TDR pressure cell for monitoring water content retention and bulk electrical conductivity curves in undisturbed soil samples

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Abstract

The water retention curve ($\theta(\psi)$), which defines the relationship between soil volumetric water content (θ) and matric potential (ψ), is of paramount importance in characterizing the hydraulic behaviour of soils. However, few methods are so far available for estimating $\theta(\psi)$ in undisturbed soil samples. We present a new design of TDR-pressure cell (TDR-Cell) for estimating $\theta(\psi)$ in undisturbed soil samples. The TDR-Cell consists of a 50-mm-long and 50-mm internal diameter stainless steel cylinder (which constitutes the outer frame of a coaxial line) attached to a porous ceramic disc and closed at the ends with two aluminium lids. A 49-mm-long and 3-mm-diameter stainless steel rod, which runs longitudinally through the centre of the cylinder, constitutes the inner rod of a coaxial TDR probe. The TDR-Cell was used to determine the $\theta(\psi)$ curves of a packed sand and seven undisturbed soil samples from three profiles of agricultural soils. These $\theta(\psi)$ curves were subsequently compared to those obtained from the corresponding 2-mm sieved soils using the pressure plate method. Measurements of bulk electrical conductivity, σ_a, as a function of the water content, $\sigma_a(\theta)$, of the undisturbed soil samples were also performed. An excellent correlation ($R^2 = 0.988$) was found between the θ values measured by TDR on the different undisturbed soils and the corresponding θ obtained from the soil gravimetric water content. A typical bimodal $\theta(\psi)$ function was found for most of the undisturbed soil samples. Comparison between the $\theta(\psi)$ curves measured with the TDR-Cell and those obtained from the 2-mm sieved soils showed that the pressure plate method overestimates θ at low ψ values. The $\sigma_a(\theta)$ relationship was well described by a

simple power expression ($R^2 > 0.95$), in which the power factor, defined as tortuosity, ranged between 1.18 and 3.75.

Keywords: Time Domain Reflectometry; Volumetric water content; Pressure plate extractor; Coaxial cell.

1. Introduction

The relationship between the soil volumetric water content (θ) [m^3m^{-3}] and the matric potential (ψ) [kPa], i.e. the water retention function, $\theta(\psi)$, has become crucial for characterizing the soil hydraulic properties, the key feature for planning and managing new irrigation schemes. The water retention curve is very dependent upon the particle-size distribution, which determines the soil texture, and the arrangement of the solid particles, which refers to the soil structure. The shape of the water retention curve is also dependent on the soil organic matter and the soil water composition (Dane and Hopmans, 2002).

Common approaches for estimating $\theta(\psi)$ require paired ψ and θ measurements. The water retention information is commonly obtained by bringing the soil sample to equilibrium by applying a constant pressure gradient across the soil, driving water movement while preventing air entering into a pressurized chamber (Dane and Hopmans, 2002). The θ is generally calculated from the gravimetric water content and the dry bulk density of the soil sample, or in cases where the sample is an undisturbed soil contained in a cylinder, by using the cylinder volume directly. The most common laboratory technique for estimating $\theta(\psi)$ is the pressure plate extractor. A pressure plate extractor referred to as a "Temple cell" is commonly used for suctions up to -100 kPa. For higher matric suctions (typically -1500 kPa) more robust pressure cells are used (Wand and Benson, 2004). Depending on the dimensions of the pressure plate extractor, disturbed or intact soil samples can be used. Measurements of $\theta(\psi)$ in undisturbed soil samples are highly desirable because changes in pore-size distribution caused by sieving soil samples produce substantial changes in $\theta(\psi)$ with respect to its original shape.

Time Domain Reflectometry (TDR) is a non-destructive technique that allows simultaneous estimations of the volumetric water content and the bulk electrical conductivity (σ_a). TDR

employs a fast-rise signal propagating through a porous medium in order to determine permittivity from travel time, and electrical conductivity from signal attenuation. Water content is inferred from the dielectric measurements due to the large contrast in the permittivity of water compared to the soil and air (Topp and Ferré, 2002). The characteristics of the TDR technique provide a flexible means of measuring θ at multiple locations without requiring soil-specific calibration in many cases. These properties make it possible to combine this technique with a classical pressure plate extractor to estimate $\theta(\psi)$. For instance, Wraith and Or (2001) measured $\theta(\psi)$ of different soils using a combination of a 15-bar pressure plate and a 20-cm-long TDR probe. Jones et al. (2005) designed a 19.6-cm-long TDR coaxial cell to measure water content at adjustable pressure heads without repacking or disturbing the soil sample. More recently, Moret-Fernández et al. (2008) developed a type of pressure cell associated with a zigzag-shaped TDR probe for determining the soil water retention curve in disturbed thin soil samples. However, although this last design reduces the length of the soil cores and, consequently, reduces the risk of soil compression (Grossman and Reinsch, 2002), the zigzag-shaped wires limit the TDR application to disturbed soil samples.

The bulk electrical conductivity of soil depends mainly on three variables: (a) the effective θ, (b) the electrical conductivity of the soil solution, and (c) a geometric factor, which accounts for the complex geometry of the soil matrix (Mualem and Friedman, 1991). For unsaturated soils, Rhoades et al. (1976) found that the $\sigma_a(\theta)$ relationship could be satisfactorily described with a polynomial function. However, as subsequently observed by Rhoades et al. (1989), this equation was only valid for σ_a values close to 0.1 S m^{-1}. On the basis of the hypothesis that the tortuosity factor affecting the bulk electrical conductivity is identical to that defined for predicting the soil hydraulic conductivity, Mualem and Friedman (1991) showed

that $\sigma_a(\theta)$ could be satisfactorily described using a simple power expression, in which the calibration coefficient was, for most soils, equal to 2.5.

The objective of this paper is to present a new design of TDR-pressure cell (TDR-Cell) for estimating $\theta(\psi)$ and $\sigma_a(\theta)$ curves in thin undisturbed soil samples (5-cm high). The TDR-Cell was calibrated in water and soils with different water content and tested in packed sand and in seven different soil samples. The undisturbed $\theta(\psi)$ curves were subsequently compared to those obtained in the corresponding 2-mm sieved soils using a conventional pressure plate method. This comparison will make possible to value the strengths of the TDR-Cell regarding to the pressure plate extractor with disturbed soil samples, which is incorrectly used in many research laboratories to estimate, for instance, the soil water retention curve or the plant available soil water content.

