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Effect of cover crops on hysteresis and anisotropy of soil hydraulic properties

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A B S T R A C T

No till is the main management system for soil conservation world-wide. In Argentina is frequently implemented in simplified crop sequences, which has negative effects on soil physical quality (SPQ). Among the suggested practices to preserve the physical fertility of soils under no till have been cited winter cover crops (CC). Generally, the estimation of pore distribution parameters and capacity SPQ indicators has been conducted from the relationship between water content (θ) and matric potential (h) obtained from desorption experiments. However, the water retention curve is considered as hysteretic. The objectives of this study were to incorporate the wetting curve (WWRC) to assess the impact of the incorporation of rye (*Secale cereale L.*) as CC on hydraulic properties in the first 10 cm of a Typic Hapludol and to analyze if the values are affected according to the sampling direction. The incorporation of CC increased the hysteretic behavior in the near and the medium saturation region. The sample direction did not affect significantly any capacity indicators, manifesting the isotropic character of the porosity. The inclusion of the WWRC analysis can give additional information when assessing the impact of different management on soil hydraulic properties.

1. Introduction

No till (NT) was proposed as an agricultural production system that allows a more efficient use of water (Friedrich et al., 2012; Palm et al., 2014). In Argentina >75% of cultivated area is managed under this system (AAPRESID, 2019). However, in the Pampean Region it is frequently implemented in simplified agricultural systems, which has negative effects on soil physical quality (SPQ), affecting the configuration of the soil pore system, in particular in the surface soil horizon (Alvarez et al., 2017; Behrends Kraemer et al., 2019; Fabrizzi et al., 2005; Lozano, 2014; Novelli et al., 2013; Sasal et al., 2006a). Among the suggested practices to preserve the physical fertility of soils under NT have been cited winter cover crops (CC). The inclusion of CC results in the generation of structural porosity, because it implies greater root activity and biological activity in the soil (Behrends Kraemer et al., 2017; Blanco-Canqui and Ruis, 2018; Domínguez and Bedano, 2016; Duval et al., 2016; Novelli et al., 2013; Villarreal et al., 2021). A better structured soil has a more suitable porous system for the development of plants and better hydraulic properties (Sasal et al., 2006b). Hydraulic properties of unsaturated soil usually refer to the features that are related to the soil water retention behavior (Gao et al., 2021). The soil water retention curve (SWRC), relating volumetric water content, θ $[L^3L^{-3}]$, to tension, h [L], provides an indirect method to estimate soil porosity. Capacity indicators can be obtained from this relationship, which can account indirectly for the ability of the soil to retain and/or transmit water and air (Reynolds et al., 2009).

Generally, the estimation of pore distribution parameters and capacity SPQ indicators has been conducted from θ(h) data obtained from desorption experiments. However, the water retention curve is considered as hysteretic. Depending on whether the soil is getting wet or dry, the θ(h) function will be different (Hillel, 1982). In field conditions hysteresis is neglected because its influence is often masked by heterogeneities and spatial variability (Haverkamp et al., 2002). However, several investigations concerning this subject show that this effect is

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significant (Bondí and Castellini, 2022; Rafraf et al., 2016; Witkowska-Walczak, 2006) and is favorable for vegetation as more water is retained in the root zone, as hysteresis retards soil water movement (van Dam et al., 1996). There are few reports about experimental approaches to obtain main wetting and drying curves, and the intermediate curves between the processes called scanning curves. In this sense, some authors estimated the wetting scanning curves from the main drying curves (Lamorski et al., 2017; Mualem, 1984; Zhai et al., 2020). Other authors obtained the wetting curve from disturbed samples by adding increasing volumes of water in separate samples and measuring the tension once they were in equilibrium (Brantley et al., 2015; Brye, 2003). Ball and Robertson (1994) obtained the drying and wetting curves on a tension table in the range of 0 to 1 m of h on undisturbed samples. Konyai et al. (2006) obtained the scanning wetting curve in the same range of h using the hanging column method on undisturbed soil samples. Kargas and Londra (2015) determined the main wetting curve using the Richards' pressure cell chamber. Hysteresis quantification has been studied from different approaches. Some authors calculated the θ differences along the entire curve of drying and wetting processes at the same h, and measured the area between the curves (Witkowska-Walczak, 2006). Another approach is to consider the maximum difference of volumetric soil water content between drying and wetting curves (Rafraf et al., 2016). It has been reported that wetting SWRC normally is not considered to determine SPQ (Bondí and Castellini, 2022). Moreover, the hysteretic behavior of SWRC has not been used to analyze the changes induced in soil pore configuration by different management systems such as CC.

