A new TDR probe for measurements of soil solution electrical conductivity

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ABSTRACT

The measurement of the soil solution electrical conductivity (σ_w) is critical for a better management of irrigation water and the effective monitoring and control of soil salinity. The objective of this work is to present the design and validation of a new time domain reflectometry (TDR) probe (WEC$_P$) for accurate and non-destructive measurements of σ_w. The probe consists in fourteen porous ceramics disks (0.5 bar bubbling pressure) arranged along the axis of a three-rod TDR probe. Using the Mualem and Friedman (1991) model, σ_w was estimated from the volumetric water content (θ) and the bulk electrical conductivity (σ_a) measured in the ceramic disk set of known pore-geometry. The τ and β factors, which describe the complex geometry of the ceramic matrix, were calculated by immersing the probe in NaCl solutions of different electrical conductivities, and in a pressure cell wetted and drained with these NaCl solutions, respectively. The reliability of the WEC$_P$ was validated under laboratory and field conditions. The laboratory experiment consisted of the TDR probe inserted in a pressure cell packed with mixed sand and 2-mm sieved loam soil that was subsequently wetted and drained with different NaCl solutions at various pressure heads. The σ_w estimated by WEC$_P$ was compared to the σ_w measured in the draining solutions after they stabilized in the soil porous system. The field experiment compared the σ_w estimated by WEC$_P$ with the corresponding σ_w values measured in the soil solution extracted with three ceramic tension lysimeters (TL) after successive wetting and drainage cycles. The τ and β factors calculated for the ceramic disks set were 1.957 and 4.282, respectively. High and significant correlations were found in both laboratory ($R^2 = 0.98$; $P < 0.001$) and field ($R^2 = 0.97$; $P < 0.001$) experiments between the σ_w estimated by the WEC$_P$ and the corresponding σ_w values measured in the column-drainage or TL-extracted soil solutions, respectively. These results demonstrate that the WEC$_P$ is a feasible instrument to accurately estimate soil solution salinity

independently of the soil water content and the porous medium in which the TDR probe is installed.

Key words: Water content; Pore-geometry; Bulk electrical conductivity; Time Domain Reflectometry

INTRODUCTION

Soil salinity, defined as the total concentration of dissolved salts in the soil solution, has a detrimental effect on crops and soil chemical and physical properties (Leone et al., 2007). Hence, the accurate measurement of soil salinity is crucial for the productivity and sustainability of irrigated agriculture. Soil salinity is most conveniently measured from the electrical conductivity (EC) of its soil solution (σ_w) (White, 2003). Currently, three basic procedures are used to measure or estimate soil salinity (Hendrickx et al., 2002): (i) the EC of soil water extracts, (ii) the EC of the soil solution extracted with tension lysimeters, and (iii) the apparent soil bulk EC (σ_a) using different methods. The classical soil water extracts using various soil:water ratios, such as the soil saturation extract, are laborious, destructive and impractical when many soil samples are analyzed. The in-situ soil solution extraction method is commonly performed using ceramic tension lysimeters (Parizek and Burke, 1970). This low-cost method allows periodic sampling of the soil solution with minimal soil disturbance. Although the tension lysimeters have evolved to new designs (i.e., Wagner, 1962; Linden, 1977; Hubbell and Sisson, 1996), the method is tiresome and limited to soils with relatively high water contents and a proper soil-ceramic contact. Indirect methods to estimate soil salinity are based on the measurement of σ_a determined with electrical resistivity, time domain reflectometry (TDR), or electromagnetic induction techniques. These non-destructive methods estimate σ_w from σ_a and the volumetric soil water content (θ) by using empirical calibration equations or physical based models (Hendrickx et al., 2002).

The TDR is a non-destructive method that allows real time and simultaneous measurements of the apparent permittivity (ε_a), which is related with θ, and σ_a (Topp and Ferré, 2002). The ε_a is calculated from the transit time of the TDR pulse propagating one return trip along a waveguide of length L. Based on the Giese and Tiemann (1975) model, σ_a is calculated from the attenuation of the long-time reflection coefficient recorded with an uncoated probe (Lin et al., 2008). The σ_a depends mainly on three variables, effective θ, σ_w, and a geometric factor which accounts for the complex geometry of the soil matrix (Rhoades et al., 1976; Mualem and Friedman, 1991). Several models relating σ_a to σ_w as a non-linear function of θ have been developed and applied to mineral soils (Rhoades et al., 1976; Rhoades et al., 1989; Mualem and Friedman, 1991; Vogeler et al., 1996; Persson, 1997; Hilhorst, 2000; Muñoz-Carpena et al., 2005). Persson (2002), working with TDR probes installed in sandy soils, showed that the Hilhorst (2000) model was as good as other commonly used models for σ_w estimates with significant dependency of the linear model on soil type. Mortl et al. (2011) compared four equations relating σ_w, σ_a and θ for three soil series encountered in the floodplain of a southeastern coastal river in USA, and found that the empirical relationship proposed by Vogeler et al. (1996) performed the best (overall $R^2 = 0.97$ for the three soils), though all models performed satisfactorily in all soils ($0.94 \leq R^2 \leq 0.98$). Despite all these efforts, σ_w can be only consistently predicted from σ_a if the relationship between σ_w, σ_a and θ is known (Hamed et al., 2006). Due to variations in responses from different soil types, soil-specific σ_w-σ_a-θ calibrations are commonly required (Mortl et al., 2011).

This work presents a new TDR design for accurate and non-destructive estimates of σ_w. The TDR probe, which consists in fourteen porous ceramics disks arranged along the axis of a three-rod TDR probe, estimates σ_w from θ and σ_a measured by TDR in the ceramic disks set. This method is based in the hypothesis that the soil solution is in equilibrium with that in the ceramic disks. Since a constant porous structure is defined inside the ceramic disks, a unique ceramic-specific σ_w-σ_a-θ calibration is required.

2. MATERIAL AND METHODS

2.1. TDR theory

The transit time of the TDR pulse propagating one return trip in a transmission line of length L (m), t_L, is expressed by

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

where c is the speed of light in free space (3 x 10^8 m s^{-1}) and ε_a is the apparent permittivity of the medium (Topp and Ferré, 2002). The t_L value is calculated as the distance between the time at which the signal enters the TDR rods (first peak) and the time when the signal arrives at the end of the TDR probe, also denoted as the second reflection or end point (Heimovaara, 1993).