2. Theory

Description of TDR

A TDR system launches an electromagnetic pulse along a transmission line and records a signal or TDR waveform, which is expressed by the voltage (V) or reflection coefficient (ρ) as a function of time (t). The transit time of the TDR pulse propagating one return trip in a transmission line of length L (m) t_L, is represented by

$$t_L = \frac{2L\sqrt{\varepsilon_a}}{c} \quad (1)$$

where c is the velocity of light in free space ($3\text{x}10^8$ m s^{-1}) and ε_a is the apparent permittivity of the medium (Topp and Férre, 2002). Estimations of θ from ε_a values are calculated by the Topp and Reynolds (1998) linear calibration form

$$\theta = 1.16\left(\frac{t_s}{t_{air}}\right) - 1.76 \quad (2)$$

where t_s and t_{air} are the travel time in soil and air, respectively

The voltage reflection coefficient of the TDR waveform, ρ, as a function of time, t, is typically defined as

$$\rho(t) = \frac{V(t) - V_0}{V_0 - V_i} \qquad -1 \le \rho \le +1 \tag{3}$$

where $V(t)$ is the measured voltage at time t, V_0 is the voltage in the cable just prior to entering the probe (standard impedance value of 50 Ω), and V_i is the incident voltage of the cable tester prior to the pulse rise. The V_i has a constant value over time and, for our case, it will be assumed to be equal to zero.

As an electromagnetic signal propagating in conductive media, the TDR waveform undergoes attenuation. On the basis of the Giese and Tiemann (1975) thin-layer model, Lin et al., (2008) showed that the sample electrical conductivity, σ (S m^{-1}), recorded with an uncoated twin-rod TDR probe, can be related to the long-time attenuation of the TDR signal according to

$$\sigma = \frac{K_P}{Z_r}\left(\frac{1 - \rho_{\infty,Scale}}{1 + \rho_{\infty,Scale}}\right) \tag{4}$$

where $\rho_{\infty,Scale}$, is the scaled steady-state reflection coefficient corresponding to the ideal condition in which there is no instrument error o cable resistance. Z_r is the output impedance of the TDR cable tester (50 Ω), and K_P (m^{-1}) is the probe-geometry-dependent cell constant value, which can be determined from the probe geometries characteristics or by immersing the probe in different electrolyte solutions of known conductivity (Wraith, 2002). The $\rho_{\infty,SC}$ to be used in the usual Giese–Tiemann equation is calculate according to

$$\rho_{\infty,Sclae} = 2\frac{(\rho_{\infty,air} - \rho_{\infty,SC})(\rho - \rho_{\infty,air})}{(1 + \rho_{\infty,SC})(\rho - \rho_{\infty,air}) + (\rho_{\infty,air} - \rho_{\infty,SC})(1 + \rho_{\infty,air})} + 1 \tag{5}$$

where ρ, $\rho_{\infty,air}$ and $\rho_{\infty,SC}$ are the steady-state reflection coefficient of the sample under measurement, open in air and short-circuited, respectively

Soil water retention curves

The most common function used to describe the soil water retention curve is the unimodal van Genuchten (1980) equation

$$\frac{\theta - \theta_r}{\theta_{sat} - \theta_r} = \left[\frac{1}{1 + (\alpha\psi)^n} \right]^m \tag{6}$$

where n is the pore-size distribution parameter, $m = 1-(1/n)$, α [kPa] is the scale factor, and θ_{sat} and θ_r are the saturated and residual volumetric water contents, respectively. Water retention curves for soil with multiple porosity are better approached using the model proposed by Durner (1994), which involves the linear superposition of van Genuchten (1980) subcurves and is expressed as

$$\theta = \theta_r + (\theta_{sat} - \theta_r) \sum_{i=1}^{k} w_i \left[\frac{1}{1 + (\alpha_i\psi)^{n_i}} \right]^{m_i} \tag{7}$$

$$0 < w_i < 1$$

$$\sum w_i = 1$$

$$\alpha_i > 0,\ m_i > 0,\ n_i > 1$$

where k is the total number of i "subsystems" that form the total pore-size distribution, and w_i is a weighting factor for the subcurves.

Water content vs. bulk electrical conductivity curves

The σ_a of a soil can be considered to consist of two components: (i) the contribution of ions in soil particles, and (ii) the contribution of ions in the soil solution (Nadler and Frenkel, 1979). The $\sigma_a(\theta)$ relationship was first described by Rhoades et al. (1976) as

$$\sigma_a(\theta) = \sigma_w \theta T + \sigma_s \quad (8)$$

where σ_w and σ_s are the electrical conductivity of the soil solution and the solid phase conductivity, respectively, and $T = a\theta + b$, with a and b being empirical coefficients. Alternatively, on the basis of the hypothesis that the tortuosity factor accounting for the reduction in hydraulic conductivity is identical to the tortuosity factor reducing the soil solution electrical conductivity, Mualem and Friedman (1991) found that $\sigma_a(\theta)$ could be described with a simple power function (neglecting σ_s) as

$$\sigma_a = \sigma_{a-sat}\left(\frac{\theta}{\theta_{sat}}\right)^{\beta} \quad (9)$$

where $\sigma_{a\text{-}sat}$ is the soil bulk electrical conductivity at saturation and β is a tortuosity factor that, dependent on the soil's water transmission porosity, defines the rate of decrease between σ_a and θ.

