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Influence of wetting process on the estimation of water retention curve of tilled soils

D. Moret-Fernández *, C. Peña-Sancho, M.V. López

Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), PO Box 202, 50080 Zaragoza, Spain

* Corresponding author.

Telf: +34 976 716140

Fax: +34 976 716145

E-mail address: david@eead.csic.es

Abstract

Correct estimations of the soil water retention curve (WRC) is of paramount importance to characterize the hydraulic behaviour of soils. This paper studies the influence of two different soil wetting processes (waterlogged soil, WP, and capillary rise to saturation, CRP) on the estimate of the WRC. The two procedures were applied on undisturbed loam soil samples with three different degrees of soil structure: (i) consolidated soils under conventional tillage (CT), reduced tillage (RT) and no tillage (NT), (ii) freshly tilled soil under CT and RT, and (iii) CT and RT after secondary tillage plus some intense rainfalls events. The WRCs were estimated with TDR-pressure cells and the volumetric water content was measured at saturation conditions (for the WP method) and at pressure heads of 0.5, 1.5, 3, 5, 10, 50, 100, 500, and 1500 kPa. The same cores were used to determine the soil bulk density (ρ_b), which was subsequently used to estimate the saturated water content under CRP. The ρ_b value of the consolidated soil under NT was significantly higher ($p < 0.001$) than that measured in CT and RT. No effect of the wetting process on the WRC of consolidated soils was observed. Only the freshly tilled soil samples under RT were significantly affected by the wetting process. In these cases, the water draining after flooding the soil (WP) collapsed the more unstable soil macropores and increased the volume of the smaller ones. This effect however was minimized by the CRP method, which prevented the collapse of the more unstable soil pores. This work demonstrates that the soil wetting process may have an important effect on the characterization of the water holding capacity on freshly tilled soils.

Key words: Conventional tillage; Reduced tillage; No tillage; Pressure cell; Undisturbed soil samples

1. Introduction

The soil water retention curve (WRC), which is defined as the relationship between the matric potential (ψ) and soil volumetric water content (θ), is essential to characterize the hydraulic and mechanical behaviour of unsaturated soils. This property is dependent upon the particle-size distribution, which determines the soil texture, and the arrangement of the solid particles, which refers to the soil structure (Dane and Hopmans, 2002). Tillage systems have a significant influence on WRC. Under well-structured soil conditions, soils under no-tillage present WRCs with a more gradual reduction in water content as tension increases, and lower water content close to saturation (Evett et al., 1999; Schwartz et al., 2003). Loosening of the soil surface by tillage increases the total soil porosity (Green et al., 2003; Moret and Arrúe, 2007; Strudley et al., 2008; da Veiga et al., 2008) through both an increase in the pore volume at the wet end of the soil water retention curve (Ahuja et al, 1998) and a decrease in the pore fractions corresponding to more negative pressure heads (Mapa et al., 1986; Schwärzel, 2011). However, the rainfall impact on the freshly tilled soils and the associated wetting and drying cycles modify again the WRC shape, which tends to reduce the volume of the largest pores and keep constant and sometimes even increase the frequency of smallest ones (Rousseva et al., 2002).

The standard laboratory apparatus used to measure WRCs is the pressure extractor. A pressure plate extractor referred to as a “Tempe cell” is commonly used for pressure heads up to 100 kPa. For higher pressure heads (typically 1500 kPa) more robust pressure cells are employed (Wand and Benson, 2004). Depending on the dimensions of the pressure plate extractor, disturbed or intact soil samples can be used. Soil samples are commonly wetted by the base until the matrix of the soil is waterlogged. The soil volumetric water content at a given pressure head is calculated from the gravimetric water content and the dry bulk density (Dane and Hopmans, 2002). The θ can also be estimated by alternative methods like TDR, which characteristics provide a flexible means of measuring θ at multiple locations without requiring soil-specific calibration in many cases (Wraith and Or, 2001; Jones et al., 2005; Moret-Fernández et al., 2008; Moret-Fernández et al., 2012)

In spite of the numerous studies available in the literature to characterize the WRC on undisturbed well-structured soils samples, data of WRC measured on freshly tilled soils, or information about the influence of the soil wetting process on the WRC are nonexistent. For instance, Moret-Fernández et al. (2008) studied the effect of the soil wetting rate on the WRC of a soil sample with 2-4-mm size aggregates, and found that fast wetting processes result in disintegration of aggregates and drastic changes in the WRC shape. The objective of this work is to study the influence of the soil wetting process on the WRC estimation on soil samples with different structure. Two wetting processes, waterlogged soil and capillary rise at 0 cm of pressure head, were applied on undisturbed soil samples collected from three different tillage systems (conventional tillage, CT, reduced tillage, RT and no tillage, NT) before and after tillage operations.