Estimations of θ from ε_a can be calculated by the Topp and Reynolds (1998) linear calibration equation:

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

where t_s and t_{air} are the travel time of the TDR pulse propagating along the transmission line when immersed in soil and air, respectively. It is well know that ε_a increases with σ_a (Robinson et al., 2003; Evett et al., 2006). Assuming that the relaxation effects are negligible, Evett et al. (2005) proposed a θ calibration equation for conventional TDR in terms of σ_a, the travel time, and the effective frequency (f_{vi}, MHz) of the TDR pulse in a probe of length L as:

$$\theta = -A + B\left(\frac{t_s}{t_{air}}\right) - 0.004933\left[\frac{\sigma_a}{2\pi f_{vi}\varepsilon_0}\right]^{0.5} \qquad (3)$$

where ε_0 is the dielectric constant of free space (8.854 10^{-12} F m^{-1}) and A and B are empirical factors calculated from a calibration experiment.

The reflection coefficient, ρ, as a function of time, t, is typically defined as

$$\rho(t) = \frac{V(t) - V_0}{V_0 - V_i} \qquad -1 \leq \rho \leq +1 \qquad (4)$$

where $V(t)$ is the measured voltage at time t, V_0 is the voltage in the cable just prior to the insertion of 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 soil bulk electrical conductivity (σ_a) estimated with the long-time analysis of the TDR waveform is calculated using the Giese and Tiemann (1975) equation:

$$\sigma_a = \frac{K_p}{Z_r}\left(\frac{1 - \rho_{\infty,\mathrm{Scale}}}{1 + \rho_{\infty,\mathrm{Scale}}}\right) \qquad (5)$$

where 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 calculated from the characteristics of the TDR probe geometry (Evett et al., 2006), or by immersing the probe in different electrolyte solutions of known EC (Wraith, 2002). The $\rho_{\infty,\mathrm{Scale}}$ is the scaled steady-state reflection coefficient corresponding to the ideal condition in which there is no instrument error or cable resistance. The $\rho_{\infty,\mathrm{Scale}}$ is calculated using the equation described by Lin et al. (2008):

$$\rho_{\infty,Scale} = 2\frac{(\rho_{air} - \rho_{SC})(\rho - \rho_{air})}{(1+\rho_{SC})(\rho - \rho_{air}) + (\rho_{air} - \rho_{SC})(1+\rho_{air})} + 1 \qquad (6)$$

where ρ, ρ_{air} and ρ_{SC} are the long-time reflection coefficients measured in the studied medium, in air and in a short-circuited probe, respectively.

2.2. Soil solution electrical conductivity (σ_w) estimation

Following the hypothesis proposed by Mualem and Friedman (1991), which assume that the tortuosity factor affecting the soil bulk electrical conductivity (σ_a) is identical to that defined for predicting the soil hydraulic conductivity, $\sigma_a(\theta)$ can be expressed as:

$$\sigma_a(\theta) = \sigma_{a-sat}\left(\frac{\theta}{\theta_{sat}}\right)^{\beta} + \sigma_{a-s} \tag{7}$$

where $\sigma_{a\text{-}sat}$ and θ_{sat} are the soil bulk electrical conductivity and the volumetric soil water content at saturation, respectively, $\sigma_{a\text{-}s}$ is the bulk electrical conductivity of the soil solid phase, and β is as factor that depends on the soil water transmission porosity and defines the decrease rate between σ_a and θ. According to Mualem and Friedman (1991), $\sigma_{a\text{-}sat}$ can be defined as:

$$\sigma_{a-sat} = \sigma_w \theta_{sat}^{\tau} \tag{8}$$

where τ is a transmission coefficient at soil water saturation that describes the tortuous nature of the current lines that decreases the mobility of ions near the soil-liquid and liquid-gas interfaces. Taking the hypothesis that σ_w only depends on the dissolved salts (Rhoades et al., 1976), σ_w could be theoretically estimated by combining equations (7) and (8) as

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

σ_w, which depends on temperature, $T_{°C}$, was corrected to 25 ºC ($\sigma_{w/25}$) according to (Rhoades et al., 1999)

$$\sigma_{w/25} = \sigma_w * f \tag{10}$$

where f is an empirical factor expressed as (US Salinity Laboratory Staff, 1954)

$$f = 1 - 0.20346 (T) + 0.03822 (T^2) - 0.00555 (T^3), \qquad (11)$$

and $T = (T_{°C} -25)/10$

2.3. TDR probe designs

All TDR measurements were performed using a TDR100 (Campbell Sci.) model cable tester. A 1.0-m 50-Ω coaxial cable directly connected the TDR probes to the TDR pulser. The TDR waveforms were transferred to a computer for display and analysis using the software TDR-Lab V.1.0. (Moret-Fernández et al., 2010), which automatically calculates ε_a and σ_a.

The TDR probe used to estimate the soil water pore electrical conductivity (WEC_P) is similar to the design developed by Or and Wraith (1999) for measuring the soil matric potential. This consists in fourteen disks (7-mm thick and 40-mm in diameter) of commercially available porous ceramics plates with a bubbling pressure of -0.5 bar (Soil Moisture Inc. UK). The disks were arranged along the axis of a three-rod TDR probe (rod length: 101.4 mm; rod diameter: 2.7 mm; spacing of the outer conductors: 20.0 mm). A second three-rod TDR probe without the ceramic disks (rod length: 100.2 mm; rod diameter: 2.4 mm; spacing of the outer conductors: 20.5 mm) for soil θ and σ_a estimations was also made (SWC_P). In both cases, a 4 cm length coaxial cable connected the three-rods of the TDR probe to a male-BNC connector. The head of the two TDR probes (3-cm height) was made of a commercial available epoxy resin.

2.4. Laboratory calibration and validation experiments

A laboratory experiment was performed to calculate the K_p values of WEC_P and SWC_P. This was experimentally estimated from Eq. (5) by immersing the WEC_P (without ceramic disks) and SWC_P in cylindrical plastic containers (200 mm internal diameter -i.d.-, and 200 mm height) filled with six NaCl solutions of EC = 0.5, 1, 2, 5, 10 and 15 dS m^{-1}. The EC was measured with a Crison conductimeter model 522, and all values were corrected to 25 ºC (Eq. 10).

A new series of laboratory experiments were performed to calculate the β and τ coefficients (Mualem and Friedman, 1991) (Eqs. 7 and 8) of the WEC_P ceramic disks. The τ coefficient (Eq. 8) was calculated in a column experiment, in which the WEC_P inserted in the ceramic disks was located in the plastic containers. A first measurement of θ and σ_a was done with the ceramic disks dry. Next, the WEC_P was immersed in the container filled with distilled water and θ and σ_a were recorded 24 h later. This procedure was repeated using the previous six NaCl solutions. In all cases, a previously free salts WEC_P was used. The τ coefficient was numerically calculated by minimizing the Root Mean Square Error (RMSE) between the TDR-measured σ_a (Eq. 5) and the calculated σ_{a-sat} (Eq. 8) for an average θ_{sat}.