In addition to the hysteresis phenomenon, some properties present anisotropy if they are direction-dependent, otherwise they would be considered as isotropic (Bear, 1972). Anisotropy is generally due to the structure of the soil, which may be laminar, or platy, or columnar, etc., thus exhibiting a pattern of micropores or macropores with a distinctly directional bias (Dörner and Horn, 2009; Hillel, 1982). It has been reported that physical deterioration can generate a change in the directionality of soil hydraulic properties (Beck-Broichsitter et al., 2020; Jing et al., 2008; Pulido-Moncada et al., 2021). Although porosity is considered a scalar property and therefore should not present differences according to the directionality of the sample (Dörner and Horn, 2006), when calculated from a dynamic method (water movement), the direction of sampling may influence its determination (Sasal et al., 2006b).

We hypothesized that (i) the incorporation of CC changes the hysteretic behavior of the SWRC in a Typic Hapludoll of the Pampas Region; (ii) the incorporation of CC changes the anisotropy of the hydraulic properties. In view of achieving a more representative analysis of the water dynamics the objectives of this study were to incorporate the wetting curve to assess the impact of CC on SPQ and hydraulic properties in a Typic Hapludoll and to analyze if the values are affected by the sampling direction.

2. Materials and methods

2.1. Site and treatments

The experiment was carried out near the town of General Villegas, Argentina (34°52′ south, 62°45′ west). The soil was classified as a Typic Hapludoll (Lincoln series) (Soil Survey Staff, 2014), with an 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. The A horizon particle size distribution is 22.4% silt, 14.3% clay, and 63.3% sand, corresponding to a sandy loam texture. The climate is temperate humid without a dry season, with a mean annual temperature of 16.2 °C and a mean annual rainfall of 929 mm.

A completely randomized experimental design was installed since year 2005 with two management systems. The treatments are: i-no tillage with bare fallow (BF); ii- no-tillage with cover fallow (CF) (rye (*Secale cereale L.*)). For both treatments, soybean (*Glycine* max L.) was sown as summer crop. Sampling campaign was carried out in 7th May 2021 after soybean harvest. Adjacent plots with the same relative position in the landscape (upper hillslope) from each treatment were selected. In each of these plots a homogeneous and representative 5 × 5 m area in the center of each treatment was selected, avoiding visible wheel tracks. Within this area, sites were selected randomly in order to carry out soil sampling. In each site three undisturbed samples were extracted in columns (8 cm height, 2.5 cm diameter, 39.3 cm^3 volume) for each direction (vertical or horizontal) and treatment in the first 10 cm of the A horizon. The total number of samples was 12.

2.2. Description of the set up and soil properties determination

2.2.1. Determination of partial drying water retention curve (DWRC)

Soil samples were saturated from the bottom during 48 h and then were placed horizontally on an analytical balance (±0.01 g), with one end sealed (left side) and the other face (right) open in order to allow a free evaporation process (Fig. 1). Two mini-tensiometers (T5 Tensiometer, METER Group, Inc. USA) were inserted at distance of 2 and 6 cm (from the left side) into the soil sample. The test was carried out under laboratory conditions (temperature ranged between 20 and 24 °C) and sample mass (m) and soil tension (h) were recorded at intervals of 5 min. The evaporation process occurred until reaching a tension value close to 10 m in the right tensiometer.

