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First-year cover crop effects on the physical and hydraulic properties of the surface layer in a loamy soil

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ABSTRACT

Soil degradation is a global problem, threating its conservation and affecting agronomic production. No-tillage (NT) is the main management system for soil conservation world-wide. However, in Argentina, simplification of the crop sequence with high proportion of soybean under NT is a very common practice, leading to soil physical constrains. Crop sequence intensification through the inclusion of cover crops has been reported as an effective tool in the long-term for the enhancement of ecosystems services, improving NT performance. The objective of this work was to follow the evolution of the structural pore domain in the surface layer during the first year after the incorporation of cover crop (cover fallow of barley (*Hordeum vulgare* L.) and vetch (*Vicia* sp. L.), CF), as compared with bare fallow (BF), under NT management in a field experiment located in the Argentinean Depressed Pampas Region. Mini-infiltration and evaporation experiments were conducted in undisturbed soil samples (0−5 cm depth) in the laboratory in order to determine the pore size distribution (PoSD) and hydraulic conductivity (K (h)) functions in three different dates (after cover crop seeding, after maize seeding and before maize harvest) in order to follow the changes in soil pore functioning during the first year of cover cropping management. Changes in the soil pore functioning were observed in the short-term after the first cover crop cycle, showing the time-dependence of the hydraulic soil properties. These changes were mainly observed during the maize cycle. Under CF an increment of structural porosity (PS) was observed at the end of the maize crop cycle, while during the fallow period this variable remained relatively constant. K (h) and structural porosity connectivity (Cw) showed a rapid increment under BF during the fallow period, while under CF the increase was more gradual, which could be related to pore clogging and roots decay cycles. From the obtained results, we found that the introduction of cover crops under NT promotes the increment of a secondary pore system related to structural soil porosity during the first year and enhances the unsaturated hydraulic conductivity and pore connectivity, especially at the end of the summer crop cycle. Our results highlight the importance of including cover crops into the crop rotation to improve the structural porosity and its connectivity. As well, the results show the necessity of including the short-term changes in the study of soil hydraulics properties.

1. Introduction

Currently, the improvement of agricultural productivity is based on the expansion and intensification of crop production systems (Olson et al., 2017). In the case of developing countries, with limited resources, management of soil quality is essential to sustain ecosystem services (Lal, 2015). Soil degradation is a global problem which, in addition to negatively affecting the soil conservation itself, also affects agronomic production, and economic growth, especially in countries where agriculture is important for economic development (Scherr, 2001). The Argentinean Pampas Region is one of the most productive areas in the world (Aparicio et al., 2018). However, in Argentina, the adoption of no-tillage (NT) has

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not been accompanied with other conservational managements, *i.e.* crop rotations, nutrient replacement, and integrated pest management. In this sense, simplification of the crop sequence with high proportion of soybean or maize under NT is a very common practice, threating soil quality and conservation (Behrends Kraemer et al., 2019).

The intensification of crop sequence through the inclusion of winter cover crop into existing cropping systems has the potential to enhance ecosystems services such as better weed control, soil conservation, and increasing carbon and nutrient cycling, improving NT performance (Blanco-Canqui et al., 2011). The inclusion of cover crops implies higher soil biological activity during the fallow period, coupled with higher input of organic carbon (OC) (Franzluebbers and Stuedemann, 2008; Restovich et al., 2012; Duval et al., 2016), being a possible alternative in order to recover degraded soils (García-González et al., 2018). It has been reported that the inclusion of cover crops in the middle and long-term (> four years) improves soil physical quality in different textured soils. For example, Calonego et al. (2017) showed that the soil structure improved in the 0−10 cm depth in a clayey soil due to cover crops root system, increasing macroporosity and decreasing BD. Sastre et al. (2018) reported in a loam soil that cover crops increased aggregate stability in the 0−5 cm depth. It has been reported in different silty loam soils, a macroporosity improvement under cover cropping management in the 10 cm top soil (Bodner et al., 2014; Yu et al., 2016; Gabriel et al., 2019) as compared with bare fallows. Related to these changes in pore structure, Joyce et al. (2002) reported in loamy and silty soils increasing values of soil water infiltration and water holding capacity in the 0−15 cm soil depth. Blanco-Canqui et al. (2011) found higher infiltration rates and lower BD values in 0−7 cm soil depth in a silty loam soil. In the short-term (< four years), contradictory results have been reported. Positive effects of cover crop inclusion on soil water dynamics in silty loam soils (Villamil et al., 2006; Castiglioni et al., 2016; Haruna et al., 2018) and on macroporosity (Nascente and Stone, 2018) has been reported in the 0−10 cm depth, while no effects on soil physical quality after cover crop inclusion has been reported in the 0−10 cm soil depth in silty clay loam soils (Acuña and Villamil, 2014; Mukherjee and Lal, 2015). These results show that the soil pore system functioning is highly complex and depends on multiple variables such as soil type, growing crop and climatic conditions (Jirku et al., 2013). Better representations of this complex dynamics are needed, including the temporal dynamics of soil structure that lead to changes in hydraulic properties (Herbrich and Gerke, 2017).

The changes of the soil structure due to cover crops affect the geometry of the soil pore space, which is controlling the soil hydraulic properties (Chandrasekhar et al., 2018) such as the soil water retention curve (SWRC) and the hydraulic conductivity function ((K(h)). In addition, soil structure could present intra-seasonal changes as consequence of rainfall events, wetting and drying cycles, biological activity and crop management (Jirku et al., 2013; Schwen et al., 2011; Chandrasekhar et al., 2018; Villarreal et al., 2020). It has been reported that roots enhance soil structure while earthworms may homogenize aggregates (Haas and Horn, 2018). Villarreal et al. (2020) mentioned that tillage increases macroporosity, while biological activity increases its connectivity during the crop cycle. On the other hand, Bodner et al. (2008) found that cover crop growth tended to reduce hydraulic conductivity during the winter period, probably due to pore clogging by roots.