The β factor was estimated in a subsequent laboratory experiment in which the WEC_P was located in a pressure cell. This consisted of a plastic tube (41.5 mm i.d. and 86.0 mm height) closed at both ends with two plastic lids (41.5 mm i.d. and 36.0 and 7.6 mm height for the top and bottom lids, respectively) drilled with a single hole. Two rubber joints placed between the lids and the plastic tube hermetically closed the pressure cell. A first measurement of θ and σ_a was done with the ceramic disks dry. Next, the WEC_P was saturated by injecting a 5 dS m^{-1} NaCl solution through the base of the pressure-cell. The ceramic disks were considered saturated and equilibrated with the NaCl solution when it exited the top of the pressure cell with the same EC then that used to saturate the WEC_P. This process took approximately 24 hours. Next, the ceramic disks of the WEC_P were sequentially desaturated at different pressure heads (3, 5, 10, 50 and 100 kPa) by injecting air through the top of the pressure cell. The extracted water was collected and its EC was measured. The values of θ and σ_a were recorded at soil saturation and 24 hours following each pressure-head step. This experiment was repeated twice using a 10 dS m^{-1} NaCl solution. Finally, assuming a negligible $\sigma_{a\text{-}s}$ (Eq. 7), the β factor was numerically calculated by minimizing the RMSE between the measured σ_w and the estimated σ_w (Eq. 7), for an average θ_{sat}.

This TDR probe was validated in a pressure cell laboratory experiment and under field conditions. The pressure cell consisted of a plastic tube (90 mm i.d., 240 mm height) with a 6 mm i.d. hole drilled at 150 mm height, and closed at the ends with two plastic lids (Fig. 1). The bottom lip had inserted a 0.5 bar ceramic plate (7-mm thick and 50-mm in diameter) (Soil Moisture Inc. UK), which was placed on a 6 mm i.d. hole. These two holes allowed the flow of air and water during the soil wetting and draining processes. Two female-female BNC connectors, in which the WEC$_P$ and SWC$_P$ were connected, were inserted though the top lip. A thermocouple was also inserted in the pressure cell for soil temperature measurements. The cell was filled up and uniformly packed with sand (80–160 μm grain size) until the head of the TDR probes were half covered. Next, a 10 dS m^{-1} NaCl solution was slowly injected through the base of the pressure cell until the EC of the outlet solution equalled the inlet one (24 hours approximately). The total volume of water added was approximately four times the total soil porosity. Once the sand was saturated and equilibrated with the NaCl solution, the column was sequentially drained at pressure heads of 0.5, 3, 5, 10, 50 and 100 kPa, by injecting air through the lateral pressure cell hole. The water drained at each pressure head was collected and the corresponding EC measured. Values of θ and σ_a obtained with the WEC$_P$ and SWC$_P$ were recorded at soil saturation and 24 hours after imposing each pressure head. According to Eq. (8), σ_w was calculated from the measured θ and σ_a values and the β and τ factors estimated in the previous experiments. The σ_w values were corrected to 25 ºC (Eq. 10). This experiment was repeated using a 2-mm sieved loam soil saturated with three different KCl solutions of 2, 5 and 10 dS m^{-1}. Finally, the TDR-estimated σ_w values were statistically compared to the measured EC values in the inlet solutions.

2.5. Field testing

The field experiment consisted in comparing the σ_w estimated by WEC$_P$ to the EC values measured in the soil solution extracted with ceramic tension lysimeters (TL). The experiment was performed on a loam soil located in an apple orchard of the Estación Experimental de Aula Dei (Zaragoza). The soil bulk density was 1.33 g cm^{-3}. Three TL (model SPS 200 - SDEC) were inserted into the soil at the vertices of a 15 cm equilateral triangle, the WEC$_P$ was inserted in the center of the triangle, and the SWC$_P$ at a 9 cm distance from the WEC$_P$. Both TDR probes were inserted at the same depth that the TL. The heads of the two TDR probes were buried 1 cm under the soil surface. The experimental plot was confined in a 40 cm diameter and 50 cm height plastic tube driven 1 cm into the soil. Successive soil wetting-drainage cycles were repeated with distilled water and KCl-water solutions of different EC (Table 1) until soil equilibrium. Systematic measurements of θ and σ_a were recorded with the WEC$_P$ and SWC$_P$, and the soil solution was extracted with the TL for the measurement of σ_w. Soil temperatures were measured with a thermocouple sensor installed at 7 cm depth inside the experimental plot. The average σ_w measured in the solutions extracted with the three TLs were compared to the corresponding σ_w values estimated with the WEC$_P$ from the recorded θ and σ_a values (Eq. 9). All σ_w were corrected at 25 ºC

3. RESULTS AND DISCUSION

The K_p value of WEC$_P$ without the ceramic disks and SWC$_P$ estimated from the laboratory experiment were 3.36 and 3.44 m^{-1}, respectively. The A and B empirical factors of Eq. (3)

applied to the WEC_P and SWC_P to calculate the volumetric water content corresponded to the respective 0.176 and 0.115 values given by Topp and Reynolds (1998) (Eq. 2).

The average θ_{sat} used in Eq. (8) and (7) to calculate the τ and β factors and estimate σ_w was 0.389 $cm^3 cm^{-3}$. The τ factor (Eq. 8) obtained from the laboratory experiment under saturated conditions was 1.957. This value, which was slightly higher than the 1.5 value proposed by Mualem and Friedman (1991) for coarse-textured soils, allowed an excellent correlation ($p < 0.001$) between the σ_{a-sat} measured by WEC_P and calculated with Eq. 8 (Fig. 2). The β value (Eq. 7), calculated from the pressure cell experiments was 4.282. This value, almost twice higher than the 2.5 value reported by Mualem and Friedman (1991) for coarse-textured soils, also allowed an excellent ($p < 0.001$) correlation between the σ_a measured by WEC_P and calculated with Eq. 7 (Fig. 3). Exponential relationships were found between θ and σ_a measured with the WEC_P (Fig. 4) in the pressure cell and the sand and 2-mm sieved loam soil columns experiments. As described by the Mualem and Friedman (1991) model, σ_a exponentially decreases with decreases in θ, and the θ-σ_a slopes get smoother with decreasing σ_w values (Fig. 4). Finally, a noble correlation ($p < 0.001$) was found between the σ_w measured in all the column experiments (water, pressure cell, sand and loam soil) and the corresponding σ_w estimates with the WEC_P (Eq. 9) for estimated θ, σ_a, θ_{sat} and β and τ factors (Eq. 7 and 8) (Fig. 5).