2. Material and methods

The soil samples were taken from a dryland research farm located at the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (latitude 418440N; longitude 08460W; altitude 270 m). The climate is semiarid with an average annual precipitation of 390 mm and an average annual air temperature of 14.5 ºC. Soil at the research site is a loam (fine-loamy, mixed thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Particle size distribution for the plough layer (0–40 cm) averages 25% clay, 47% silt and 28% sand. Selected physical and chemical properties of the soil for this layer were given in Blanco-Moure et al. (2012). The experimental plots, which were set up on a nearly level area (slope 0–2%) of land in 1992, were in winter barley (Hordeum vulgare L.)-fallow rotation. The study was conducted when the field was in the long-fallow phase of this rotation, which extends from harvest (June–July) to sowing

(November–December) of the following year. The soil samplings were taken during the 2013-2014 fallow season.

Three different fallow management treatments were compared: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of mouldboard ploughing of fallow plots to a depth of 30–40 cm in late winter or early spring, followed by secondary tillage with a sweep cultivator to a depth of 10–15 cm in late spring. In RT, primary tillage was chisel ploughing to a depth of 25–30 cm (non-inverting action), followed by a pass of the sweep cultivator in late spring. NT used exclusively herbicides (glyphosate) for weed control throughout the fallow season. The tillage treatments were arranged in a complete block design, with three replications per treatment. The size of the basic plot was 33.5 m x 10 m, with a separation of 1 m between plots. Two sampling sites existed in each plot. With this sampling scheme, a total of 18 measurements (6 per treatment) were made. Three sampling dates were selected: (i) before primary tillage on consolidated soil (CT, RT, NT) (S_1), after 15 months without soil alteration, (ii) just after primary tillage on freshly tilled soil (CT, RT) (S_2), and (iii) after secondary tillage plus a post-tillage cumulative rainfall of 53 mm (CT, RT) (S_3). Due to the soil properties under NT does not change along a fallow period (Moret and Arrue, 2007), only one NT-sample has been included in this study.

Soil samples were taken from the 1-10 cm depth soil layer. Two soil cores (50 mm diameter and 50 mm height) were taken per sampling site, one for the WP and the other one for the CRP method. The same cores were used to estimate the soil bulk density, ρ_b, (Grossman and Reinsch, 2002) and the WRC. The soil cores were air dried in laboratory during several weeks, and the WRC were measured with TDR-pressure cells (Moret-Fernández et al., 2012). Two soil wetting processes were considered:

(i) Waterlogged soil (WP), in which the soil cylinder was wetted by the bottom at positive pressure heads until the water starts to flow by the top of the cylinder. To prevent a fast soil wetting, a 0.5 bars ceramic disc was placed on the base of the TDR-cell.

(ii) Soil water capillary rise at 0 cm of pressure head (CRP) at the cylinder base. In this case, the soil cylinder was placed on a saturated ceramic disc which, connected to a water reservoir, allowed the soil was slowly wetted by capillarity rise. This process lasted about 24 h, and finished when no more water was taken by the soil.