3. Material and methods

Description of the TDR-Cell

The pressure head TDR-Cell consists of a commercially available stainless steel cylinder (50-mm long and 50-mm in internal diameter), commonly used to estimate soil bulk density, joined through the base to a commercially available porous ceramic disc (7-mm thick and 50-mm in diameter) and hermetically closed at the ends with two aluminium single-hole drilled lids (Fig. 1). A 49-mm-long and 3-mm-diameter stainless steel rod, which was vertically

inserted in the upper lid of the TDR-Cell, runs longitudinally along the axis at the centre of the stainless steel cylinder. This rod is connected to the inner wire of a female BNC connector, which is glued onto the upper lid of the TDR pressure cell. The two elements, the stainless steel rod and the cylinder, form a cylindrical coaxial line of 49-mm length and 50-mm internal diameter. Two aluminium rings attached to several rubber joints hermetically close the lids of the TDR-Cell against the stainless steel cylinder (Fig. 1). The TDR-Cell is connected to a TDR cable tester (Campbell TDR100) by a 1.2-m-long RG 58 coaxial cable of 50 Ω nominal impedance, and the TDR signals are transferred to a computer that records and analyses the TDR waveforms using the software TDR-Lab V.1.0 (Moret-Fernández et al., 2010). The TDR volumetric water content (θ_{TDR}) and the bulk electrical conductivity (σ_a) are estimated using the Topp and Reynolds (1998) (Eq. 2) and Lin et al. (2008) (Eq. 4) models, respectively.

TDR-Cell testing and experimental design

A first laboratory experiment was performed to calibrate the effective length and the cell constant (K_p) (Eq. 4) of the TDR coaxial probe. The effective length was calculated with the TDR-Lab software by immersing the coaxial probe in distilled water, and the K_p was determined by immersing the probe in different electrolyte solutions of known conductivity (Moret-Fernández et al., 2010). Additionally, the theoretical K_p value was also calculated. Although the probe constant for a purely coaxial cell can be calculated analytically, the specific geometry of the TDR-Cell, in which the effect of the top and bottom metallic flanges are not negligible, makes necessary to calculate K_p by means of numerical methods. To this end a commercial finite elements modelling software (COMSOL Multiphysics http://www.comsol.com/) was used. In a two-dimensional axisymmetric mode, the cell nominal geometry was finely meshed to approximately 40000 nodes and the subsequent DC conductivity problem was solved. The viability of the TDR-Cell for estimating water retention

curves ($\theta(\psi)$) was tested in sand (average grain size of 80-160 μm) and in seven different undisturbed soil samples. The gypsum of the soil samples was titrated by the loss of crystal water from the gypsum, in accordance with Artieda et al. (2006). The undisturbed soil samples were taken, using the core method (Grossman and Reinsch, 2002), from the genetic horizons of three different pits (Table 1) opened for soil profile study. Two replications were performed per soil horizon. The preparation of the soil samples required the following phases. In a first step, the surfaces of the undisturbed soil core were carefully levelled with a scraper. The bottom of the core was covered with a nylon base (20-μm mesh) which, glued to a stainless steel open ring, was inserted at the bottom of the cylinder. Using a power drill, a 3-mm-diameter and 45-mm-long hole was drilled longitudinally through the top and down the centre of the undisturbed soil sample. The stainless steel rod of the TDR-Cell was inserted in the drilled hole, and the top of the TDR-Cell was hermetically closed by screwing the upper aluminium ring to the upper TDR-Cell lid (Fig. 1). A dry ceramic disc was placed on the bottom lid of the TDR-Cell, and the stainless steel core plus the upper TDR-Cell lid were attached to the ceramic disc. The system was finally hermetically closed by screwing the lower aluminium ring to the bottom lid of the TDR-Cell. A first measurement of θ_{TDR} was performed in air-dry soil conditions, which have been calculated to correspond to a soil pressure head of about 166 MPa (Munkholm and Kay, 2002). Next, the soil sample was saturated by injecting distilled water through the base of the TDR-Cell, and the soil was considered saturated when the water started to leave via the top of the pressure cell. Once the soil was saturated, pressure steps were sequentially applied at 1.7, 3, 5, 10, 50, 100, 500, and 1500 kPa. Ceramic plates (Soil Moisture Inc. UK) with bubbling pressures of -0.5, -3 and -5 bar (Soil Moisture Inc. UK) were used to regulate the outlet water flow for pressure heads up to 50, 100 and 500 kPa, respectively. The outlet water flow at a pressure head of 1500 kPa was regulated using a cellophane membrane plus a -0.5 bar ceramic plate system. Values of θ_{TDR} and σ_a were

recorded at soil saturation, and 24, 48 and 72 hours after starting each pressure head step for ψ values up to -100, -500 and -1500 kPa, respectively. Preliminary measurements of θ_{TDR} performed in the BU7-Ap and BU7-R1 soil cores at 500 and 1500 kPa of pressure heads and 24 h of time intervals during 4 days showed that 48 and 72 h were enough to reach the soil the respective water equilibrium.

The $\theta(\psi)$ curves were fitted to the unimodal (van Genuchten, 1980) or bimodal functions (Durner, 1994) using SWRC Fit Version 1.2 software (http://seki.webmasters.gr.jp/swrc/) (Seki, 2007). The gravimetric water content (W) of the different undisturbed soil samples was measured in air-dry conditions and at pressure heads up to -50 kPa, and the corresponding volumetric water contents (θ_W) were calculated from W and the undisturbed soil dry bulk density (ρ_b). The dry bulk density of the undisturbed soil samples was calculated as the soil weight dried at 50 ºC for 72 hours divided by the soil volume. Since gypsum content was relevant in the studied soils, the 50ºC temperature was used to avoid the constitutional water release by the gypsum crystal because of the transformation of gypsum into bassanite or anhydrite at temperatures > 50ºC (Nelson et al., 1978; Artieda et al., 2006; Lebron et al., 2009; Herrero et al., 2009). Accounting these water molecules as moisture would be erroneous; moreover the "dry" weight of the "cooked" soil at 105ºC would also differ from the true weight of the naturally dry gypsum, flawing further determinations related to weight.

The different undisturbed soil $\theta(\psi)$ curves estimated with the TDR-Cell were compared to the corresponding curves measured for disturbed soil samples using a conventional pressure plate method (Table 1). The air-dry soil samples were ground, sieved at 2-mm diameter, and poured into 5-cm internal diameter and 0.4-cm thick rubber rings, which were placed on the ceramic plate of the pressure plate apparatus. The soil samples were wetted to saturation and pressure steps were sequentially applied at 1.7, 3, 5, 10, 50, 100, 500, and 1500 kPa. A new

disturbed soil sample was used for each pressure head, and W was measured 24 hours after starting each pressure head step. The volumetric water content of the disturbed soil samples was calculated as the gravimetric water content (W) multiplied by the ρ_b of the sieved soil samples (Table 1). Two replications of the water content measurements were performed per pressure head and sampling point.