In order to quantify these changes in soil pore space and the related hydraulic properties, the determination of the soil water retention curve (SWRC) and the hydraulic conductivity function ((K(h)) becomes crucial. In general, these two functions are described by uni-modal functions such as the closed-form Mualem–van Genuchten model (van Genuchten, 1980), leading to inaccurate predictions (Priesack and Durner, 2006). In rigid and moderate expansive soils, the pore space is often self-organized in a bi-modal size distribution of small matrix domain pores (*e.g.* mineral grains, organic materials) and larger "structure domain" pores (*e.g.* inter-aggregate spaces, root channels, fauna burrows, and inter-pedal cracks) (Durner, 1994; Reynolds, 2017). Fitting SWRC and K(h) data to a bi-modal model, allows to identify and quantify a secondary pore system related to the soil structure, which is the most affected by agricultural practices (Durner, 1994). Using this approach, Kreiselmeier et al. (2019) compared the evolution of the pore size distribution (PoSD) under different tillage treatments. These authors observed a shift from larger to smaller pores under conventional tillage during the winter, decreasing the bimodality, while NT hardly experienced any changes in their pore space. However, these authors reported that after harvest, when roots growth and organic matter decayed, a restoration of structural domain was observed. Kreiselmeier et al. (2020) recently studied the temporal changes in K (h), during the crop cycle under different tillage systems, including NT. These authors mentioned that under drier conditions the variability of K decreased due to the decreasing influence of larger pores, especially under NT, which showed more stable values of K along the studied period. However, there is still little information about the effect of cover crops on soil structural evolution over the cover cropping period (Bacq-Labreuil et al., 2019).

To identify, quantify and understand the geometry, connectivity, formation and dynamics of structural pores under different agricultural practices is still a challenge in soil physics. There are several studies about the post-tillage changes in pore structure and related hydraulic properties under different tillage managements (Peña-Sancho et al., 2017; Sandin et al., 2018; Kreiselmeier et al., 2019; Villarreal et al., 2020). However, there are few studies accounting the immediately effects after cover cropping management inclusion. It has been reported that particular crops could differ in their impact on soil pore system, but the effects are not permanent and are visible in the year when the crop is cultivated (Głab et al., 2013). The description of soil pore system evolution in the short-term after the introduction of cover cropping management will help to understand the complex dynamics of soil structure that lead to changes in hydraulic properties (Herbrich and Gerke, 2017). Moreover, this information could be useful for frameworks development for modelling soil structure dynamics (Meurer et al., 2020) and for the evaluation of cover crops as bio-tillage management, which is gaining increasing attention in the last years (Zhang and Peng, 2021). Additionally, this kind of study provides crucial information in order to identify possible, both positive and negative, effects in the short-term after introduction of cover cropping management, which is important for farmers when the adoption of this practice is evaluated. We hypothesize that: i- cover crop introduction into the crop sequence under NT during the first year produces a shift of the PoSD from matrix to structural domain; and ii- cover crop introduction improves the structural pore connectivity, increasing K (h), especially in the near-saturated region. The objective of this work was to follow the evolution of the PoSD, including matrix and structural domains, and K (h) during the first year after incorporation of cover crop management, as compared with bare fallow, under NT management.

2. Materials and methods

2.1. Site and treatments

The field experiment was set up in 2018 in the Argentinean Depressed Pampas Region, near Chascomús city (35°44′37.61″ south and 58°03′10.22″ west). The soil was classified as a fine, illitic, thermic abruptic Argiudoll (Soil Survey Staff, 2014), Luvic Phaeozem (IUSS Working Group WRB., 2007), with an A horizon (0–0.3 m depth, 24.3, 42.9 and 32.8 % of clay, silt and sand, respectively, 6.0 soil-water pH (1:2.5 relation) and 2.29 % OC), followed by a clay-illuvial Bt horizon (0.3–0.6 m depth, 40.5, 59.0 and 0.5 % of clay, silt and sand, respectively, 6.2 soil-water pH (1:2.5 relation) 0.54 % OC and 1.43 g cm^{-3} bulk density) over the mature silty sediments (C horizon, > 0.6 m). The A horizon has a loam texture, with low expansible capacity due to its dominant clay mineral type (illite). The climate in the region is temperate. The mean annual precipitation is 946 mm and the mean annual potential reference evapotranspiration is 929 mm (SIGA, 2020).

In the year 2018 a completely randomized experimental design was installed with two management systems (three plots of 20 m wide and 87 m long for each treatment): i- no tillage with bare fallow (BF); ii- no-tillage with cover fallow (CF) (barley (*Hordeum vulgare* L.) and vetch (*Vicia* sp. L.). For both treatments, maize (*Zea mays* L.) was sown as summer crop. Seeding and termination of the cover crop were on September 1st and December 20th, 2018, respectively. In December 28th, 2018 maize seeding was carried out for both treatments. Maize harvest was done in May 5th, 2019. Before the experiment was arranged, the used field was under NT with maize monoculture during the last 10 years, and before that the field was under natural grassland. Precipitation between August 2018 and April 2019 was 900.5 mm which is higher as compared with the long-term average for the same period (751 mm). During the cover crop growing, no water-limiting periods were observed (September-December 2018 cumulative precipitation: was 448 mm; long term average for the same period: 357 mm). During the maize growing, water-limiting period was observed (January-April 2019 cumulative precipitation: 230 mm; long-term average for the same period: 424 mm).

Sampling campaigns were carried out in 24th October, 2018 (during the fallow period after cover crop seeding, FP), 4th January, 2019 (after maize seeding, MS) and 3th March, 2019 (before maize harvest, MH). Adjacent plots with the same relative position in the landscape from each treatment were selected. In each of these plots a homogeneous and representative 5 × 5 m area in the center of each treatment and sampling date 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 diameter, 98 cm^3 volume) from the first 5 cm (0−5 cm) of soil in each treatment and date. Visible disturbances of the soil surface such as wheel tracks were avoided. Additionally, five undisturbed soil samples (10 cm height, 7 cm diameter) were collected for soil bulk density (ρd, g cm^{-3}) determination (Blake and Hartge, 1986). Disturbed soil samples for OC content determination (Walkley and Black, 1934) were extracted from the direct surroundings of the intact cores at the end of the crop cycle (April 2019). Similar water content values in the top soil between treatments were observed in all sampling dates (mean values ± standard deviations were 0.18 ± 0.05, 0.35 ± 0.01 and 0.27 ± 0.04 m^3 m^{-3} under BF for FP, MS and MH, respectively; and 0.22 ± 0.02, 0.33 ± 0.02 and 0.24 ± 0.01 m^3 m^{-3} under CF for FP, MS and MH, respectively). All samples were air-dried at room temperature and stored at 4 °C until further processing. No visible shrinkage or cracking were observed after this process.

