and infiltration. *Water Resources Research*, *49*(10), 7037–7047. https://doi.org/10.1002/wrcr.20508

Taboada, M. A., Barbosa, O. A., & Cosentino, D. J. (2008). Null creation of air-filled structural pores by soil cracking and shrinkage in silty loamy soils. *Soil Science*, *173*(2), 130–142. https://doi.org/10.1097/SS.0b013e31815d8e9d

Tarawally, M. A., Medina, H., Frómeta, M. E., & Itza, C. A. (2004). Field compaction at different soil-water status: Effects on pore size distribution and soil water characteristics of a Rhodic Ferralsol in western Cuba. *Soil and Tillage Research*, *76*(2), 95–103. https://doi.org/10.1016/j.still.2003.09.003

Tillman, R. W., Scotter, D. R., Wallis, M. G., & Clothier, B. E. (1989). Water-repellency and its measurement by using intrinsic sorptivity. *Australian Journal of Soil Research*, *27*, 637–644. https://doi.org/10.1071/SR9890637

van Genuchten, M. Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

van Genuchten, M. Th., Leij, F. J., & Yates, S. R. (1991). The RETC code for quantifying the hydraulic functions of unsaturated soils. Roberts Kerr Environ. Reseach Laboratory. https://doi.org/10.1002/9781118616871

Vandervaere, J. P., Vauclin, M., & Elrick, D. E. (2000). Transient flow from tension infiltrometers II. Four methods to determine sorptivity and conductivity. *Soil Science Society of America Journal*, *64*, 1272–1284. https://doi.org/10.2136/sssaj2000.6441272x

Villamil, M. B., Bollero, G. A., Darmody, R. G., Simmons, F. W., & Bullock, D. G. (2006). No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Soil Science Society of America Journal*, *70*(6), 1936–1944. https://doi.org/10.2136/sssaj2005.0350

Villarreal, R., Lozano, L. A., Melani, E. M., Salazar, M. P., Otero, M. F. , & Soracco, C. G. (2019). Diffusivity and sorptivity determination at different soil water contents from horizontal infiltration. *Geoderma*, *338*, 88–96. https://doi.org/10.1016/j.geoderma.2018.11.045

Villarreal, R., Lozano, L. A., Salazar, M. P., Bellora, G. L., Melani, E. M., Polich, N., & Soracco, C. G. (2020). Pore system configuration and hydraulic properties. Temporal variation during the crop cycle in different soil types of Argentinean Pampas Region. *Soil and Tillage Research*, *198*, 104528. https://doi.org/10.1016/j.still.2019.104528

Villarreal, R., Soracco, C. G., Lozano, L. A., Melani, E. M., & Sarli, G. O. (2017). Temporal variation of soil sorptivity under conventional and no-till systems determined by a simple laboratory method. *Soil and Tillage Research*, *168*, 92–98. https://doi.org/10.1016/j.still.2016.12.013

Walkley, A., & Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, *37*(1), 29–38.

Watson, K. W., & Luxmoore, R. J. (1986). Estimating macroporosity in a forest watershed by use of a tension infiltrometer. *Soil Science Society of America Journal*, *50*(3), 578–582. https://doi.org/10.2136/sssaj1986.03615995005000030007x

White, I., & Sully, M. J. (1987). Macroscopic and microscopic capillary length and time scales from field infiltration. *Water Resources Research*, *23*(8), 1514–1522. https://doi.org/10.1029/WR023i008p01514

Wilson, M. G., Maggi, A. E., Castiglioni, M. G., Gabioud, E. A., & Sasal, M. C. (2020). Conservation of ecosystem services in Argiudolls of Argentina. *Agriculture*, *10*(12), 1–21. https://doi.org/10.3390/agriculture10120649

Wulanningtyas, H. S., Gong, Y., Li, P., Sakagami, N., Nishiwaki, J., & Komatsuzaki, M. (2021). A cover crop and no-tillage system for enhancing soil health by increasing soil organic matter in soybean cultivation. *Soil and Tillage Research*, *205*, 104749. https://doi.org/10.1016/j.still.2020.104749

Yu, Y., Loiskandl, W., Kaul, H. P., Himmelbauer, M., Wei, W., Chen, L., & Bodner, G. (2016). Estimation of runoff mitigation by morphologically different cover crop root systems. *Journal of Hydrology*, *538*, 667–676. https://doi.org/10.1016/j.jhydrol.2016.04.060

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal*, *61*, 1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x

How to cite this article: Villarreal, R., Lozano, L. A., Polich, N., Salazar, M. P., Barraco, M., & Soracco, C. G. (2022). Cover crops effects on soil hydraulic properties in two contrasting Mollisols of the Argentinean Pampas region. *Soil Science Society of America Journal*, *86,* 1397–1412. https://doi.org/10.1002/saj2.20373