4. Results and discussion

The effective length and theoretical and experimental K_P values calculated for the coaxial probe used in the TDR-Cell were 5.14 cm, and 7.29 and 6.38 m^{-1}, respectively. The 12% discrepancy between the experimental and theoretical K_P values can be considered as a good approximation for a calculation derived from nominal simplified geometry parameters. The good correlation (R^2 = 0.988) and the low RMSE (RMSE = 0.017) found between the θ_{TDR} values measured for the packed sand and for the different undisturbed soil samples and pressure heads (in air-dry soil conditions and with ψ ranging between 0 and -0.5 bar) and the corresponding θ_W indicate that the coaxial TDR probe used in this experiment is accurate enough to estimate the volumetric water content (Fig. 2).

The ρ_b measured in the sand sample was 1.47 g cm^{-3} and the $\theta(\psi)$ obtained with the TDR pressure cell showed a typical van Genuchten (1980) unimodal function (Fig. 3), with an excellent fit between the measured and modelled $\theta(\psi)$ (Table 2). The undisturbed soil samples used in the experiment had loam to silty clay loam textures, and ρ_b ranged from 1.21 g cm^{-3} for the upper soil horizons to 1.70 g cm^{-3} for the deeper ones (Table 1). Assuming a θ_r = 0, the $\theta(\psi)$ estimated with the TDR-Cell shows a double hump for all the undisturbed samples, which indicates that the soils presented a relevant double pore-size distribution. In these cases, a significant w_1 value (Eq. 7) was observed (Table 2). Figure 3 shows an example of the

unimodal and bimodal $\theta(\psi)$ functions obtained for the sand and the second replication of the BU 7-R2 soil, respectively.

Significant differences were observed between the $\theta(\psi)$ functions estimated with the TDR-Cell for undisturbed soil samples, $\theta(\psi)_{TDR}$, and the corresponding curves obtained with the pressure plate method, $\theta(\psi)_{PPM}$ (Fig. 4). Overall, $\theta(\psi)_{PPM}$ presented a significantly higher volumetric water content for the soil macropore range (ψ > -10 kPa) (Kay and VandenBygaart, 2002), which should be attributed to the different structural characteristics between the undisturbed and the 2-mm sieved soil samples. As noted by Ahuja et al. (1998), the larger porosity in loose soil, which is related to a lower ρ_b (Rab, 2004; Moret and Arrúe, 2007), is generally associated with an increase in soil water retention at the wet end of the $\theta(\psi)$ curve (i.e. pores corresponding to ψ > - 6 kPa). In contrast, for pressure heads higher than 100 kPa, a significantly higher volume of mesopores (-10 > ψ > - 1400 kPa) was observed in the compacted undisturbed soil samples. As compared to the sieved soils, the extremely high ρ_b observed in some undisturbed soil samples (Table 1) (i.e. the "BU9 Cy" soil which came from a lutitic horizon) should increase the fraction of micropores (ψ > -1400 kPa), and consequently enhance the water content at permanent wilting point (-1500 kPa) (Fig. 4). The similar average and standard deviation values found between the gravimetric water content measured with the pressure plates (W_{PPM}) at low pressure heads (from 100 to 1500 kPa) and the corresponding values estimated for the undisturbed soils with the TDR-Cell (W_{TDR}) (calculated as the quotient between θ_{TDR} and the undisturbed ρ_b) (Table 3) indicate that the TDR-Cell satisfactorily approaches the $\theta(\psi)$ section corresponding to the soil's textural properties.

As described in the literature (Rhoades et al., 1976; Mualem and Friedman, 1991), the bulk electrical conductivity increased with the volumetric water content (Fig. 5). The high electrical

conductivity around saturation found in the BU 7-R2, BU 9-Cy, and BU 10-Ap and By soil samples can be related to the high gypsum content measured in these soil horizons (Table 1). The electrical conductivity of the air-dry soils, which would correspond to the apparent electrical conductivity of the solid phase of the soil (σ_s) (Eq. 8) (Rhoades et al., 1976), was in all cases negligible. Preliminary analysis of the $\sigma_a(\theta)$ relationship showed that the polynomial function proposed by Rhoades et al. (1976) (Eq. 8), which presented incongruent negative b coefficients in some cases (i.e. BU 9-Cy, BU 10-Ap, and BU 10-By), was not appropriate for describing the relationship between the bulk electrical conductivity and the volumetric water content. These results agree with Rhoades et al. (1989), who concluded that the simplified polynomial model (Eq. 8) was valid for σ_a values above approximately 0.1 S m^{-1}. However, an excellent fit was found between the experimental and the modelled Mualem and Friedman (1991) $\sigma_a(\theta)$ curves (Eq. 9) (neglecting σ_s) (Table 4). However, unlike Mualem and Friedman (1991), who found a β value close to 2.5 for both consolidated and unconsolidated coarse soils, the β parameter obtained in this study ranged between 1.18 and 3.75. Since all measurements have been performed on undisturbed soil samples, with bulk densities ranging from 1.24 to 1.70 g cm^{-3}, these results indicate that the β factor was largely affected by the structural characteristics of the soils. No clear correlation ($R^2 = 0.17$) between the β factor and the soil bulk density was found.

5. Conclusions

This paper presents a new design of TDR-pressure cell (TDR-Cell) for estimating $\theta(\psi)$ and $\sigma_a(\theta)$ curves on 5-cm-high undisturbed soil samples. The TDR-Cell was tested with different soils, and the $\theta(\psi)$ curves were compared with the corresponding curves obtained with 2-mm sieved soils using the conventional pressure plate method. The results show that the TDR-Cell

measures θ satisfactorily. Thus, these results indicate that the proposed TDR-Cell is, in comparison to the pressure plate extractor, a significant advance in estimating the $\theta(\psi)$ and $\sigma_a(\theta)$ functions in undisturbed soil samples. However, some caution is due for the time selected to achieve the water equilibrium in the soil bulk at the largest pressure heads, since the 48 and 72 h used at 500 and 1500 kPa of pressure head may be insufficient for fixed clayey soils. On the other hand, further efforts should be made to improve the TDR-Cell design, using a single ceramic plate for all ranges of pressure heads. This could be achieved by replacing the different ceramic plates that regulate the outlet water flow by a single -0.5 bar ceramic disc plus an adjustable valve running up to a pressure head of -15 bar. In addition, these results open the door to further research studying the relationship between the β factor and the tortuosity parameter of the hydraulic conductivity curves.