2.2. Soil properties determination

2.2.1. Near saturated hydraulic conductivity

A mini-infiltrometer (Soracco et al., 2019) was used in order to determine water infiltration under different water pressure heads in the undisturbed air-dried 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 and 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 directly with the tension disc by rising the jack. Infiltration runs were performed at −6 cm, −3 cm and 0 cm water pressure head (h), applied in this order and in the same sample. Every determination at each tension took approximately 5 min to reach the steady state and the mass of water which 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 $K_{6\text{-MI}}$, $K_{3\text{-MI}}$ and $K_{0\text{-MI}}$, were determined from the cumulative water infiltration using the multiple-head method (Ankeny et al., 1991) with the steady-state data.

2.2.2. Soil water retention curve and unsaturated hydraulic conductivity

After near saturation hydraulic conductivity determination, the samples were saturated with degassed tap water for 48 h from the bottom, gradually raising the water level to avoid trapping air inside the pores. After that, the SWRC and K (h) were determined using the simplified evaporation method (Schindler and Müller, 2006). Saturated soil samples were sealed on the bottom and placed on an analytical balance and two mini-tensiometers (T5 Tensiometer, METER Group, Inc. USA) were inserted vertically at depths of 1.25 and 3.75 cm into the soil sample. Free evaporation from the upper surface was allowed under laboratory conditions (temperature ranged between 20 and 24 °C) and sample mass (m) and soil pressure heads (h) at two depths (h_{upper} and h_{lower} for 1.25 and 3.75 cm, respectively) were continuously recorded. The function K (h) was determined according to the simplified evaporation method. Water volume loss, ΔV, was determined from mass loss recorded from the balance (1 g = 1 cm^3). The pressure head values in the sample at the two depths, $h_{upper}(t)$ and $h_{lower}(t)$, were used to calculate a mean hydraulic gradient, i_m [−], for each time interval, $\Delta t = t_2 - t_1$, across the vertical distance, Δz, between the tensiometers (2.5 cm) as:

$$i_m = \frac{1}{2}\left(\frac{h_{upper}(t_1) - h_{lower}(t_1)}{\Delta z} + \frac{h_{upper}(t_2) - h_{lower}(t_2)}{\Delta z}\right) - 1 \tag{1}$$

The K (h) is obtained according to Darcy-Buckingham's law

$$K(h^*) = \frac{\Delta V}{2A\Delta t i_m} \tag{2}$$

Where h* is the mean pressure head between the two tensiometers between the time interval (Δt, 10 min), and A is the cross-sectional area of the soil core (19.6 cm^2). Because the gradient is close to zero, K (h) in the wet range has to be rejected. In this paper we use the filter criterion for valid K data proposed by Peters and Durner (2008), considering the tensiometer noise according the user manual.

Water retention data were fitted to bimodal van Genuchten model (Durner, 1994):

$$\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^{k} w_i \left[\frac{1}{\left(1 + |\alpha_i h|^{n_i}\right)^{m_i}}\right] \tag{3}$$

Where θ_r and θ_s are the residual and saturated volumetric water content, respectively, α, n, and m (m = 1−1/n) are empirical parameters for the two pore domains (index i), and w_i is a pore-domain (1 for matrix domain, 2 for structural domain), weighing factor ($w_1 = 1 - w_2$). The unsaturated hydraulic conductivity was described with the coupled Mualem (1976) and van Genuchten model for bimodal retention function (Priesack and Durner, 2006):

$$K(h) = K_0\left\{\sum_{i=1}^{k} w_i\left[1+(a_i h)^{n_i}\right]^{-m_i}\right\}^2 \left(\frac{\sum_{i=1}^{k} w_i\alpha_i\left\{1-(a_i h)^{n_i-2}\left[1+(a_i h)^{n_i}\right]^{-m_i}\right\}}{\sum_{i=1}^{k} w_i\alpha_i}\right) \tag{4}$$

where k indicates the modality of the model (*i.e.*, k = 2 for bimodal), w is a dimensionless weighing factor for the sub-curves of each pore domain, K_0 corresponds to the saturated hydraulic conductivity, and α, n, and m are the van Genuchten model parameters (Eq. (3)).

Water retention data was fitted in a first step and the derived fitting parameters, α_i, n_i, m_i, and K_0 were then used in a second step for fitting the K (h) data obtained from the evaporation method (Beck-Broichsitter et al., 2020). More weight was put on the water retention, since more data points were available (Kreiselmeier et al., 2019). Pore tortuosity parameter was fixed to a value of 0.5 in order to reduce the number of unknown variables. The data fitting was carried out with RETC code version 6.02 (van Genuchten et al., 1991), using a nonlinear least-squares optimization approach to estimate the unknown model parameters. Fitted parameters are shown in Table 1.

The PoSD was determined from the first derivative of the SWRC (Reynolds, 2017) against the equivalent pore diameter, determined as:

$$d_e = \frac{2977.4}{|h_i|} \tag{5}$$

where d_e is the equivalent pore diameter (µm) and h is the pressure head (cm), assuming 1 cm is proportional to −1 hPa, for each pore size class (Reynolds, 2017).