Figure 6 shows the time-evolution of θ and σ_a measured with SWC_P and WEC_P and σ_w estimated with WEC_P (Eq. 9) in the sand and 2-mm sieved loam soil column after being saturated with solutions of 2, 5 and 10 dS m^{-1} EC, and subsequently drained at pressure heads ranging between 3 and 100 kPa. The θ and σ_a values measured with the two TDR probes decreased with increasing pressure heads, but the decrease was in general much smaller with WEC_P than with SWC_P. As shown in Fig. 4, the amplitude of σ_a as a function of θ increases with increasing solution EC. Important differences in σ_a measured with the SWC$_P$ were observed between the sand and the loam soil columns. This should be attributed to the different β and τ factors of these porous media. Thus, the τ and β factors approached from the θ and σ_a measured in the laboratory experiments with the SWC$_P$ were 1.66 and 1.45 for the sand and 2.04 and 1.69 for the 2-mm sieved loam soil, respectively. The most relevant result shown in Fig. 6 is that σ_w estimated with the WEC$_P$ using Eq. 9 was independent of θ and the porous media in which the probe was inserted, and that it was similar to the σ_w imposed with the different NaCl or KCl solutions. These results indicate that the new TDR probe is a feasible method for accurate and non-destructive estimates of soil solution EC for the porous media and pressure heads examined in this work.

The results obtained in the laboratory experiments were supported by those obtained under field conditions where the σ_w values estimated with the WEC$_P$ were compared to those measured in the soil solutions extracted with the three tension lysimeters (TL). Overall, an excellent correlation ($P < 0.001$) was observed between the TDR-estimated σ_w and the TL-measured σ_w, with a regression coefficient not significantly different from one (Fig. 7).

The dynamics of θ and σ_a measured with SWC$_P$ and WEC$_P$ and the σ_w measured with the TL and estimated with the WEC$_P$ were similar to those observed in the laboratory. While σ_a was in all cases dependent on θ and on the EC of the infiltrating solution, σ_w estimated with the WEC$_P$ was only dependent on the EC of the infiltrating solution. Hence, σ_w did not change appreciably with time (i.e., with decreases in θ), in contrast with the observed sharp decreases of σ_a with time (Fig. 8). An increase of σ_w was observed when the KCl solutions were added in subsequent events to the soil, so that they were similar to the σ_w measured in the soil solution extracted by the TL. Similarly, the WEC$_P$ estimated σ_w and the TL-measured σ_w were also similar during the leaching process (i.e., addition of distilled water in cumulative days 58 and 65), except in the 48 hrs following the application of distilled water (Fig. 8). These results suggest that the WEC_P needs almost two days to equilibrate the solution within the ceramic discs with the solution within the soil pores. This response time of the WEC_P is not a relevant handicap for the long-term assessment of soil salinity.

4. CONCLUSIONS

This work presents a new TDR probe (WEC_P) to estimate the soil solution electrical conductivity. The design, consisting in a three-rod TDR probe embedded in fourteen porous ceramics disks, is based in the hypothesis that the solution in the ceramic disks equilibrates with the soil solution present in the soil pores. Since the ceramic disks have a constant porous-geometry, a unique ceramic-specific σ_w-σ_a-θ calibration is required. The new probe was calibrated and subsequently validated in laboratory and field experiments. The results demonstrate that the new TDR probe allows accurate estimates of soil solution EC (σ_w) independently of the soil water contents imposed in these experiments. Although the TDR equipment used in these experiments is relatively expensive, the large versatility of this technique, which allows working with homemade TDR probes, allows achieving a return on the investment. Some advantages of this new design of TDR probe can be summarized as: (a) low cost sensor (made from a simple TDR probe and commercial available ceramic discs); (b) quick and easy field installation; and (c) robustness and low maintenance cost. However, further efforts should be done to (i) incorporate a temperature sensor that will correct σ_w to a reference temperature of 25 ºC, (ii) use alternative porous media to estimate σ_w at higher pressure heads while minimizing the response time to changes in the external soil solution, (iii) improve the TDR probe design to allow simultaneous estimates of σ_w and the soil matric potential, and (iv) include the Mualem and Friedman (1991) model, or similars to estimate σ_w

in available TDR software (i.e. TDR-Lab) for faster estimates of the soil solution electrical conductivity.

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Figure captions

Figure 1. Diagram of the pressure cell used to validate the TDR probe to estimate the water solution electrical conductivity ($\mathrm{WEC_P}$). $\mathrm{SWC_P}$ denotes a 10-cm long standard TDR probe.

Figure 2. Relationship and linear regression equation between $\sigma_{a\text{-}sat}$ measured by TDR and model-calculated $\sigma_{a\text{-}sat}$ with Eq. 8 using the optimized τ factor obtained with the $\mathrm{WEC_P}$ from the column experiments under saturated conditions.

Figure 3. Relationship and linear regression equation between σ_a measured by TDR and model-calculated σ_a with Eq. 7 using the optimized τ and β factors and the averaged θ_{sat} from all the column experiments.

Figure 4. Relationships between σ_a and θ model-calculated with Eq. 7 (lines) and measured with the $\mathrm{WEC_P}$ (circles) obtained from the pressure cell, sand and loam soil column experiments using three NaCl solutions of 2, 5 and 10 dS $\mathrm{m^{-1}}$ ECs.

Figure 5. Relationship and linear regression equation between σ_w CC measured in all the column experiments (water, pressure cell, sand and loam soil) and σ_w estimated with $\mathrm{WEC_P}$ (σ_w TDR) using Eq. (9).

Figure 6. Time evolution of σ_a and θ measured with $\mathrm{SWC_P}$ and $\mathrm{WEC_P}$, and σ_w estimated with $\mathrm{WEC_P}$ in the sand and loam soil column experiments after being saturated with solutions

of 2, 5 and 10 dS m^{-1} EC (right Y-axis), and subsequently drained at pressure heads ranging between 3 and 100 kPa.

Figure 7. Relationship and linear regression equation between the average soil solution EC measured in the solutions extracted with the three tension lysimeters (σ_w TL) and the corresponding σ_w values estimated with the WEC_P (σ_w TDR). The horizontal segments denote ± one standard deviation of the mean σ_w TL.

Figure 8. Time evolution of soil temperature, θ and σ_a measured with SWC_P and WEC_P, σ_w estimated with WEC_P, and mean σ_w measured in the soil solutions extracted with the three tension lysimeters (TL). The cumulative days at which the solutions of a given EC were added to the soil are also shown in the bottom figure. The vertical segments denote ± one standard deviation of the mean σ_w TL.