2.2.2. Determination of partial wetting water retention curve (WWRC)

After the drying process was complete the right face was sealed thus beginning a process of redistribution of the sample humidity. The balance continued to register to verify that there was no loss in the mass of the sample. The process continued until h values in both tensiometers equalized, taking 12 to 24 h depending on the sample. After this, the left side of the column was opened and a mini infiltrometer was connected, with a tension of 2 cm in order to generate a slow water flux (Fig. 1). Lateral water infiltration was determined using a mini-infiltrometer (Soracco et al., 2019). 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 attached to its end. This tube was connected to a water reservoir placed on an analytical balance (±0.001 g), connected to a computer. The increment of water from the sample was determined by the loss of water from the reservoir. In order to capture changes in tensions, the data recording interval was decreased to 2 min. The process ended once the sample was saturated, evidenced by h values close to 0 m in both tensiometers.

2.2.3. Capacity indicators

For the determination of the SWRC the following assumptions were made: The flow was assumed quasi-steady, which means that the flow and the hydraulic gradient were approximately constant during the evaluated time interval and the moisture along the column was linear for drying and wetting processes during the evaluated time interval (Schindler and Müller, 2006). Single points of the water-retention curve were calculated on the basis of the difference of water per volume (ΔV) of the sample at time i and were related to the mean tension, which was calculated as:

$$\bar{h}_i = \frac{h_1(t_i) + h_2(t_i) + h_1(t_{i+1}) + h_2(t_{i+1})}{4} \quad (1)$$

where h_1 is the tension in the tensiometer placed at 2 cm and h_2 is the tension in the tensiometer placed at 6 cm from the left side of the sample.

For drying and wetting processes, the values of θ at each h value ($\theta_i(h_i)$) were calculated following Eqs. 2 and 3, respectively:

$$\theta_i\left(\bar{h}_i\right) = \theta_s - \Delta\theta_i \quad (2)$$

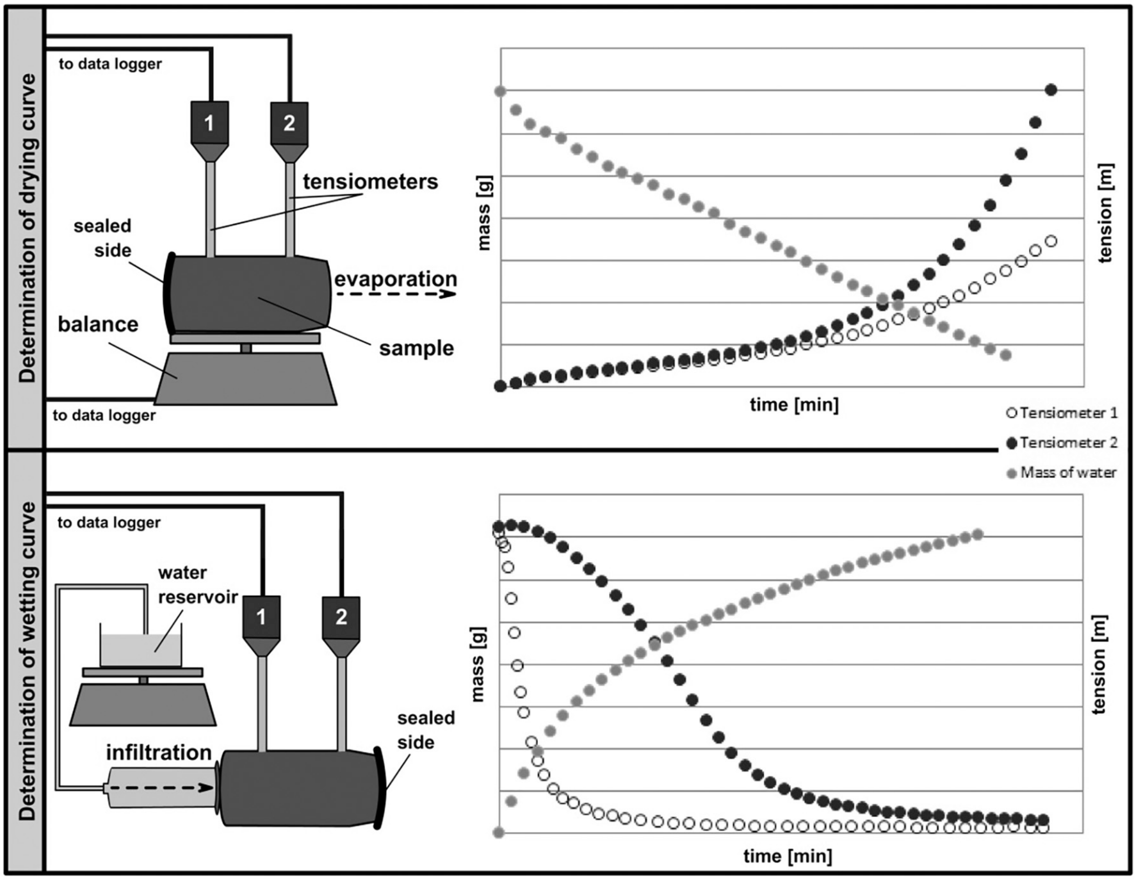

Fig. 1. Laboratory set up for the determination of drying and wetting soil water retention curve in a column of soil and their respective evolution of the measured parameters for a representative sample.

$$\theta_i\left(\bar{h}_i\right) = \theta_f + \Delta\theta_i \tag{3}$$

where θ_s is saturated volumetric water content corresponding to h = 0, and assumed to be equal to the calculated total porosities of the samples, θ_f is the final water content for the drying process, and $\Delta\theta_i$ is the change in water content calculated as:

$$\Delta\theta_i\left(\bar{h}_i\right) = \frac{\Delta V(h_i)}{2\,V_T} \tag{4}$$

where V_T is the total volume loss of water.

Water retention data of both processes were fitted separately to bimodal van Genuchten model (Durner, 1994). The observed points were obtained taking values of h at fixed intervals and its corresponding θ value, with a total of 27 observed points (Fig. 2):

$$\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \sum\nolimits_i^k w_i \left[\frac{1}{(1 + |\alpha_i h|\, n_i\,) m_i}\right] \tag{5}$$

where θ_r is the residual volumetric water content, 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 data fitting was carried out with RETC code

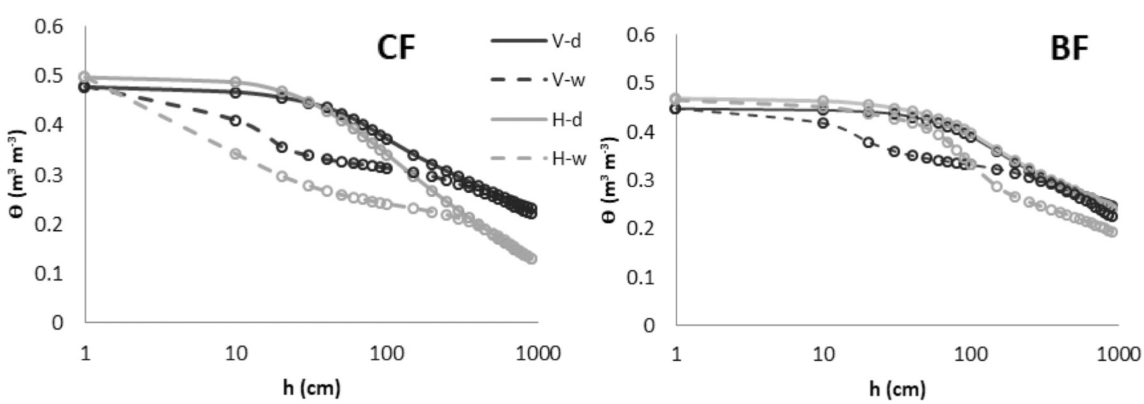

Fig. 2. Representative soil water retention curves under different management systems (No tillage with cover crop, CF; No tillage with bare fallow, BF), in both sampling directions (vertical, V; horizontal, H), in two directions of SWRC (drying, d; wetting, w). The lines correspond to the fitted curve and the circles to the observed fixed points.