2.2.3. Pore structure connectivity

In order to determine structural porosity connectivity, the pore continuity index (Cw) based on water flux (Lozano et al., 2013) was calculated for the structure porosity. Cw was calculated as the ratio between $K_0 - K(h_{INT})$ and the pore volume fraction occupied by structure domain (where h_{INT} is the water pressure head at the intersection between pore structure domain and pore matrix domain, which corresponds to the lower limit of the pore structure domain). The h_{INT} was calculated according to Reynolds (2017):

$$\frac{m_2 n_2 P_s (\alpha_2 h_{INT})^{n_2} \left[1 + (\alpha_1 h_{INT})^{n_1}\right]^{m_1+1}}{m_1 n_1 P_M (\alpha_1 h_{INT})^{n_1} \left[1 + (\alpha_2 h_{INT})^{n_2}\right]^{m_2+1}} = 1 \tag{6}$$

Where α_1, n_1, and m_1 are the van Genuchten parameters corresponding to the matrix domain, α_2, n_2, and m_2 are the van Genuchten parameters corresponding to the structure domain, P_M and P_S are the matrix and structural porosities, respectively, calculated from the total porosity (TP) as:

$$P_M = w_1 TP \tag{7}$$

$$P_S = w_2 TP \tag{8}$$

Then, the Cw for the structural porosity was calculated by:

$$Cw = \frac{K_0 - K_{(hINT)}}{P_S} \tag{9}$$

The $K_{0\text{-}MI}$ values from mini-infiltration experiments were used in order to calculate the Cw. K at the h_{INT} was obtained from the fittings of K (h) data from the evaporation method. This index allows to compare 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 since it integrates dynamic (hydraulic conductivity) and capacity (pore volume) information in a single value (Soracco et al., 2019). This index is analogous to the pore continuity index calculated with air permeability and air-filled porosity (Reszkowska et al., 2011).

2.3. Statistical analysis

Two-way ANOVAs, with two factors (soil management system with two levels, and sampling date with three levels) were performed in order to determine main and interaction effects on K (h), P_S, P_M, Cw and ρd. A test for normality (Shapiro–Wilks test) was performed. Because the statistical distribution of K (h) and Cw data were skewed and non-normal, logarithmic values were used for the analysis. Fisher's least significant difference (LSD) test (Sokal and Rohlf, 1995) was used to compare the means when interaction between factors were observed. For all analysis the significance was determined at $p = 0.05$. These statistical analyses were performed in STATISTICA software (Statsoft Inc., 2004).

The Solver® add-in (Frontline Systems, Incline Village, NV) was used in the Excel® spreadsheet (Microsoft Corporation, Redmond, WA) to numerically solve Eq. (6) in order to obtain h_{INT}.

In order to evaluate the performance of the fitted model the root mean square error (RMSE) was calculated (Beck-Broichsitter et al., 2020):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{k}(x_{sim} - x_{obs})^2} \tag{10}$$

Where x_{sim} are fitted and x_{obs} observed values of θ and K(h).

3. Results

3.1. General soil properties

The values of ρ_d were affected by both management system and sampling date ($p < 0.05$). Mean values of ρ_d were 1.22, 1.25 and 1.18 g cm^{-3} under BF for FP, MS and MH, respectively; and 1.17, 1.19 and 1.14 g cm^{-3} under CF for FP, MS and MH, respectively. BF management showed higher ρ_d as compared to CF management along the whole studied period. During the fallow period (October 2018 – January 2019) relatively constant values of ρ_d were observed, followed by a decrease during the maize cycle, when lower values of ρ_d were observed before the harvest. Mean values of OC measured at the end of the maize growing period (April 2019), were 3.54 and 3.42 % under BF and CF, respectively. No differences between management systems were found ($p > 0.05$).

3.2. Near saturated hydraulic conductivity

Values of $K_{0\text{-}MI}$, $K_{3\text{-}MI}$ and $K_{6\text{-}MI}$ for different sampling dates and systems in the 0–5 cm soil depth are shown in Fig. 1. No interactions between factors were observed for these three variables, that were only affected by sampling date (Table 2). The values of $K_{0\text{-}MI}$, $K_{3\text{-}MI}$ and $K_{6\text{-}MI}$ ranged between 3.2 and 0.02 cm h^{-1}, depending on management system and sampling date. At the beginning of the fallow period (corresponding to FP sampling), the observed values of $K_{0\text{-}MI}$, $K_{3\text{-}MI}$ and $K_{6\text{-}MI}$ were relatively low, as compared with previous reports for the same region (Villarreal et al., 2020). Between FP and MS, the values of $K_{0\text{-}MI}$, $K_{3\text{-}MI}$ and $K_{6\text{-}MI}$ showed an increment and remained constant until MH, previous to the maize harvest (Fig. 1). However, $K_{0\text{-}MI}$ under CF showed a continual increase until MH, while under BF the strong increment between FP and MS was followed by a tendency to decrease towards MH (Fig. 1).

Table 1

Mean values (± standard deviation, n = 6) of the fitting parameters obtained with the data from the evaporation method (saturated water content, θs; α, n, for the two pore domains (1 for matrix domain, 2 for structural domain); weighing factor ($w_1 = 1 - w_2$); saturated hydraulic conductivity, K_0) during the studied period (October, 2018 (fallow period after cover crop seeding, FP), January, 2019 (after maize seeding, MS) and March, 2019 (before maize harvest, MH) for the two management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF).

Sampling date	Treatment	θs $m^3\ m^{-3}$	α cm^{-1}	n –	α_2 cm^{-1}	n_2 –	w_2 –
FP	BF	0.48 ± 0.01	0.004 ± 0.002	1.73 ± 0.32	0.15 ± 0.05	1.88 ± 0.55	0.32 ± 0.10
	CF	0.49 ± 0.01	0.007 ± 0.007	1.39 ± 0.17	0.13 ± 0.16	1.69 ± 0.27	0.24 ± 0.09
MS	BF	0.47 ± 0.01	0.011 ± 0.004	1.47 ± 0.16	0.30 ± 0.21	1.82 ± 0.44	0.25 ± 0.15
	CF	0.50 ± 0.01	0.011 ± 0.008	1.39 ± 0.19	0.26 ± 0.09	1.96 ± 0.72	0.26 ± 0.10
MH	BF	0.49 ± 0.01	0.024 ± 0.04	1.44 ± 0.33	0.10 ± 0.07	1.84 ± 0.59	0.24 ± 0.18
	CF	0.51 ± 0.01	0.009 ± 0.007	1.73 ± 0.44	0.24 ± 0.22	1.45 ± 0.44	0.41 ± 0.23