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Figure captions

Figure 1. Schematic diagram of the proposed TDR pressure cell.

Figure 2. Correlation between the volumetric water content measured with the TDR-Cell (θ_{TDR}) in sand samples and in different undisturbed soil samples and the corresponding values calculated from the soil gravimetric water content and the dry bulk density of the undisturbed soil (θ_W).

Figure 3. Water retention curves measured with the TDR-Cell (points) in sand and in the second replication of the BU 7-R2 soil and the corresponding modelled unimodal and bimodal functions (lines).

Figure 4. Comparison between the water retention curves measured with the TDR-Cell in the two replications of undisturbed soil samples, and the corresponding average curves measured in the 2-mm sieved soil samples using the pressure plate method (PPM).

Figure 5. Comparison between the measured (points) and modelled (lines) (Eq. 8) soil volumetric water content vs. bulk electrical conductivity relationships obtained for different undisturbed soil samples (Table 1).

Table 1. Characteristics of the 2-mm sieved and undisturbed soil samples used to test the pressure head TDR-Cell

Trench	Genetic horizon	Depth	2-mm sieved soil bulk density	Undisturbed soil bulk density	Gypsum content	Sand	Silt	Clay	Texture
		cm	g cm^{-3}		%				
BU-7	A_P	0-30	1.07	1.23	5.0	6.6	30.1	63.3	Silty clay loam
	R1	40-60	1.22	1.59	10.5	35.8	23.3	40.9	Loam
	R2	60-160	1.15	1.70	20.0	1.7	28.2	70.1	Silty clay loam
BU-9	A_P	0-30	1.03	1.21	6.1	7.4	35.8	56.9	Silty clay loam
	Cy	30-160	1.11	1.68	22.2	1.7	34.4	63.9	Silty clay loam
BU-10	A_P	0-30	1.00	1.24	17.3	7.4	35.7	56.9	Silty clay loam
	By	30-100	1.00	1.52	26.8	3.1	36.7	60.3	Silty clay loam

Table 2. Parameters defining the unimodal (Eq. 5) and bimodal (Eq. 6) water retention curves estimated in packed sand and in different undisturbed soil samples (Table 1), and the coefficient of determination (R^2) for the best fit between the measured and modelled volumetric water content vs. soil pressure head.

Soil sample	Soil horizon	Replication	Model	θ_S	θ_r	w_1	α_1	n_1	α_2	n_2	R^2
				$m^3\ m^{-3}$			kPa		kPa		
Sand		1	Unimodal	0.39	0.09	-	0.41	5.48			0.99
BU 7	A_P	1	Bimodal	0.43	≈ 0	0.47	0.31	1.90	$6.7\ 10^{-4}$	1.32	0.99
		2	Bimodal	0.48	≈ 0	0.42	0.25	1.88	$6.0\ 10^{-4}$	1.33	0.99
	R1	1	Bimodal	0.46	≈ 0	0.20	3.36	1.27	0.012	1.19	0.97
		2	Bimodal	0.44	≈ 0	0.45	0.41	1.19	$1.4\ 10^{-5}$	3.14	0.99
	R2	1	Bimodal	0.47	≈ 0	0.33	0.10	1.27	$2.4\ 10^{-4}$	1.56	0.99
		2	Bimodal	0.39	≈ 0	0.26	0.34	1.91	$9.8\ 10^{-4}$	1.31	0.99
BU 9	A_P	1	Bimodal	0.51	≈ 0	0.66	1.44	1.24	$6.8\ 10^{-4}$	1.29	0.99
		2	Bimodal	0.49	≈ 0	0.38	0.33	2.92	$9.4\ 10^{-3}$	1.21	0.99
	C_y	1	Bimodal	0.43	≈ 0	0.04	27.87	38.97	$1.4\ 10^{-3}$	1.22	0.99
		2	Bimodal	0.44	≈ 0	0.20	0.03	1.23	$1.4\ 10^{-4}$	1.32	0.99
BU 10	A_P	1	Bimodal	0.49	≈ 0	0.30	0.15	3.07	$8.9\ 10^{-4}$	1.35	0.99
		2	Unimodal	0.48	≈ 0	0.19	0.086	3.03	$1.0\ 10^{-4}$	1.52	0.99
	B_y	1	Bimodal	0.51	≈ 0	0.25	0.085	3.21	$7.4\ 10^{-5}$	1.74	0.99
		2	Bimodal	0.49	≈ 0	0.59	0.63	1.15	$2.4\ 10^{-4}$	3.17	0.99

Table 3. Average and standard deviation (SD) values of the gravimetric water content measured in all soil samples with the pressure plate method (W_{PPM}) and corresponding values calculated with the TDR-Cell (W_{TDR}).

Pressure head	W_{PPM}		W_{TDR}	
	Average	SD	Average	SD
kPa	$m^3\ m^{-3}$			
0.01	0.615	0.067	0.358	0.088
1.7	0.498	0.063	0.331	0.084
3	0.488	0.048	0.329	0.088
5	0.447	0.044	0.308	0.082
10	0.416	0.050	0.291	0.076
50	0.332	0.056	0.257	0.059
100	0.268	0.057	0.240	0.062
500	0.217	0.048	0.234	0.061
1500	0.192	0.057	0.214	0.079

Table 4. Parameters defining the simple power equation (Eq. 7) relating the volumetric water content with the bulk electrical conductivity for the first (R_1) and the second (R_2) soil replications of the different undisturbed soil samples (Table 1). R^2 and RMSE: coefficient of determination and root mean square error for the best fit between the measured and modelled volumetric water content vs. bulk electrical conductivity.