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. There are different approaches to analyze and compare SWRCs, such as the comparison of adjustment parameters. In this work, indicators obtained from specific points of the SWRC were calculated. Macroporosity (P_{MAC}, $m^3\ m^{-3}$), air capacity (AC, $m^3\ m^{-3}$), plant available water content (PAWC, $m^3\ m^{-3}$) and relative field capacity (RFC) indicators were calculated according to Reynolds et al. (2009) for each process.

$$P_{MAC} = \theta_S(h = 0\ m) - \theta_m(h = 0.1\ m) \tag{6}$$

where θ_m ($m^3\ m^{-3}$) is the saturated volumetric water content of the soil matrix.

$$AC = \theta_S(h = 0\ m) - \theta_{FC}(h = 1\ m) \tag{7}$$

where θ_{FC} ($m^3\ m^{-3}$) is the field capacity water content.

$$PAWC = \theta_{FC}(h = 1\ m) - \theta_{PWP}(h = 150\ m) \tag{8}$$

where θ_{PWP} ($m^3\ m^{-3}$) is the permanent wilting point water content. The values of θ at h = 150 m for both processes were obtained from fitted data using the van Genuchten model.

$$RFC = \left(\frac{\theta_{FC}}{\theta_S}\right) = \left[1 - \left(\frac{AC}{\theta_S}\right)\right] \tag{9}$$

2.2.4. Hysteresis

The degree of the hysteresis value (H) can be defined as the ratio between the maximum difference in volumetric water content between wetting and drying curve and the difference between θ_s and θ_r (Rafraf et al., 2016), written in an equation form as:

$$H = \frac{\Delta\theta_{max}}{\theta_s - \theta_r} \tag{10}$$

2.3. Statistical analysis

Paired *t*-test at fixed intervals of h was performed in order to detect differences between DWRC and WWRC. Two-way ANOVAs, with two factors were performed for each process (drying; wetting) separately in order to determine main and interaction effects on AC, Pmac, PAWC, and RFC. The analyzed factors were: soil *treatment* with two levels (CF; BF) and *sampling direction* with two levels (vertical, V; horizontal, H). The standard deviation was calculated for all parameters. Fisher's least significant difference (LSD) test (Sokal and Rohlf, 1995) was used to compare the mean values. For all analyses the significance was determined at $P = 0.05$ and $P = 0.10$. The statistical analyses were performed using InfoStat software (Di Rienzo et al., 2008).

For evaluating the performance of the fitted bimodal van Genuchten model, the root mean square error (RMSE) was used, giving the mean deviation between the fitted and observed data:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{fit} - x_{obs}\right)^2} \tag{11}$$

where x_{fit} are fitted and x_{obs} observed values of θ.

3. Results and discussion

3.1. Hysteretic behavior of SWRCs

The van Genuchten model adequately fitted the water retention data as detected by the low RMSE values (1.2×10^{-3} for drying curves and 5.0×10^{-3} for wetting curves). From the analysis of the t-test for paired samples at fixed intervals of *h*, it was found that DWRC and WWRC exhibited a typical hysteretic behavior. For CF treatment the values of θ at a given *h* were higher for DWRC in the range of 0 m to 1.5 m of h with a maximum $\Delta\theta = 0.14\ m^3m^{-3}$ at h = 0.3 m. For BF treatment the values of θ were higher for DWRC in the range of 0.1 m to 1 m of h with a maximum $\Delta\theta = 0.06\ m^3m^{-3}$ at h = 0.50 m. The two soil water retention curves provided different information and, consequently, the estimation of the SPQ indicators differed too. The capacity indicators P_{MAC} and AC calculated from the WWRC were higher than those calculated from the DWRC (Table 2). These indicators cover the range of 0 to 1 m of h of the curves. For RFC the value of DWRC was higher than WWRC. For PAWC, covering the range of 1 m to 150 m, there were no differences between drying and wetting curves. From the analysis of the fixed points of h and the capacity indicators, it could be said that the hysteresis behavior was observed from saturation to ≈ 1 m of h, corresponding to the macro and mesoporosity.