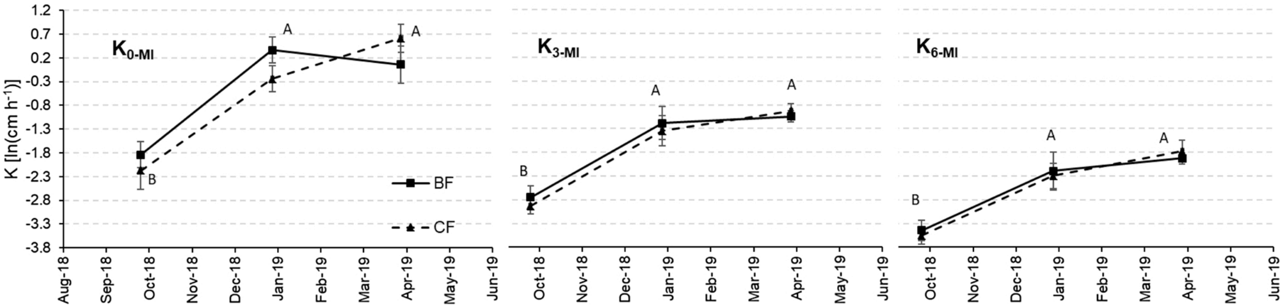

Fig. 1. Mean values of $K_{0\text{-MI}}$, $K_{3\text{-MI}}$, and $K_{6\text{-MI}}$ during the studied period under different management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF) in the 0-5 cm soil depth. Uppercase letter indicates significant differences among sampling dates (LSD, $P < 0.05$). The error bars indicate the standard deviation.

Table 2
Analysis of variance of the effects of soil management system (S),sampling date (D) and interaction (SxD) on soil physical properties (hydraulic conductivity at 0, -3, -6 and −316 cm water pressure head, K_0, K_3 K_6, K pF 2.5, respectively, cm h^{-1}; Structural porosity, PS, m^3 m^{-3}; Matrix porosity, PM, m^3 m^{-3}; structural porosity connectivity, Cw, cm h^{-1}; bulk density, ρd, g cm^{-3}).

Factor	S		D		S x D	
Variable	F-value	p	F-value	p	F-value	p
$K_{0\text{-MI}}$	0.25	ns	30.03	**	1.77	ns
$K_{3\text{-MI}}$	0.10	ns	21.62	**	0.16	ns
$K_{6\text{-MI}}$	0.01	ns	15.23	**	0.12	ns
K pF 2.5	4.50	*	8.20	*	0.42	ns
PS	2.28	ns	2.10	ns	4.01	*
PM	0−37	ns	0.88	ns	4.05	*
Cw	0.97	ns	48.22	**	1.08	ns
ρd	11.82	**	6.99	**	0.12	ns

Significance level.
* $p < 0.05$.
** $p < 0.01$; ns, $p > 0.05$.

3.3. *Pore size distribution, unsaturated hydraulic conductivity and pore connectivity*

The SWRC with the derived PoSD, and K (h) functions for different dates and systems in the 0−5 cm soil depth are shown in Figs. 2 and 3, respectively. The overall fits to bimodal model were very good for both SWRC and K (h) functions, with low values of RMSE ranging between 0.002 and 0.004 m^3 m^{-3} for SWRC and between 0.001 and 0.01 cm h^{-1} for K (h) data. Pore matrix was mostly dominating, with mean values of w_1 ranging between 0.59 and 0.76. The bimodality of the SWRC showed different temporal trends between management systems. Under BF, the bimodality was disappearing during the studied period, while under CF the presence of a secondary pore system increased (Fig. 2, PoSD). The derived values of PS and PM are shown in Fig. 4. From ANOVA results, interaction between factors showed that the PS was time-dependent. In general, similar values of PS and PM were observed between management systems during the fallow period, while the differences were observed at the end of the maize cycle, before the harvest. Under BF, the values of PS and PM remained constant during the studied period, while under CF these variables remained constant between FP and MS and increased and decreased for PS and PM, respectively, between MS and MH (Fig. 4). Under CF, the increment of the structural domain was at the expense of matrix domain, showing a shift of the h_{INT} towards the larger pores.

From the fitting data obtained with the evaporation method, K_0 values were higher in one or two magnitude orders as compared with the $K_{0\text{-MI}}$ (Table 3). However, K_0 and $K_{0\text{-MI}}$ follow the same temporal trend; under BF, K_0 showed a strong increase between FP and MS, remaining relatively constant until MH, while under CF, K_0 increased more gradually during the studied period. Under both management systems, the unsaturated hydraulic conductivity within the measured range was affected by management system and sampling date ($p < 0.05$). Between FP and MS, K (h) remained relatively constant and increased in MH, before the maize harvest, when BF management showed higher values as compared to CF (Fig. 3). Mean values of K at h equal to −316 cm (pF 2.5) are shown in Table 3.

The structural porosity connectivity, determined through the connectivity index, Cw, showed similar values between management systems during the studied period ($p > 0.05$) and was affected by the sampling date ($p < 0.05$) (Fig. 5). In FP, Cw values were very low, increased between FP and MS and remained constant until MH. As was observed for $K_{0\text{-MI}}$, the increment in Cw under BF was stronger in comparison with CF, where the increment was more continual (Fig. 5).

Overall, from the obtained data, changes in the soil pore functioning were observed in the short-term after the first cover crop cycle, showing the time-dependence of the hydraulic soil properties. These changes were mainly observed during the maize cycle. The used approach allowed to identify the increment of a structure pore domain after cover cropping, with increasing values of K (h).

4. Discussion

4.1. *General soil properties*

Lower values of ρ_d under CF management are in agreement with several authors who mentioned an improvement of this property in the short-term under cover crop management (Castiglioni et al., 2016). No differences in OC values between management systems at the end of the studied period were observed. It has been reported that changes in OC are expected in long-term experiments. In agreement with our results, other authors reported no differences in OC in the short-term with the inclusion of winter cover crops (Acuña and Villamil, 2014). The improvement on soil structure under CF management without changes in OC, was also reported by other authors in short-term experiments (Hermawan and Bomke, 1996; Kabir and Koide, 2002; Liu et al., 2005). Álvarez et al. (2014) mentioned that the most likely cause is the aggregation effects of fine roots.