A new TDR probe for measurements of soil solution electrical conductivity

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ABSTRACT

The measurement of the soil solution electrical conductivity (σ_w) is critical for a better management of irrigation water and the effective monitoring and control of soil salinity. The objective of this work is to present the design and validation of a new time domain reflectometry (TDR) probe (WEC$_P$) for accurate and non-destructive measurements of σ_w. The probe consists in fourteen porous ceramics disks (0.5 bar bubbling pressure) arranged along the axis of a three-rod TDR probe. Using the Mualem and Friedman (1991) model, σ_w was estimated from the volumetric water content (θ) and the bulk electrical conductivity (σ_a) measured in the ceramic disk set of known pore-geometry. The ~~tortuosity~~ τ and β factors, which ~~(τ),~~ describ~~ing~~e the complex geometry of the ceramic matri~~x,~~x, ~~was~~ were calculated by immersing the probe in NaCl solutions of different electrical conductivities, and ~~. The β factor, which depends on the soil water transmission porosity, was estimated~~ in a pressure cell wetted and drained with these NaCl solutions, respectively. The reliability of the WEC$_P$ was validated under laboratory and field conditions. The laboratory experiment consisted of the TDR probe inserted in a pressure cell packed with mixed sand and 2-mm sieved loam soil that was subsequently wetted and drained with different NaCl solutions at various pressure heads. The σ_w estimated by WEC$_P$ was compared to the σ_w measured in the draining solutions after they stabilized in the soil porous system. The field experiment compared the σ_w estimated by WEC$_P$ with the corresponding σ_w values measured in the soil solution extracted with three ceramic tension lysimeters (TL) after successive wetting and drainage cycles. The τ and β factors calculated for the ceramic disks set were 1.957 and 4.282, respectively. High and significant correlations ~~($R^2 = 0.975$; $P < 0.001$)~~ were found in both laboratory ($R^2 = 0.98$; $P < 0.001$) and field ($R^2 = 0.97$; $P < 0.001$) experiments between the σ_w estimated by the WEC$_P$ and the corresponding σ_w values measured in the column-drainage or TL-extracted soil solutions, respectively. These results demonstrate that the WEC_P is a feasible instrument to accurately estimate soil solution salinity independently of the soil water content and the porous medium in which the TDR probe is installed.

Key words: Water content; Pore-geometry; Bulk electrical conductivity; Time Domain Reflectometry

INTRODUCTION

Soil salinity, defined as the total concentration of dissolved salts in the soil solution, has a detrimental effect on crops and soil chemical and physical properties (Leone et al., 2007). Hence, the accurate measurement of soil salinity is crucial for the productivity and sustainability of irrigated agriculture. Soil salinity is most conveniently measured from the electrical conductivity (EC) of its soil solution (σ_w) (White, 2003). Currently, three basic procedures are used to measure or estimate soil salinity (Hendrickx et al., 2002): (i) the EC of soil water extracts, (ii) the EC of the soil solution extracted with tension lysimeters, and (iii) the apparent soil bulk EC (σ_a) using different methods. The classical soil water extracts using various soil:water ratios, such as the soil saturation extract, are laborious, destructive and impractical when many soil samples are analyzed. The in-situ soil solution extraction method is commonly performed using ceramic tension lysimeters (Parizek and Burke, 1970). This low-cost method allows periodic sampling of the soil solution with minimal soil disturbance. Although the tension lysimeters have evolved to new designs (i.e., Wagner, 1962; Linden, 1977; Hubbell and Sisson, 1996), the method is tiresome and limited to soils with relatively high water contents and a proper soil-ceramic contact. Indirect methods to estimate soil salinity are based on the measurement of σ_a determined with electrical resistivity, time domain reflectometry (TDR), or electromagnetic induction techniques. These non-destructive methods estimate σ_w from σ_a and the volumetric soil water content (θ) by using empirical calibration equations or physical based models (Hendrickx et al., 2002).

The TDR is a non-destructive method that allows real time and simultaneous measurements of the apparent permittivity (ε_a), which is related with θ, and σ_a (Topp and Ferré, 2002). The ε_a is calculated from the transit time of the TDR pulse propagating one return trip along a waveguide of length L. Based on the Giese and Tiemann (1975) model, σ_a is calculated from the attenuation of the long-time reflection coefficient recorded with an uncoated probe (Lin et al., 2008). The σ_a depends mainly on three variables, effective θ, σ_w, and a geometric factor which accounts for the complex geometry of the soil matrix (Rhoades et al., 1976; Mualem and Friedman, 1991). Several models relating σ_a to σ_w as a non-linear function of θ have been developed and applied to mineral soils (Rhoades et al., 1976; Rhoades et al., 1989; Mualem and Friedman, 1991; Vogeler et al., 1996; Persson, 1997; Hilhorst, 2000; Muñoz-Carpena et al., 2005). Persson (2002), working with TDR probes installed in sandy soils, showed that the Hilhorst (2000) model was as good as other commonly used models for σ_w estimates with significant dependency of the linear model on soil type. Mortl et al. (2011) compared four equations relating σ_w, σ_a and θ for three soil series encountered in the floodplain of a southeastern coastal river in USA, and found that the empirical relationship proposed by Vogeler et al. (1996) performed the best (overall $R^2 = 0.97$ for the three soils), though all models performed satisfactorily in all soils ($0.94 \leq R^2 \leq 0.98$). Despite all these efforts, σ_w can be only consistently predicted from σ_a if the relationship between σ_w, σ_a and θ is known (~~Yasser~~ Hamed et al., 2006). Due to variations in responses from different soil types, soil-specific σ_w-σ_a-θ calibrations are commonly required (Mortl et al., 2011).

This work presents a new TDR design for accurate and non-destructive estimates of σ_w. The TDR probe, which consists in fourteen porous ceramics disks arranged along the axis of a three-rod TDR probe, estimates σ_w from θ and σ_a measured by TDR in the ceramic disks set. This method is based in the hypothesis that the soil solution is in equilibrium with that in the ceramic disks. Since a constant porous structure is defined inside the ceramic disks, a unique ceramic-specific σ_w-σ_a-θ calibration is required.

2. MATERIAL AND METHODS

2.1. TDR theory

The transit time of the TDR pulse propagating one return trip in a transmission line of length L (m), t_L, is expressed by

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

where c is the speed of light in free space (3 x 10^8 m s^{-1}) and ε_a is the apparent permittivity of the medium (Topp and Ferré, 2002). The t_L value is calculated as the distance between the time at which the signal enters the TDR rods (first peak) and the time when the signal arrives at the end of the TDR probe, also denoted as the second reflection or end point (Heimovaara, 1993).

Estimations of θ from ε_a can be calculated by the Topp and Reynolds (1998) linear calibration equation:

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

where t_s and t_{air} are the travel time of the TDR pulse propagating along the transmission line when immersed in soil and air, respectively. It is well know that ε_a increases with σ_a (Robinson et al., 2003; Evett et al., 2006). Assuming that the relaxation effects are negligible, Evett et al. (2005) proposed a θ calibration equation for conventional TDR in terms of σ_a, the travel time, and the effective frequency (f_{vi}, MHz) of the TDR pulse in a probe of length L as:

$$\theta = -A + B\left(\frac{t_s}{t_{air}}\right) - 0.004933\left[\frac{\sigma_a}{2\pi f_{vi}\varepsilon_0}\right]^{0.5} \qquad (3)$$

where ε_0 is the dielectric constant of free space (8.854 10^{-12} F m^{-1}) and A and B are empirical factors calculated from a calibration experiment.