These results agree with the reports that the hysteresis phenomenon is not negligible and should be considered (Bondí and Castellini, 2022; Rafraf et al., 2016; Witkowska-Walczak, 2006). Kargas and Londra (2015) also found greater differences between drying and wetting curves in the same range of tensions (0.2 m to 1.50 m) in a loamy soil under NT. The values of maximum difference of θ between the curves are similar to those reported in other works (≈0.15 m^3m^{-3}) (Bondí and Castellini, 2022; Witkowska-Walczak, 2006). The soil hysteretic effect could be the result of distinct phenomena: (i) irregularities in the cross-sections of the void passages or the "ink-bottle" effect; (ii) the contact angle being greater in an advancing meniscus than in a receding meniscus; (iii) entrapped air, which has a different volume when the soil suction is increasing or decreasing; (iv) swelling and shrinkage of the soil (Pham

Table 1
Mean values of the fitting parameters of bimodal van Genuchten model to 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 ($w_1 = 1 - w_2$) for the two treatments (No tillage with cover crop, CF; No tillage with bare fallow, BF) and the two sampling directions (Vertical, V; Horizontal, H) for both processes (drying; wetting).

	Treatment	Sampling direction	θ_s	α_1	n_1	α_2	n_2	w_2
			$m^3\ m^{-3}$	cm^{-1}	–	cm^{-1}	–	–
Drying	CF	V	0.48	0.021	1.27	0.012	2.73	0.26
		H	0.50	0.010	2.01	0.022	2.23	0.39
	BF	V	0.45	0.012	1.20	0.009	2.67	0.21
		H	0.48	0.022	1.20	0.010	4.03	0.14

	Treatment	Sampling direction	θ_s	α_1	n_1	α_2	n_2	w_2
			$m^3\ m^{-3}$	cm^{-1}	–	cm^{-1}	–	–
Wetting	CF	V	0.48	0.002	1.47	0.151	2.83	0.33
		H	0.52	0.002	2.39	0.332	1.72	0.59
	BF	V	0.45	0.002	1.61	0.096	2.64	0.24
		H	0.48	0.002	1.52	0.082	2.54	0.38

Table 2
Mean values (± standard deviation, $n = 3$) of macroporosity (P_{MAC}), air capacity (AC), plant available water content (PAWC) and relative field capacity (RFC) for the treatments (No tillage with cover crop, CF; No tillage with bare fallow, BF) and the two sampling directions (Vertical, V; Horizontal, H) for both processes (drying; wetting). Lowercase letter indicates significant differences among treatments; (LSD, P < 0.05).

–	–	–	P_{MAC} ($m^3\ m^{-3}$)	AC ($m^3\ m^{-3}$)	PAWC ($m^3\ m^{-3}$)	RFC –
Drying	CF	V	0.010 ± 0.015	0.11 ± 0.08	0.26 ± 0.08	0.78 ± 0.17
		H	0.010 ± 0.002	0.16 ± 0.05	0.30 ± 0.04	0.68 ± 0.10
	BF	V	0.003 ± 0.002	0.06 ± 0.01	0.24 ± 0.06	0.87 ± 0.01
		H	0.006 ± 0.002	0.08 ± 0.02	0.25 ± 0.04	0.84 ± 0.04

–	–	–	P_{MAC} ($m^3\ m^{-3}$)		AC ($m^3\ m^{-3}$)		PAWC ($m^3\ m^{-3}$)	RFC –	
Wetting	CF	V	0.069 ± 0.020	b	0.17 ± 0.07	b	0.24 ± 0.01	0.66 ± 0.13	a
		H	0.156 ± 0.072		0.26 ± 0.06		0.23 ± 0.06	0.48 ± 0.14	
	BF	V	0.031 ± 0.007	a	0.12 ± 0.05	a	0.27 ± 0.04	0.74 ± 0.09	b
		H	0.027 ± 0.026		0.13 ± 0.03		0.29 ± 0.03	0.73 ± 0.07	

et al., 2005; Zhai et al., 2020). In this work the latter cause could be neglected because shrinkage or swelling was not visible during drying or wetting processes, respectively. The lack of differences found between the curves at h > 1 m could be attributed to the fact that the WWRC represents a scanning curve, that is, an intermediate curve that was obtained starting from the last point of the DWRC. This point corresponded to h = 9 m which was the highest tension that could be achieved with the measure method.