4.2. *Soil pore functioning and hydraulic properties*

From the obtained results, all studied variables showed time variation in the short-term over the studied period. These findings were also reported by other authors, who mentioned that soil hydraulic properties are highly time-variable, even at the seasonal scale, as was observed here (Chandrasekhar et al., 2018). The changes in the soil pore functioning at the seasonal scale, related to the inclusion of cover crop, are mainly attributed to the biological activity of the root system (Gabriel et al., 2019).

Under BF management, constant values of PS (Fig. 4) together with lower bimodality were found (Fig. 2). Similar results were reported by Kreiselmeier et al. (2019), who observed that NT treatment, as compared with other tillage systems, showed a little change in soil pore functioning

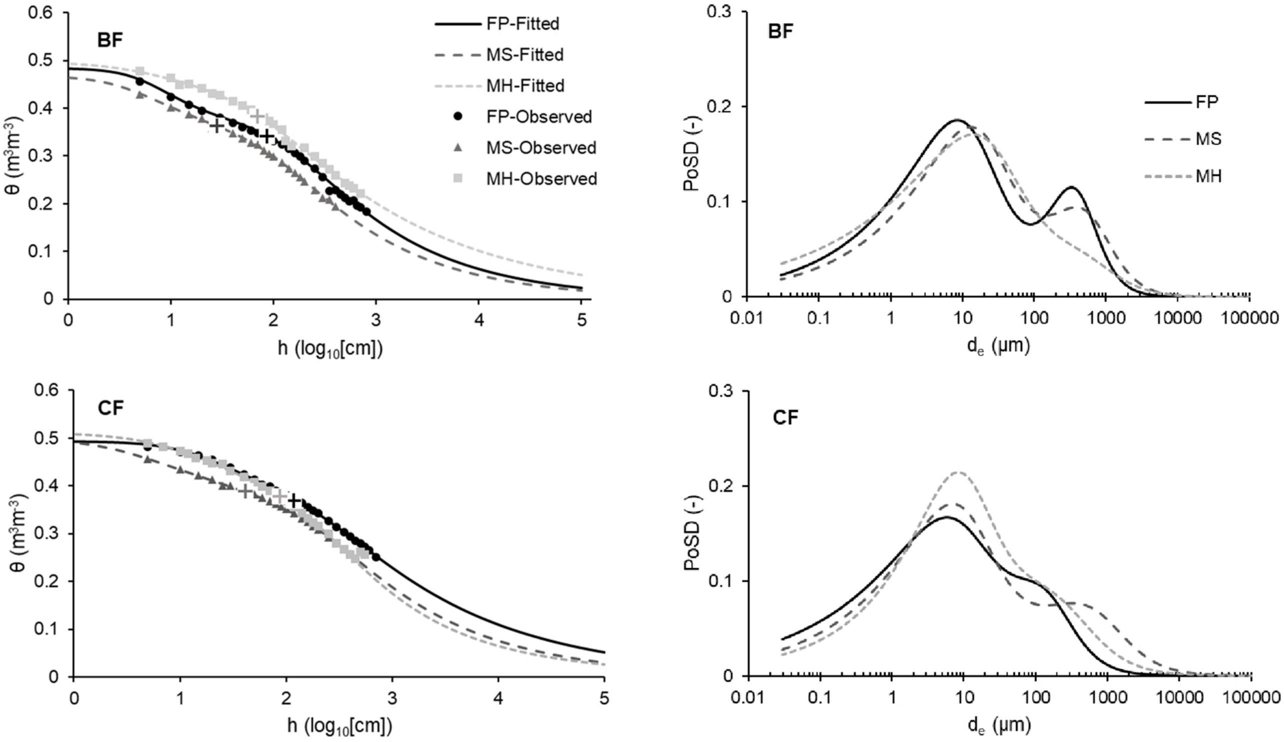

Fig. 2. Soil water retention curves (left) and their respective bimodal pore size distributions (right) evolution under different management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF) during the studied period in the 0-5 cm soil depth. Different colours represent different sampling dates (October, 2018 (during the fallow period after cover crop seeding, FP), January, 2019 (after maize seeding, MS) and March, 2019 (before maize harvest, MH)). Crosses denote the water pressure head at the intersection between pore structure domain and pore matrix domain (h_{INT}).

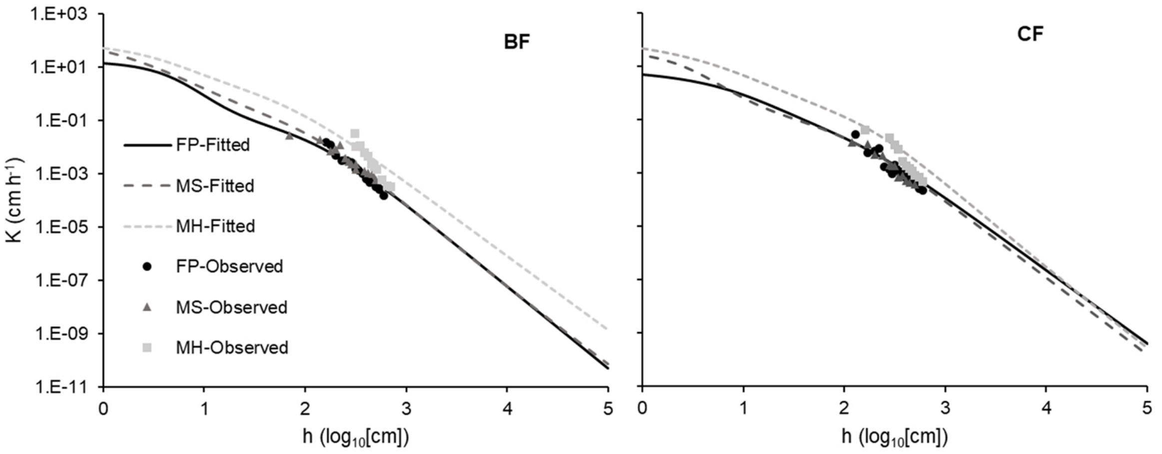

Fig. 3. Observed and fitted values of hydraulic conductivity (K) at different soil water pressure heads (h) evolution under different management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF) during the studied period in the 0-5 cm soil depth. Different colors represent different sampling dates (October, 2018 (during the fallow period after cover crop seeding, FP), January, 2019 (after maize seeding, MS) and March, 2019 (before maize harvest, MH)).