The volumetric water content (θ) was measured by TDR at saturation conditions (for WP) and at pressure heads (h) of 0.5, 1.5, 3, 5, 10, 50, 100, 500, and 1500 kPa. Once finished the last tension, the soil cores were dried at 105ºC for 24 h, weighted, and the ρ_b calculated. The WRCs and the corresponding effective saturation curves, S_e, were fitted to the Durner (1994) bimodal function using the SWRC Fit Version 1.2. software (Seki, 2007) (http://seki.webmasters.gr.jp/swrc/), according to

$$S_e = \frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}} = w\left[\frac{1}{1+(\alpha_1\psi)^{n_1}}\right]^{m_1} + (1-w)\left[\frac{1}{1+(\alpha_2\psi)^{n_2}}\right]^{m_2} \qquad (1)$$

$$0 < w < 1$$

$$\sum w_i = 1$$

$$\alpha_i > 0; m_i > 0; n_i > 0$$

where ψ is the soil matric potential (ψ = -h), n_i is the pore-size distribution parameter, $m_i = 1 - \frac{1}{n_i}$, α_i is the scale factor, θ_{sat} and θ_{res} are the saturated and residual volumetric water content, respectively, and w is a weighting factor for the subcurves. The θ_{res} was automatically calculated by the SWRC Fit from the pair of ψ-θ values measured by the TDR-pressure cells. The θ_{sat} used in the CRP method corresponded to the soil total porosity, ϕ, calculated according to

$$\phi = \left[1 - \left(\frac{\rho_b}{\rho_p}\right)\right]100 \qquad (2)$$

where ρ_p is the particle bulk densities. The average ρ_p measured in laboratory for the three treatments was 2.60 g cm^{-3}. In WP, the θ_{sat} was calculated as the average between ϕ and the water content at saturation measured by TDR. The first summatory of Eq.(1) was assigned to the soil macropores ($0 < \psi < -0.5$ kPa). Because not data was available within this range of soil tensions, no consistent statistical analysis was possible. In this case, the estimated α_1 and n_1 were taken as merely indicative data. Thus, the statistical analysis was limitated to the θ_{sat}, θ_{res}, α_2 and n_2.

The WRC can be also analyzed by the equivalent pore-size density, C^*, expressed as (Durner, 1994)

$$C^* = \frac{dS_e}{d\psi} \tag{3}$$

Although C* does not provide direct information about the porosity, it gives a measure of the relative abundance of pore size (Or et al., 2000).

The effect of wetting process on the soil water content was evaluated within each suction head, tillage treatment and sampling date by an one-way analysis of variance (ANOVA). This analysis was also used to compare the effect of wetting process on the θ_{sat}, θ_{res}, α_2 and n_2. When tillage treatment was evaluated, statistical comparisons were made using analysis of variance (ANOVA) for the randomized complete block design with three replicates per treatment. All statistical analysis were performed with the R software (V. 3.1.1; copyright © 2014 The R Foundation for Statistical Computing).

3. Results and discussion

The ρ_b for consolidated soils under NT was significantly higher ($p < 0.001$) than under CT and RT (Fig. 1). After 15 months without soil alteration (S_1), no significant differences between CT and RT were observed. The influence of the tillage operation (S_2) was more pronounced in RT, where ρ_b was significantly lower ($p < 0.001$) than that measured under CT (Fig. 1). This effect, however, was transient, since ρ_b tended to recover its initial value after a copious rainfall period (S_3). Similar results were obtained by Moret and Arrúe (2007), Strudley et al. (2008) and da Veiga et al. (2008), among others. While no significant effect of the sampling date on ρ_b was observed in CT, the ρ_b in S_2 under RT was significant lower that that measured in S_3 (Fig. 1). No significant differences ($p < 0.05$) between the ρ_b taken for WP and CRP were observed.

Except for NT, where the van Genuchten (1980) (Eq. 1 for $w = 0$) model yielded satisfactory fit, CT and RT treatments required a bimodal WRC function (Fig. 2). These results indicate that a marked double porosity system, with macro- ($\psi < -0.5$ kPa) and meso- plus micropores ($\psi > -0.5$ kPa), was found in the tilled systems. According to Clothier and White (1981), soil macropores are defined as those pores that drain at $\psi > -0.4$ kPa. The absence of double porosity in NT can related to the higher soil compaction under this treatment (Fig. 1), that reduces the volume of soil pores at near saturation conditions (Schwartz, et al. 2003; da Veiga et al., 2008). Under these conditions, NT showed the smallest α values (Table 1), which should be also related to a higher soil compaction (Fig .1) (Schwartz et al., 2003; Calonego et al., 2011).