3.2. Effect of CC on hysteresis

When analyzing the hysteresis indicator H in the studied tension range (0 to 9 m), CF treatment showed higher values of H than BF treatment ($p < 0.10$) (Table 3). From the two-way ANOVA we can conclude that in drying process, the *treatment* did not affect any indicator. However, in the wetting process P_{MAC} and AC were affected by *treatment*. For wetting process P_{MAC} under CF treatment was significantly higher than under BF treatment. Furthermore, CF treatment showed values of AC significantly higher than BF treatment ($p < 0.05$). As stated above, the hysteretic behavior was observed in the range of h values from 0 to 1 m, and was greater in the CF treatment. Then, it is expectable to find differences between treatments for these indicators since they cover this range. PAWC indicator, covering the range of 1 m to 150 m was not affected by *treatment.*

Our results for P_{MAC} and AC are in agreement with Bondí and Castellini (2022) who reported that these capacity indicators calculated from the WWRC were generally higher than those calculated from the DWRC, concluding that the use of the WWRC in spite of the DWRC yielded larger estimates of SPQ indicators related to soil aeration. These results reflect the fact that depending on the branch of SWRC that is being analyzed, different conclusions can be reached for the same soil management. Although infiltration into the soil occurs in a relatively short period of time, compared to the drying process, the soil is constantly oscillating between drying and wetting processes. The well-known “ink bottle” cause of the hysteresis is that on wetting processes the larger pores control the water movement while on draining processes the smaller pores control the flow (Konyai et al., 2006). Bondí and Castellini (2022) reported that additional information can be obtained if sorption data is considered. Therefore, it could be proposed that to indicate the value of a certain indicator, a maximum value (from WWRC) and a minimum value (from DWRC) could be given.

Table 3
Mean values of Hysteresis indicator (H) for the two treatments (No tillage with cover crop, CF; No tillage with bare fallow, BF) and the two sampling directions (Vertical, V; Horizontal, H). Lowercase letter indicates significant differences (LSD, P < 0.05); uppercase letter indicates significant differences (LSD, P < 0.10).

Treatment	Sampling direction	H		
CF	V	0.23	a	B
	H	0.35	a	B
BF	V	0.18	a	A
	H	0.19	a	A

There is a lack of reports about the impact of soil management systems on the water retention hysteresis (Bondí and Castellini, 2022) and even less about the effect of the incorporation of CC. It has been reported that CC generate porosity improving soil structure (Behrends Kraemer et al., 2019; Celette et al., 2008; Sastre et al., 2018; Villamil et al., 2006; Villarreal et al., 2021). Bacq-Labreuil et al. (2019) reported that the effect of CC on soil structure and porosity varies significantly with root morphology and architecture of the CC plant. Our results are in agreement with Villamil et al. (2006) who reported a significant increase in the volume of macropores when a rye CC was included in the rotation. The inclusion of CC also increases soil organic content which can cause a higher content of water retained, which may be related to the high water absorption capacity, the presence of hydrophilic compounds and the effect of organic matter on the structure (Lal, 2020). In a previous report at the same experimental plot a higher content of organic matter was observed for the treatment with CC (Salazar et al., 2022).

3.3. Effect of CC on anisotropy

From the two-way ANOVA test for each process, the *sample direction* did not affect significantly any capacity indicators, manifesting the isotropic character of the porosity (Dörner and Horn, 2006). Our results are in agreement with Pulido-Moncada et al. (2021) who reported an isotropic behavior of the air-filled porosity (at 100 cm of h) studying the effects of CC in a sandy loam soil.

4. Conclusions

The inclusion of winter cover crop under no-tillage in an Hapludoll of the Argentinean Pampas region modifies the soil pore configuration increasing the structure porosity and impacts the hysteretic behavior in the near and the medium saturation region. The incorporation of the CC does not change the anisotropy of the pore size distribution, which behaves as isotropic as expected for a scalar variable. The inclusion of the WWRC analysis can give additional information when assessing the impact of different management on soil hydraulic properties. In this sense the proposed laboratory setup allows to determine the DWRC and WWRC in a simple way. However further studies should analyze different soil types and managements and its extension to the dry range.

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Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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