and a decrease in the bimodality during the winter period. However, these authors mentioned that shortly after harvest, the restoration of the pore structure domain was observed, as consequence of roots decay. Under CF management, increasing PS values together with an increment in the bimodality were observed in MH, while during the fallow period the PS remained relatively constant. This could be attributed to the cover crop roots decay after cover crop termination (December 2018). It was suggested by Bodner et al. (2014) that legume species as cover crop with coarse roots increase inter-aggregate porosity. Additionally, Bodner et al. (2008) mentioned that flow-weighted mean pore radius increasing under cover cropping management was related to the stabilization of pores and the enhancement of the formation of new pores remaining after roots decay. Kreiselmeier et al. (2019) mentioned that the roots decay at the end of the crop cycle has the potential to contribute to a more heterogeneous and stable soil structure. Our findings are in agreement with several authors who mention that the inclusion of cover crops improves soil structure, (Villamil et al., 2006; Celette et al., 2008; Behrends Kraemer et al., 2019; Sastre et al., 2018) and macroporosity (Bodner et al., 2014; Yu et al., 2016; Gabriel et al., 2019) due to their roots systems (Calonego et al., 2017). Another possible explanation for our findings is the soil consolidation due to the shrink-swell activity as a result of different seasonal drying between management systems. The CF management showed higher water content in the 0–10 cm soil depth, as compared to BF during the water-limiting period between January and

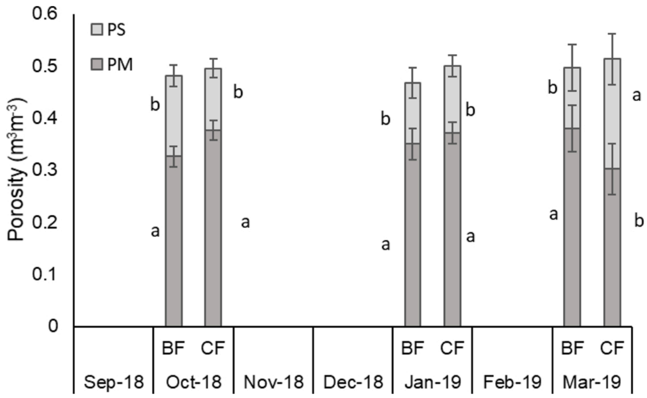

Fig. 4. Soil structural porosity (PS), matrix porosity (PM) and total porosity (TP, TP = PS + PM) during the studied period for the two management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF) in the 0-5 cm soil depth. Lowercase case letter indicates significant differences among system x sampling date (LSD, $P < 0.05$). The error bars indicate the standard deviation for each porosity.

Table 3
Mean values (± standard deviation, n = 6) of fitted Saturated hydraulic conductivity (K_0) and hydraulic conductivity at $h=-316$ cm (K pF 2.5) obtained with the data from the evaporation method during the studied period (October, 2018 (fallow period after cover crop seeding, FP), January, 2019 (after maize seeding, MS) and March, 2019 (before maize harvest, MH) for the two management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF).

Sampling date	Treatment	K_0 cm h^{-1}	K pF 2.5 cm h^{-1}
FP	BF	18.2 ± 18.0	0.003 ± 0.002
	CF	9.1 ± 13.01	0.002 ± 0.001
MS	BF	469.0 ± 703.0	0.002 ± 0.003
	CF	53.2 ± 56.4	0.002 ± 0.001
MH	BF	106.8 ± 118.5	0.014 ± 0.009
	CF	221.9 ± 219.01	0.006 ± 0.005

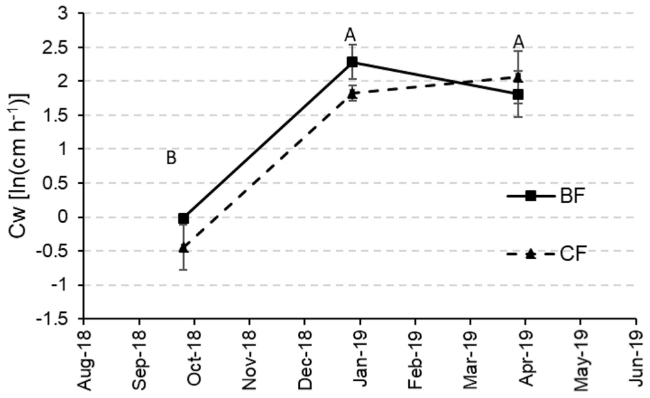

Fig. 5. Mean values of pore structure connectivity (Cw) evolution under different management systems (No tillage with bare fallow, BF; No tillage with cover crop, CF) during the studied period in the 0-5 soil depth. Uppercase letter indicates significant differences among sampling date (LSD, $P < 0.05$). The error bars indicate the standard deviation.

March (data not shown) probably related to surface residues left by the cover crop, leading to lower evapotranspiration (Alfonso et al., 2020). However, these differences in the top soil water content between management were relatively low. Additionally, the soils in the studied region, composed by a high content of illitic clay type, present nonexistent or very small swell-shrink potential (Taboada et al., 1998).

From the statistical analysis, no significant differences in near-saturated hydraulic conductivity values were observed between management systems at any sampling date. However, despite the absence of statistical differences, the values of near-saturated hydraulic conductivity showed a rapid increment under BF during the fallow period ($K_{0\text{-MI}}$ increased by a factor of 8.7 between FP and MS), followed by a decrease between MS and MH (decreased factor of 0.53). Under CF the increase was continual ($K_{0\text{-MI}}$ increased by a factor of 8.5 and 1.76 between FP and MS, and MS and MH, respectively). This behavior could be related to the roots decay cycles. Under BF, the root decay of the previous summer crop occurred during the fallow period, increasing water-conducting porosity, as can be seen in higher values of $K_{0\text{-MI}}$, $K_{3\text{-MI}}$ and $K_{6\text{-MI}}$ between FP and MS (Fig. 1). On the other hand, under CF, these increments were more continual. Besides the pore formation due to root decay of the previous summer crop, the less pronounced increment of $K_{0\text{-MI}}$ under CF could be attributed to the pore clogging by the living roots of the cover crop, reducing the water flux during the fallow period (Bodner et al., 2008). Scanlan (2009) showed that K_0 decreases when the root system is relatively young, and increases when the roots senesce and begin to decay, creating water conducting porosity. It needs to be stressed that these results are from the first year of cover cropping management; then, the lack of significant difference between management systems could be related to the short duration of the experiment, together with the inherent high variability of K (h).