Trench	Genetic horizon	σ_{sat}		β		θ_{sat}		R^2		RMSE	
		R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2
		S m^{-1}				m^3 m^{-3}					
BU 7	Ap	0.045	0.055	1.180	1.381	0.45	0.47	0.99	0.98	0.005	0.001
	R1	0.110	0.099	1.609	1.615	0.45	0.45	0.98	0.98	0.002	0.001
	R2	0.220	0.073	3.267	1.900	0.46	0.39	0.91	0.94	0.015	0.002
BU 9	Ap	0.053	0.039	1.350	1.397	0.51	0.49	0.96	0.98	0.001	0.001
	Cy	0.133	0.190	2.770	3.753	0.43	0.44	0.99	0.98	0.002	0.031
BU 10	Ap	0.400	0.649	2.133	2.322	0.50	0.49	0.96	0.97	0.008	0.017
	By	0.472	0.699	2.421	3.594	0.52	0.49	0.95	0.96	0.013	0.017

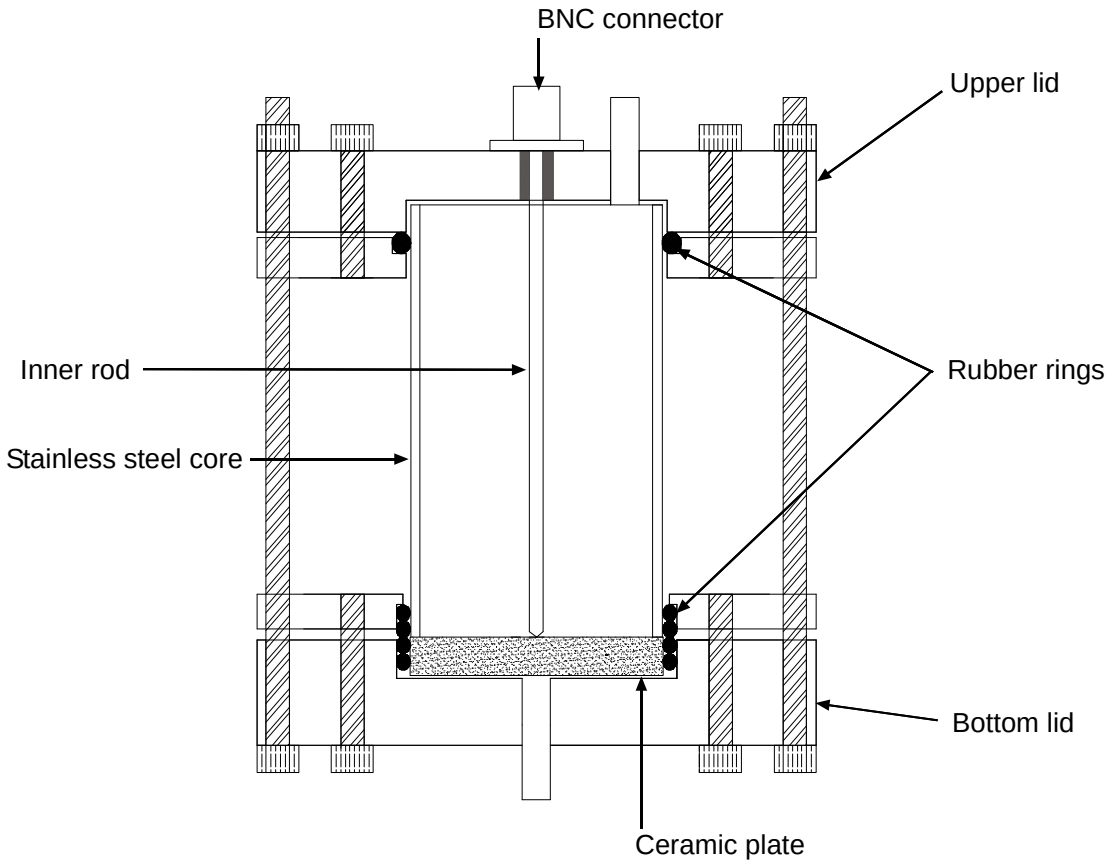
BNC connector
Upper lid
Inner rod
Rubber rings
Stainless steel core
Bottom lid
Ceramic plate