No significant effect of the wetting process on WRC (Fig. 2) and the corresponding the θ_{sat}, θ_{res}, α_2 and n_2 parameters (Table 1) were observed for all tillage treatments on the consolidated soils samples (S_1 and S_3 samplings). Analysis of C^* (Eq. 3) (Fig. 3) show differences between CRP and WP for soil suctions < -0.5 kPa, however the lack of data between 0 and -0.5 kPa makes that these differences are merely indicative. A different behaiviour was observed on the freshly tilled soils samples (S_2) under RT, where the wetting process showed a significant influence ($p < 0.05$) on the WRC curves (Fig. 2) and the Durner (1994) parameters (Table 1). In this case, the α_2 and n_2 under CRP was significantly higher and lower, respectively, than the corresponding values estimated with WP. The main differences were contained between 0 and -10 kPa of soil tensions (Fig. 3), which corresponds to the structural soil component ($\psi > -100$ kPa). As observed by Rousseva et al. (2002), these results should be attributed to the drainage effect after flooding the soil, which collapses the more unstable macropores (ψ < -0.5 kPa) and keeps constant and sometimes even increases the frequency of smallest ones (ψ > -0.5 kPa) (Fig.3). This problem, however, vanished under CRP where the soil wetted by capillary rise allows keeping almost intact the most unstable pores. For CT, however, the influence of the wetting process was not as pronounced as in RT. In this case, no statistical differences in the WRC parameters on the freshly tilled soils were found between both soil wetting processes (Table 1.). This different behaviour between CT and RT may be related to the soil structure created by tillage. The cutting action of chisel plough (RT) produces channels and cracks between soil aggregates, creating a porosity consisting of inter-connected packing voids with large equivalent diameters (Kribaa et al., 2001; Leão et al., 2014), which results in a significantly lower ρ_b (Fig. 1) However, this favorable macroporosity for water and air movement with non-inverting tillage seems to be short-lived due to fast soil reconsolidation (Busscher et al., 1995; Xu and Mermoud, 2001). This may reflect a more unstable macroporosity and explain the higher effect of the wetting method under RT (Figs. 2 and 3). The copious rainfall events recorded before the S_3 sampling (53 mm) consolidated the structure of the freshly tilled soil, which prevented the pore collapse during the wetting-drying process.

4.- Conclusions

This paper compares the influence of two different soil wetting processes (waterlogged soil, WP, and capillary rise to saturation, CRP) on the estimation of the water retention curve (WRC) of undisturbed soil samples with different structure: consolidated soil samples from three different tillage systems (conventional tillage, CT, reduced tillage, RT and no tillage, NT), and freshly tilled and tillage plus some intense rainfalls (CT and RT) soil samples. Only the freshly tilled soil samples were affected by wetting process. In these cases, the water draining after flooding the soil tended to collapses the more unstable soil macrostructure and increases the volume of the smaller ones. This effect however was minimized with CRP method, which prevents the collapse of the more unstable soil pores. Thus, this work demonstrates that the soil wetting process can have an important effect on the characterization of the water holding capacity on freshly tilled soils.

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Figure captions

Figure 1. Average soil bulk density (ρ_b) measured at the different sampling dates (S_1, S_2, S_3; see text for details) and tillage managements (conventional tillage, CT, reduced tillage, RT and no tillage, NT). Different lowercase letters indicate significant differences among tillage treatments within the same sampling date ($p < 0.05$). Different uppercase letters indicate significant differences among sampling dates for a same tillage treatment ($p < 0.05$). Vertical bar within each column denotes the standard deviation.

Figure 2. Average measured (exp) and modelled (mod) (Eq. 1) water retention curves estimated at the different sampling dates (S_1, S_2, S_3; see text for details) and tillage managements (conventional tillage, CT, reduced tillage, RT and no tillage, NT), wetted by waterlogged (WP) and capillary rise to saturation (CRP) processes. Vertical lines and '***', '**' and '*' indicate the standard deviation and significant differences within each suction head at $p < 0.001$, 0.01 and 0.05, respectively.

Figure 3. Equivalent pore-size density (C*) simulated from the water retention parameters of Table 1 at the different sampling dates (S_1, S_2, S_3; see text for details) and tillage managements (conventional tillage, CT, reduced tillage, RT and no tillage, NT) wetted by waterlogged (WP) and capillary rise to saturation (CRP) processes. Vertical dash-dot line denotes the 0.5 kPa soil tension threshold.