The reflection coefficient, ρ, as a function of time, t, is typically defined as

$$\rho(t) = \frac{V(t) - V_0}{V_0 - V_i} \qquad -1 \le \rho \le +1 \qquad (4)$$

where $V(t)$ is the measured voltage at time t, V_0 is the voltage in the cable just prior to the insertion of 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 soil bulk electrical conductivity (σ_a) estimated with the long-time analysis of the TDR waveform is calculated using the Giese and Tiemann (1975) equation:

$$\sigma_a = \frac{K_p}{Z_r}\left(\frac{1 - \rho_{\infty,\mathrm{Scale}}}{1 + \rho_{\infty,\mathrm{Scale}}}\right) \qquad (5)$$

where 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 calculated from the characteristics of the TDR probe geometry (Evett et al., 2006), or by immersing the probe in different electrolyte solutions of known EC (Wraith, 2002). The $\rho_{\infty,\mathrm{Scale}}$ is the scaled steady-state reflection coefficient corresponding to the ideal condition in which there is no instrument error or cable resistance. The $\rho_{\infty,\mathrm{Scale}}$ is calculated using the equation described by Lin et al. (2008):

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

~~[illegible]~~ (6)

where ρ, ρ_{air} and ρ_{SC} are the long-time reflection coefficients measured in the studied medium, in air and in a short-circuited probe, respectively.

2.2. Soil solution electrical conductivity (σ_w) estimation

Following the hypothesis proposed by Mualem and Friedman (1991), which assume that the tortuosity factor affecting the soil bulk electrical conductivity (σ_a) is identical to that defined for predicting the soil hydraulic conductivity, $\sigma_a(\theta)$ can be expressed as:

$$\sigma_a(\theta) = \sigma_{a-sat}\left(\frac{\theta}{\theta_{sat}}\right)^{\beta} + \sigma_{a-s} \tag{7}$$

where $\sigma_{a\text{-}sat}$ and θ_{sat} are the soil bulk electrical conductivity and the volumetric soil water content at saturation, respectively, $\sigma_{a\text{-}s}$ is the bulk electrical conductivity of the soil solid phase, and β is as factor that depends on the soil water transmission porosity and defines the decrease rate between σ_a and θ. According to Mualem and Friedman (1991), $\sigma_{a\text{-}sat}$ can be defined as:

$$\sigma_{a-sat} = \sigma_w \theta_{sat}^{\tau} \tag{8}$$

where τ is a transmission coefficient at soil water saturation that describes the tortuous nature of the current lines that decreases the mobility of ions near the soil-liquid and liquid-gas interfaces. Taking the hypothesis that σ_w only depends on the dissolved salts (Rhoades et al., 1976), ~~it~~ σ_w could be theoretically estimated by combining equations (7) and (8)~~from:~~ as

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

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σ_w, which depends on temperature, T~~(~~$_{^oC}$~~)~~, was corrected to 25 ºC ($\sigma_{w/25}$) according to ~~as given by the empirical equation:~~ (Rhoades et al., 1999)

$$\sigma_{w/25} = \sigma_w * f \qquad (10)$$

where f is an empirical factor expressed as (US Salinity Laboratory Staff, 1954)

$$f = 1 - 0.20346\,(T) + 0.03822\,(T^2) - 0.00555\,(T^3), \qquad (11)$$

and $T = (T_{^oC} - 25)/10$

~~$\sigma_w = 0.0004748\,T^2 - 0.0439144\,T + 1.7995021 \quad R^2 = 0.999 \quad (10)$~~

2.3. ~~Design,~~ TDR probe designs ~~calibration and validation of the TDR probe~~

All TDR measurements were performed using a TDR100 (Campbell Sci.) model cable tester. A 1.0-m 50-Ω coaxial cable directly connected the TDR probes to the TDR pulser. The TDR waveforms were transferred to a computer for display and analysis using the software TDR-Lab V.1.0. (Moret-Fernández et al., 2010), which automatically calculates ε_a and σ_a.

The TDR probe used to estimate the soil water pore electrical conductivity (WEC$_P$) is similar to the design developed by Or and Wraith (1999) for measuring the soil matric potential. This consists in fourteen disks (7-mm thick and 40-mm in diameter) of commercially available porous ceramics plates with a bubbling pressure of -0.5 bar (Soil Moisture Inc. UK). The disks were arranged along the axis of a three-rod TDR probe (rod length: 101.4 mm; rod diameter: 2.7 mm; spacing of the outer conductors: 20.0 mm). A second three-rod TDR probe without the ceramic disks (rod length: 100.2 mm; rod diameter: 2.4 mm; spacing of the outer conductors: 20.5 mm) for soil θ and σ_a estimations was also made

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(SWC$_P$). In both cases, a 4 cm length coaxial cable connected the three-rods of the TDR probe to a male-BNC connector. The head of the two TDR probes (3-cm height) was made of a commercial available epoxy resin.

2.4. Laboratory calibration and validation experiments

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A laboratory experiment was performed to calculate the K_p values of WEC$_P$ and SWC$_P$. This was experimentally estimated from Eq. (5) by immersing the WEC$_P$ (without ceramic disks) and SWC$_P$ in cylindrical plastic containers (200 mm internal diameter -i.d.-, and 200 mm height) filled with six NaCl solutions of EC = 0.5, 1, 2, 5, 10 and 15 dS m^{-1}. The EC was measured with a Crison conductimeter model 522, and all values were corrected to 25 ºC (Eq. 10).

A new series of laboratory experiments were performed to calculate the β and τ coefficients (Mualem and Friedman, 1991) (Eqs. 7 and 8) of the WEC$_P$ ceramic disks. The τ coefficient (Eq. 8) was calculated in a column experiment, in which the WEC$_P$ inserted in the ceramic disks was located in the plastic containers. A first measurement of θ and σ_a was done with the ceramic disks dry. Next, the WEC$_P$ was immersed in the container filled with distilled water and θ and σ_a were recorded 24 h later. This procedure was repeated using the previous six NaCl solutions. In all cases, a previously free salts WEC$_P$ was used. The τ coefficient was numerically calculated by minimizing the Root Mean Square Error (RMSE) between the TDR-measured σ_a (Eq. 5) and the calculated $\sigma_{a\text{-}sat}$ (Eq. 8) for an average θ_{sat}.