Fig. 1

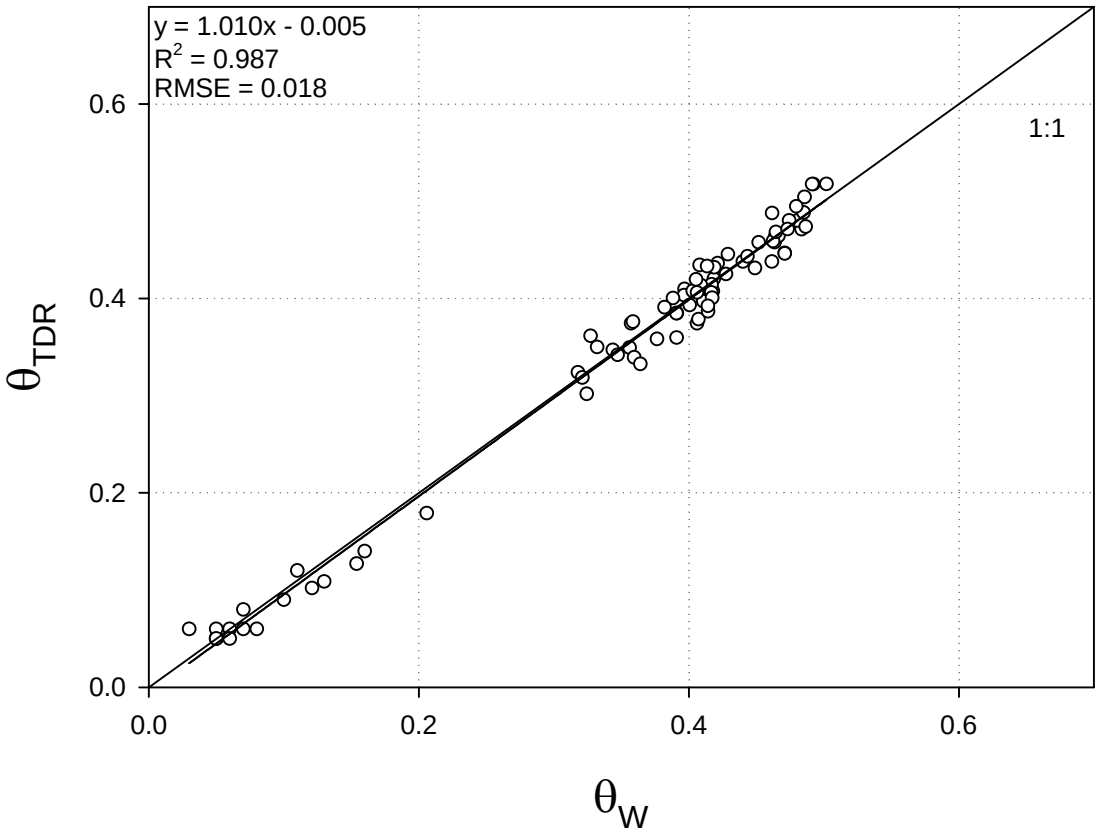

Fig. 2

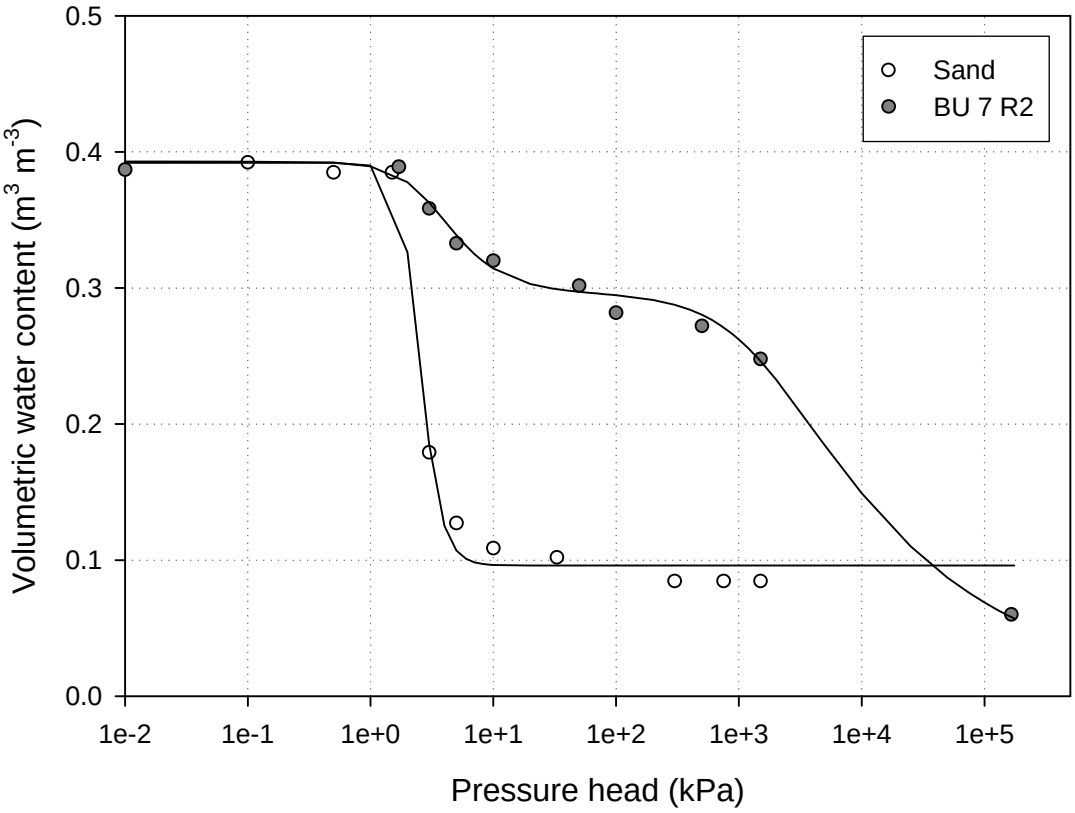
0.5
0.4
0.3
0.2
0.1
0.0
Volumetric water content (m3 m-3)
1e-2
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
1e+5
Pressure head (kPa)
Sand
BU 7 R2

Fig. 3

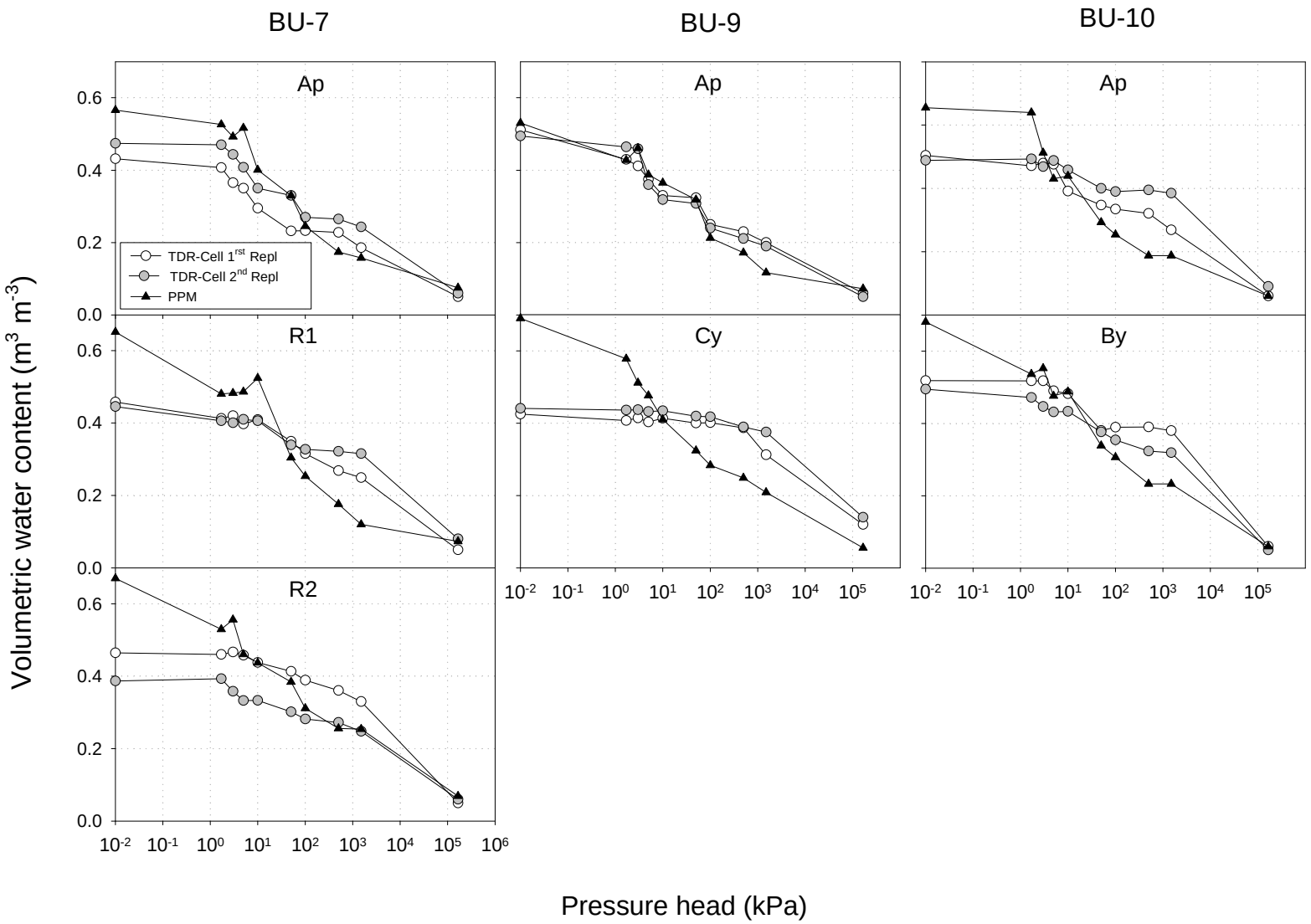
BU-7
BU-9
BU-10
Ap
R1
R2
Cy
By
TDR-Cell 1rst Repl
TDR-Cell 2nd Repl
PPM
Volumetric water content (m3 m-3)
Pressure head (kPa)