Table 1. Values for the parameters of the bimodal water retention curves (Eq. 1) estimated for the different samplings dates (S_1, S_2 and S_3; see text for details), soils tillage treatments (conventional tillage, CT, reduced tillage, RT and no tillage, NT) and soil wetting processes (soil water flooding, WP, and soil water capillarity rise, CRP), and coefficient of determination (R^2) for the best fit between the averaged measured and modeled water retention curves. Pair of WP and CRP values with different letter indicates significant differences between soil wetting processes at $p < 0.05$.

			θ_{sat}	θ_{res}	w	α_1 (kPa^{-1})	n_1	α_2 (kPa^{-1})	n_2	R^2
		WP	0.50 **a**	0.26 **a**	0.08	43.65	23.49	0.41 **a**	1.56 **a**	0.99
S_1	CT	CRP	0.48 **a**	0.29 **a**	0.24	12.32	31.83	0.56 **a**	1.82 **a**	0.99
		WP	0.51 **a**	0.27 **a**	0.14	2.21	14.41	0.42 **a**	1.58 **a**	0.99
	RT	CRP	0.52 **a**	0.25 **a**	0.29	8.60	12.26	0.49 **a**	1.75 **a**	0.99
		WP	0.46 **a**	0.33 **a**	-	-	-	0.32 **a**	1.64 **a**	0.99
	NT	CRP	0.45 **a**	0.28 **a**	-	-	-	0.38 **a**	2.18 **a**	0.99
		WP	0.52 **a**	0.27 **a**	0.09	230.05	17.16	0.28 **a**	1.86 **a**	0.99
S_2	CT	CRP	0.49 **a**	0.28 **a**	0.27	54.56	2.10	0.20 **a**	1.68 **a**	0.97
		WP	0.51 **b**	0.27 **a**	0.08	5.99	2.92	0.89 **a**	1.55 **b**	0.99
	RT	CRP	0.55 **a**	0.24 **b**	0.53	29.52	2.42	0.29 **b**	1.92 **a**	0.98
		WP	0.48 **a**	0.26 **a**	0.08	4.61	19.92	0.35 **a**	1.70 **a**	0.99
S_3	CT	CRP	0.47 **a**	0.29 **a**	0.19	17.78	16.63	0.29 **a**	1.90 **a**	0.99
		WP	0.50 **a**	0.29 **a**	0.02	7.55	9.64	0.36 **a**	1.97 **a**	0.99
	RT	CRP	0.50 **a**	0.25 **a**	0.36	19.40	17.82	0.22 **a**	1.59 **a**	0.98

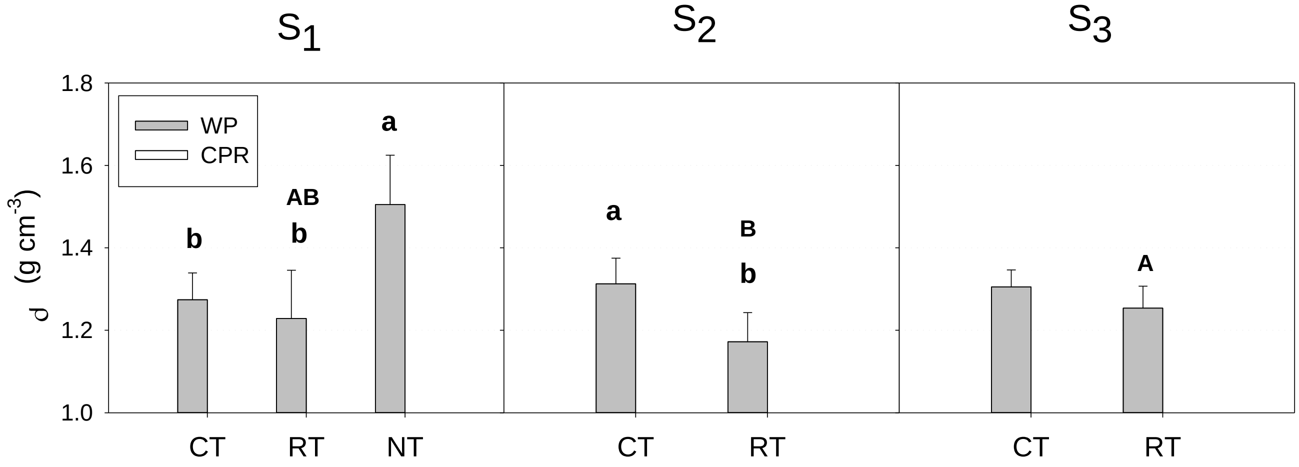

Figure 1.