From the evaporation experiments, the unsaturated hydraulic conductivity showed similar trends (Fig. 3). Differences between management systems and sampling dates were observed both in the near-saturation region (data from mini-infiltration experiments) and in the range of evaporation method measurements. This is partially in disagreement with several previous reports which mention that the impact of management on water flow is greatest in the nearer saturation region (Imhoff et al., 2010; Schwen et al., 2011; Lozano et al., 2013; Kreiselmeier et al., 2020). Both BF and CF managements showed in MH higher values of K (h) at the dry region as compared with the previous dates (Fig. 3). Despite that the fitted K_0 showed the same trend than $K_{0\text{-MI}}$ values, the values were one or two orders of magnitude higher. Peters and Durner (2008) mentioned that the values and the shape of the conductivity function in the wet range must be interpreted carefully. In addition, discrepancies between K_0 and $K_{0\text{-MI}}$ could be related to the hysteric effects between methodologies; evaporation method is based on water desorption, while mini-infiltration is based on a wetting process. Durner (1994) mentioned that for heterogeneous soils with secondary pore systems the problem of K (h) measurements near saturation is further complicated by macropores, entrapped air and hysteresis effects. However, the addition of measurements representing the soil structural part, *i. e.* the near saturated range, is crucial for an adequate description of the hydraulic conductivity function (Weninger et al., 2018). In this sense the inclusion of K (h) obtained with the mini-infiltration experiments in the same soil cores could be a useful, rapid and inexpensive method in order to complement the evaporation experiment data (Soracco et al., 2019) and further studies should be focus in order to arrive to a satisfactory agreement between measured and estimated data.

From evaporation experiment data, it was observed under both management systems, an increment in the unsaturated hydraulic conductivity at the end of the crop cycle. This is in disagreement with a recent study which mentioned that K at values of h equals to -100 cm (pF 2), −316 cm (pF 2.5) and -1000 cm (pF 3) did not show differences during the crop cycle under NT management (Kreiselmeier et al., 2020). These results show that unsaturated hydraulic conductivity could be limited by pore clogging under CF management, since lower values of K at h equals to −316 cm were observed as compared with BF at the end of the crop cycle (Table 3). Bodner et al. (2014) found that fine roots use existing pore spaces to penetrate the soil, stabilizing the soil structure but reducing pore space. The values of Cw showed a similar trend as compared with $K_{0\text{-MI}}$. Again, the role of roots growth and decay is crucial for pore connectivity, showing that biological activity is a main driving factor for pore formation (Jirku et al., 2013; Villarreal et al., 2020). Imhoff et al. (2010) mentioned the importance of including a high proportion of graminaceous species of great root production into the crop rotation, to improve the connectivity and continuity of soil pore system. The temporal trends of Cw values showed that the intra-seasonal changes of soil pore system functioning are complex and depend on the growing crop and climatic conditions (Jirku et al., 2013), and cannot be easily extrapolated. Despite the lack of significant differences between management systems during the studied period, it should also be mentioned that, as was observed for $K_{0\text{-MI}}$, Cw showed a more continual increment during the studied period under CF (Cw increased by a factor of 9.2 and 1.5 between FP and MS, and MS and MH, respectively); on the other hand, under BF, Cw increased rapidly between FP and MS (increased by a factor of 11.6), followed by a tendency to decrease in MH. This behavior could be related to higher stability of pore structure under CF management. It has been reported that cover crops' roots exudates and mucilages stabilize soil structure over short-time periods (Naveed et al., 2017; Baumert et al., 2018). However, these results should be taken with care, due to the lack of significant difference between management systems, probably related to the short duration of the experiment, as was mention before.

Overall, our results show that the inclusion of cover crops into the crop sequence in the studied soil creates a secondary pore system at the end of the maize growing period. This behavior suggests partial pore clogging by the cover crop roots during their growing period (Bodner et al., 2008), increasing the soil structural porosity after the roots decay. In this sense, cover cropping could enhance the performance of NT management, improving in the short-term soil structure and its stabilization. It should be stressed that our results are site specific and were obtained from the first year of cover cropping management in the soil surface layer (0−5 cm). However, it is important to mention the lack of negative impact on soil structure and physical and hydraulic properties in the short-term, as was reported by other authors (Jensen et al., 2020), which could encourage the adoption of this management, especially in the Depressed Pampas Region. In this sense, it has been reported that the inclusion of short growing cover crops in the rotation should be considered as a precautionary measure for soil compaction (Bodner et al., 2014), which is one of the major negative impacts under NT (Li et al., 2020). Furthermore, our results highlight the importance of including the temporal variation of the soil hydraulic properties and pore structure formation during the inclusion of cover crops, including the unsaturated K. Under standard meteorological conditions, where preferential flow only plays a minor role and the macropore fraction is excluded, the determination of K (h) in drier conditions becomes essential (De Pue et al., 2019; Kreiselmeier et al., 2020). In addition, this kind of study could improve the modelling frameworks in order to predict the evolution of soil pore dynamics (Kreiselmeier et al., 2019).

5. Conclusions

The intensification of crop sequence through the cover crop introduction under NT increases a secondary pore system related to structural soil porosity during the first year. The increment of structural porosity enhances the unsaturated hydraulic conductivity and pore connectivity, especially at the end of the summer crop cycle. The results found in this paper highlight the importance of including cover crops into the crop rotation to improve the structural porosity and its connectivity. As well, the results show the necessity of including the short-term changes in the study of soil hydraulics properties. Further studies should analyze longer time series data in order to determine the intra-seasonal temporal dynamics of soil pore system functioning.

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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