The β factor was estimated in a subsequent laboratory experiment in which the WEC$_P$ was located in a pressure cell. This consisted ~~in~~ of a plastic tube (41.5 mm i.d. and 86.0 mm height) closed at both ends with two plastic lids (41.5 mm i.d. and 36.0 and 7.6 mm height for the top and bottom lids, respectively) drilled with a single hole. Two rubber joints placed between the lids and the plastic tube hermetically closed the pressure cell. A first measurement of θ and σ_a was done with the ceramic disks dry. Next, the WEC$_P$ was saturated by injecting a 5 dS m^{-1} NaCl solution through the base of the pressure-cell. The ceramic disks were considered saturated and equilibrated with the NaCl solution when it exited the top of the pressure cell with the same EC then that used to saturate the WEC$_P$. This process took approximately 24 hours. Next, the ceramic disks of the WEC$_P$ were sequentially desaturated at different pressure heads (3, 5, 10, 50 and 100 kPa) by injecting air through the top of the pressure cell. The extracted water was collected and its EC was measured. The values of θ and σ_a were recorded at soil saturation and 24 hours following each pressure-head step. This experiment was repeated twice using a 10 dS m^{-1} NaCl solution. Finally, assuming a negligible σ_{a-s} (Eq. 7), the β factor was numerically calculated by minimizing the RMSE between the measured σ_w and the estimated σ_w (Eq. 7), for an average θ_{sat}.

This TDR probe was validated in a pressure cell laboratory experiment and under field conditions. The pressure cell consisted of a plastic tube (90 mm i.d., 240 mm height) with a 6 mm i.d. hole drilled at 150 mm height, and closed at the ends with two plastic lids (Fig. 1). The bottom lip had inserted a 0.5 bar ceramic plate (7-mm thick and 50-mm in diameter) (Soil Moisture Inc. UK), which was placed on a 6 mm i.d. hole. These two holes allowed the flow of air and water during the soil wetting and draining processes. Two female-female BNC connectors, in which the WEC$_P$ and SWC$_P$ were connected, were inserted though the top lip. A thermocouple was also inserted in the pressure cell for soil temperature measurements. The cell was filled up and uniformly packed with sand (80–160 μm grain size) until the head of the TDR probes were half covered. Next, a 10 dS m^{-1} NaCl solution was slowly injected through the base of the pressure cell until the EC of the outlet solution equalled the inlet one (24 hours approximately). The total volume of water added ~~using a volume of~~ was approximately four times the total soil porosity~~. (24 hours approximately), and the EC of the outlet solution equalled the inlet one~~. Once the sand was saturated and equilibrated with the NaCl solution, the column was sequentially drained at pressure heads of 0.5, 3, 5, 10, 50 and 100 kPa, by injecting air through the lateral pressure cell hole. The water drained at each pressure head was collected and the corresponding EC measured. Values of θ and σ_a obtained with the $\mathrm{WEC_P}$ and $\mathrm{SWC_P}$ were recorded at soil saturation and 24 hours after imposing each pressure head. According to Eq. (8), σ_w was calculated from the measured θ and σ_a values and the β and τ factors estimated in the previous experiments. The σ_w values were corrected to 25 ºC (Eq. 10). This experiment was repeated using a 2-mm sieved loam soil saturated with three different KCl solutions of 2, 5 and 10 dS m^{-1}. Finally, the TDR-estimated σ_w values were statistically compared to the measured EC values in the inlet solutions.

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2.5. Field testing

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The field experiment consisted in comparing the σ_w estimated by $\mathrm{WEC_P}$ to the EC values measured in the soil solution extracted with ceramic tension lysimeters (TL). The experiment was performed on a loam soil located in an apple orchard of the Estación Experimental de Aula Dei (Zaragoza). The soil bulk density was 1.33 g cm^{-3}. Three TL (model SPS 200 - SDEC) were inserted into the soil at the vertices of a 15 cm equilateral triangle, the $\mathrm{WEC_P}$ was inserted in the center of the triangle, and the $\mathrm{SWC_P}$ at a 9 cm distance from the $\mathrm{WEC_P}$. Both TDR probes were inserted at the same depth that the TL. The heads of the two TDR probes were buried 1 cm under the soil surface. The experimental plot was confined in a 40 cm diameter and 50 cm height plastic tube driven 1 cm into the soil. Successive soil wetting-drainage cycles were repeated with distilled water and KCl-water solutions of different EC

(Table 1) until soil equilibrium. Systematic measurements of θ and σ_a were recorded with the WEC$_P$ and SWC$_P$, and the soil solution was extracted with the TL for the measurement of σ_w. Soil temperatures were measured with a thermocouple sensor installed at 7 cm depth inside the experimental plot~~ (Fig. 1)~~. The average σ_w measured in the solutions extracted with the three TLs were compared to the corresponding σ_w values estimated with the WEC$_P$ from the recorded θ and σ_a values (Eq. 9). All σ_w were corrected at 25 ºC

3. RESULTS AND DISCUSION

The K_p value of WEC$_P$ without the ceramic disks and SWC$_P$ estimated from the laboratory experiment were 3.36 and 3.44 m^{-1}, respectively. The A and B empirical factors of Eq. (3) applied to the WEC$_P$ and SWC$_P$ to calculate the volumetric water content corresponded to the respective 0.176 and 0.115 values given by Topp and Reynolds (1998) (Eq. 2).

The average θ_{sat} used in Eq. (8) and (7) to calculate the τ and β factors and estimate σ_w was 0.389 cm^3 cm^{-3}. The τ factor (Eq. 8) obtained from the laboratory experiment under saturated conditions was 1.957. This value, which was slightly higher than the 1.5 value ~~that ~~proposed by Mualem and Friedman (1991) for coarse-textured soils, allowed an excellent correlation (p < 0.001) between the $\sigma_{a\text{-}sat}$ measured by WEC$_P$ and calculated with Eq. 8 (Fig. 2). The β value (Eq. 7), calculated from the pressure cell experiments was 4.282. This value, almost twice higher than th~~at~~e 2.5 value reported by Mualem and Friedman (1991) for coarse-textured soils, also allowed an excellent (p < 0.001) correlation between the σ_a measured by WEC$_P$ and calculated with Eq. 7 (Fig. 3). Exponential relationships were found between θ and σ_a measured with the WEC$_P$ (Fig. 4) in the pressure cell and the sand and 2-mm sieved loam soil columns experiments. As described by the Mualem and Friedman (1991) model, σ_a exponentially decreases with decreases in θ, and the θ-σ_a slopes get smoother with decreasing

σ_w values (Fig. 4). Finally, a~~n~~ ~~excellent~~ noble correlation ($p < 0.001$) was found between the σ_w measured in all the column experiments (water, pressure cell, sand and loam soil) and the corresponding σ_w estimates with the WEC$_P$ (Eq. 9) for estimated θ, σ_a, θ_{sat} and β and τ factors (Eq. 7 and 8) (Fig. 5).