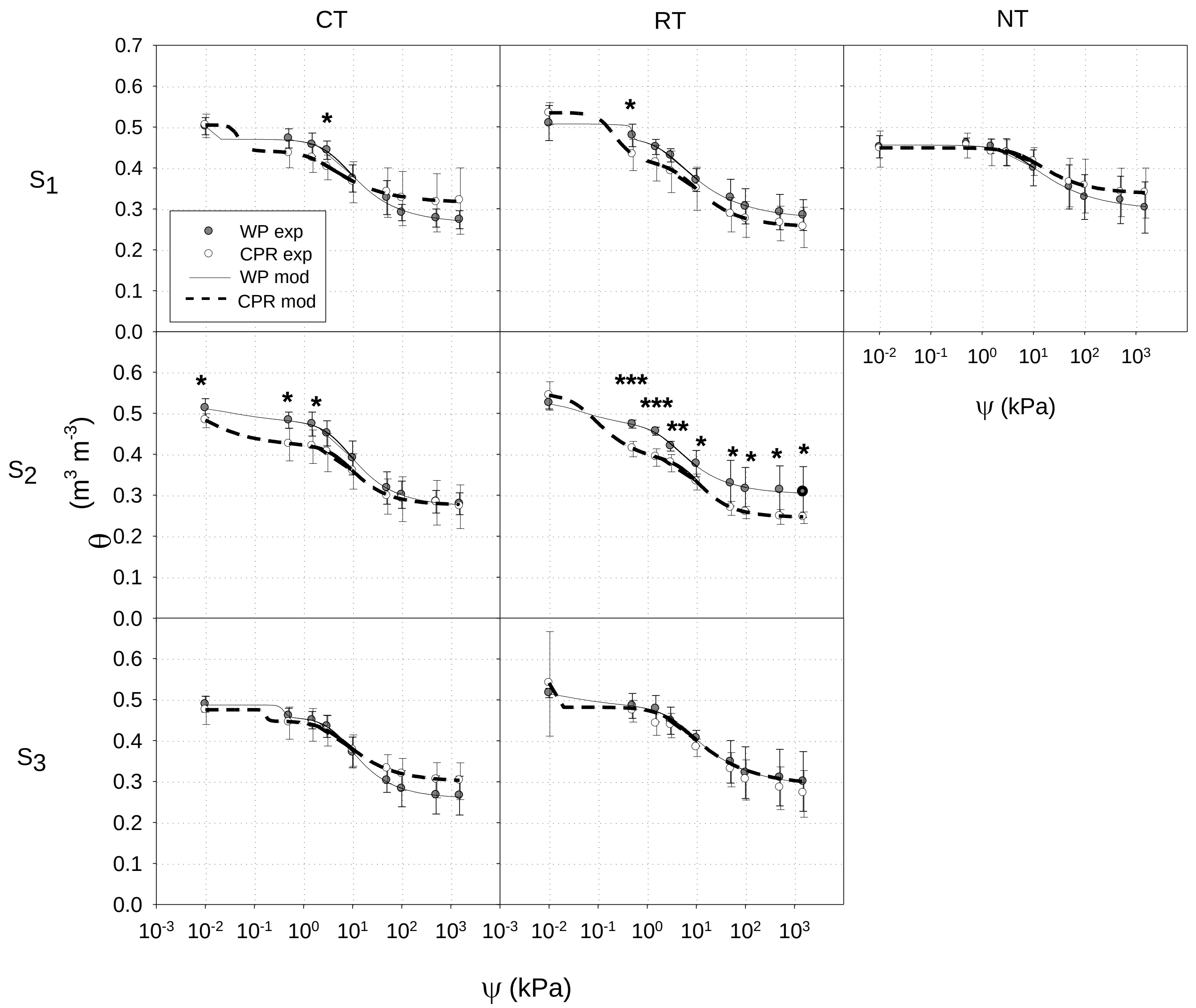

Figure 2.