Fig. 4

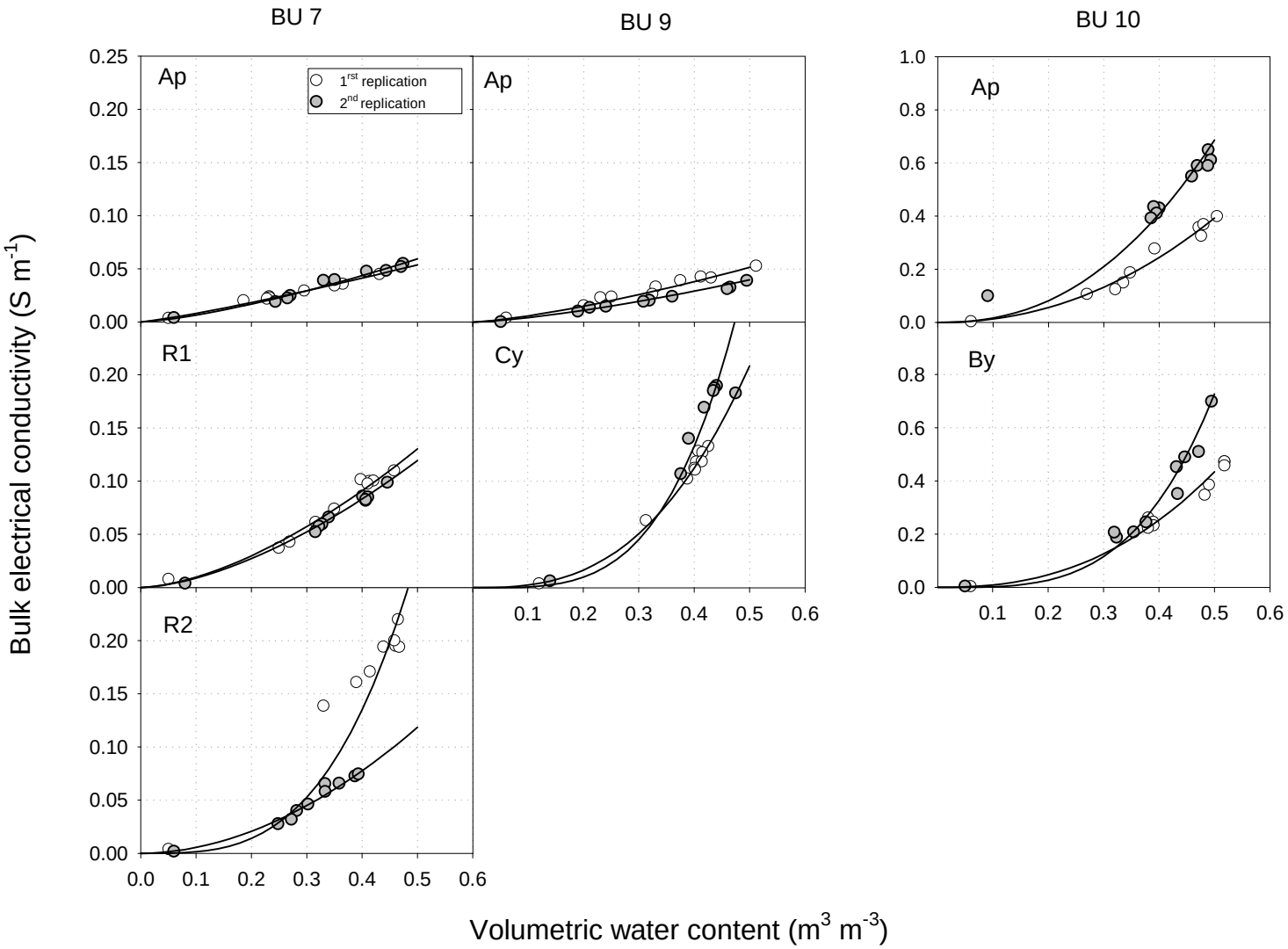
BU 7
BU 9
BU 10
Ap
1rst replication
2nd replication
Ap
Ap
R1
Cy
By
R2
Bulk electrical conductivity (S m-1)
Volumetric water content (m3 m-3)

Fig. 5