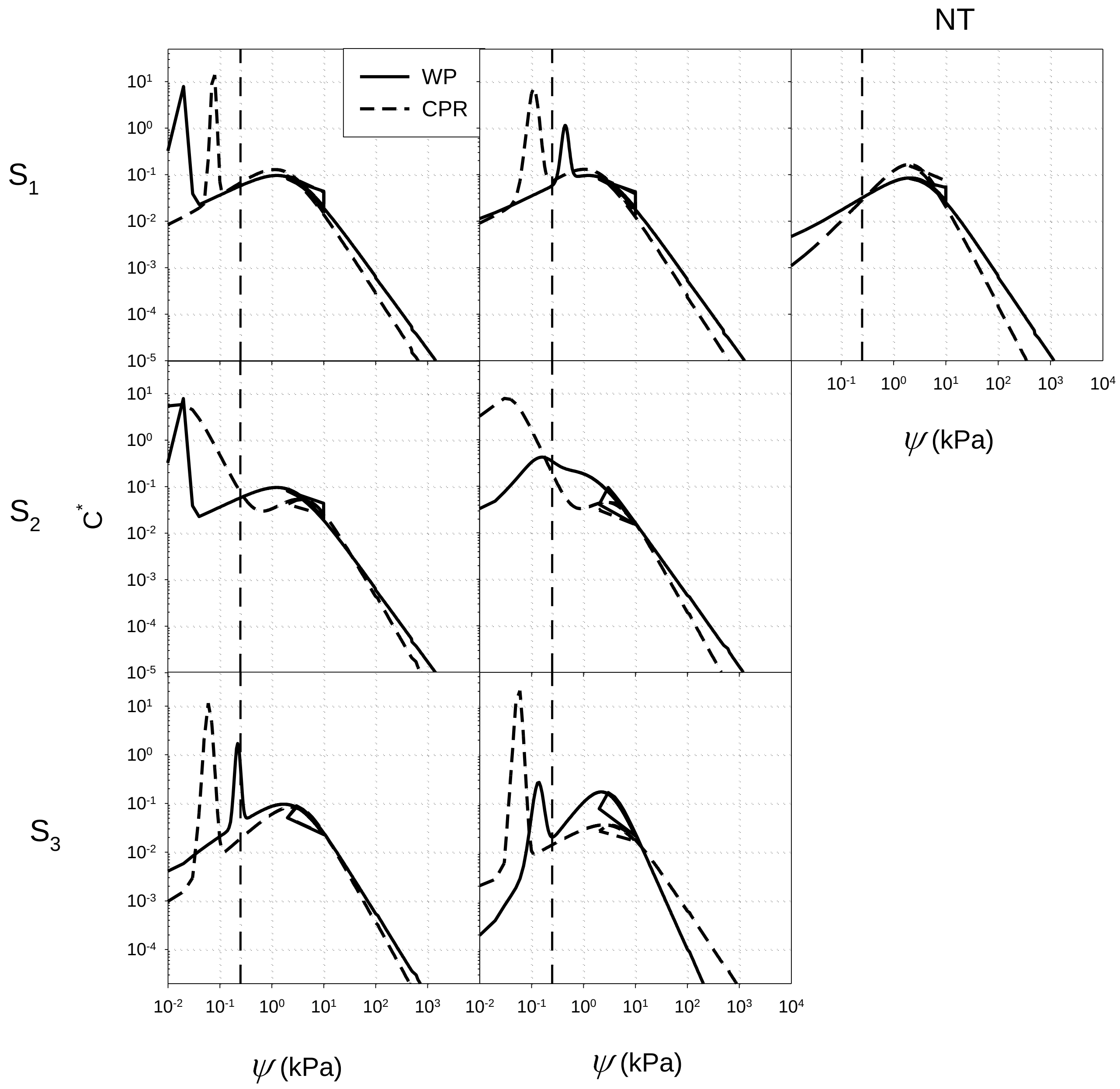

Figure 3.