Figure 6 shows the time-evolution of θ and σ_a measured with SWC$_P$ and WEC$_P$ and σ_w estimated with WEC$_P$ (Eq. 9) in the sand and 2-mm sieved loam soil column after being saturated with solutions of 2, 5 and 10 dS m^{-1} EC, and subsequently drained at pressure heads ranging between 3 and 100 kPa. The θ and σ_a values measured with the two TDR probes decreased with increasing pressure heads, but the decrease was in general much smaller with WEC$_P$ than with SWC$_P$. As shown in Fig. 4, the amplitude of σ_a as a function of θ increases with increasing solution EC. Important differences in σ_a measured with the SWC$_P$ were observed between the sand and the loam soil columns. This should be attributed to the different β and τ factors of these porous media. Thus, the τ and β factors approached from the θ and σ_a measured in the laboratory experiments with the SWC$_P$ were 1.66 and 1.45 for the sand and 2.04 and 1.69 for the 2-mm sieved loam soil, respectively. The most relevant result shown in Fig. 6 is that σ_w estimated with the WEC$_P$ using Eq. 9 was independent of θ and the porous media in which the probe was inserted, and that it was similar to the σ_w imposed with the different NaCl or KCl solutions. These results indicate that the new TDR probe is a feasible method for accurate and non-destructive estimates of soil solution EC for the porous media and pressure heads examined in this work.

The results obtained in the laboratory experiments were supported by those obtained under field conditions where the σ_w values estimated with the WEC$_P$ were compared to those measured in the soil solutions extracted with the three tension lysimeters (TL). Overall, an excellent correlation ($P < 0.001$) was observed between the TDR-estimated σ_w and the TL-measured σ_w, with a regression coefficient not significantly different from one (Fig. 7).

The dynamics of θ and σ_a measured with SWC_P and WEC_P and the σ_w measured with the TL and estimated with the WEC_P were similar to those observed in the laboratory. While σ_a was in all cases dependent on θ and on the EC of the infiltrating solution, σ_w estimated with the WEC_P was only dependent on the EC of the infiltrating solution. Hence, σ_w did not change appreciably with time (i.e., with decreases in θ), in contrast with the observed sharp decreases of σ_a with time (Fig. 8). An increase of σ_w was observed when the KCl solutions were added in subsequent events to the soil, so that they were similar to the σ_w measured in the soil solution extracted by the TL. Similarly, the WEC_P estimated σ_w and the TL-measured σ_w were also similar during the leaching process (i.e., addition of distilled water in cumulative days 58 and 65), except in the 48 hrs following the application of distilled water (Fig. 8). These results suggest that the WEC_P needs almost two days to equilibrate the solution within the ceramic discs with the solution within the soil pores. This response time of the WEC_P is not a relevant handicap for the long-term assessment of soil salinity.

4. CONCLUSIONS

This work presents a new TDR probe (WEC_P) to estimate the soil solution electrical conductivity. The design, consisting in a three-rod TDR probe embedded in fourteen porous ceramics disks, is based in the hypothesis that the solution in the ceramic disks equilibrates with the soil solution present in the soil pores. Since the ceramic disks have a constant porous-geometry, a unique ceramic-specific σ_w-σ_a-θ calibration is required. The new probe was calibrated and subsequently validated in laboratory and field experiments. The results demonstrate that the new TDR probe allows accurate estimates of soil solution EC (σ_w)

independently of the soil water contents imposed in these experiments. Although the TDR equipment used in these experiments is relatively expensive, the large versatility of this technique, which allows working with homemade TDR probes, allows achieving a return on the investment. Some advantages of this new design of TDR probe can be summarized as: (a) low cost sensor (made from a simple TDR probe and commercial available ceramic discs); (b) quick and easy field installation; and (c) robustness and low maintenance cost. However, further efforts should be done to (i) incorporate a temperature sensor that will correct σ_w to a reference temperature of 25 ºC, (ii) use alternative porous media to estimate σ_w at higher pressure heads while minimizing the response time to changes in the external soil solution, (iii) improve the TDR probe design to allow simultaneous estimates of σ_w and the soil matric potential, and (iv) include the Mualem and Friedman (1991) model, or similars to estimate σ_w in available TDR software (i.e. TDR-Lab) for faster estimates of the soil solution electrical conductivity.

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Figure captions

Figure 1. Diagram of the pressure cell used to validate the TDR probe to estimate the water solution electrical conductivity ($\mathrm{WEC_P}$). $\mathrm{SWC_P}$ denotes a 10-cm long standard TDR probe.

Figure 2. Relationship and linear regression equation between $\sigma_{a\text{-}sat}$ measured by TDR and model-calculated $\sigma_{a\text{-}sat}$ with Eq. 8 using the optimized τ factor obtained with the $\mathrm{WEC_P}$ from the column experiments under saturated conditions.

Figure 3. Relationship and linear regression equation between σ_a measured by TDR and model-calculated σ_a with Eq. 7 using the optimized τ and β factors and the averaged θ_{sat} from all the column experiments.

Figure 4. Relationships between σ_a and θ model-calculated with Eq. 7 (lines) and measured with the $\mathrm{WEC_P}$ (circles) obtained from the pressure cell, sand and loam soil column experiments using three NaCl solutions of 2, 5 and 10 dS $\mathrm{m^{-1}}$ ECs.

Figure 5. Relationship and linear regression equation between σ_w CC measured in all the column experiments (water, pressure cell, sand and loam soil) and σ_w estimated with $\mathrm{WEC_P}$ (σ_w TDR) using Eq. (9).

Figure 6. Time evolution of σ_a and θ measured with $\mathrm{SWC_P}$ and $\mathrm{WEC_P}$, and σ_w estimated with $\mathrm{WEC_P}$ in the sand and loam soil column experiments after being saturated with solutions

of 2, 5 and 10 dS m^{-1} EC (right Y-axis), and subsequently drained at pressure heads ranging between 3 and 100 kPa.

Figure 7. Relationship and linear regression equation between the average soil solution EC measured in the solutions extracted with the three tension lysimeters (σ_w TL) and the corresponding σ_w values estimated with the WEC_P (σ_w TDR). The horizontal segments denote ± one standard deviation of the mean σ_w TL.

Figure 8. Time evolution of soil temperature, θ and σ_a measured with SWC_P and WEC_P, σ_w estimated with WEC_P, and mean σ_w measured in the soil solutions extracted with the three tension lysimeters (TL). The cumulative days at which the solutions of a given EC were added to the soil are also shown in the bottom figure. The vertical segments denote ± one standard deviation of the mean σ_w TL.

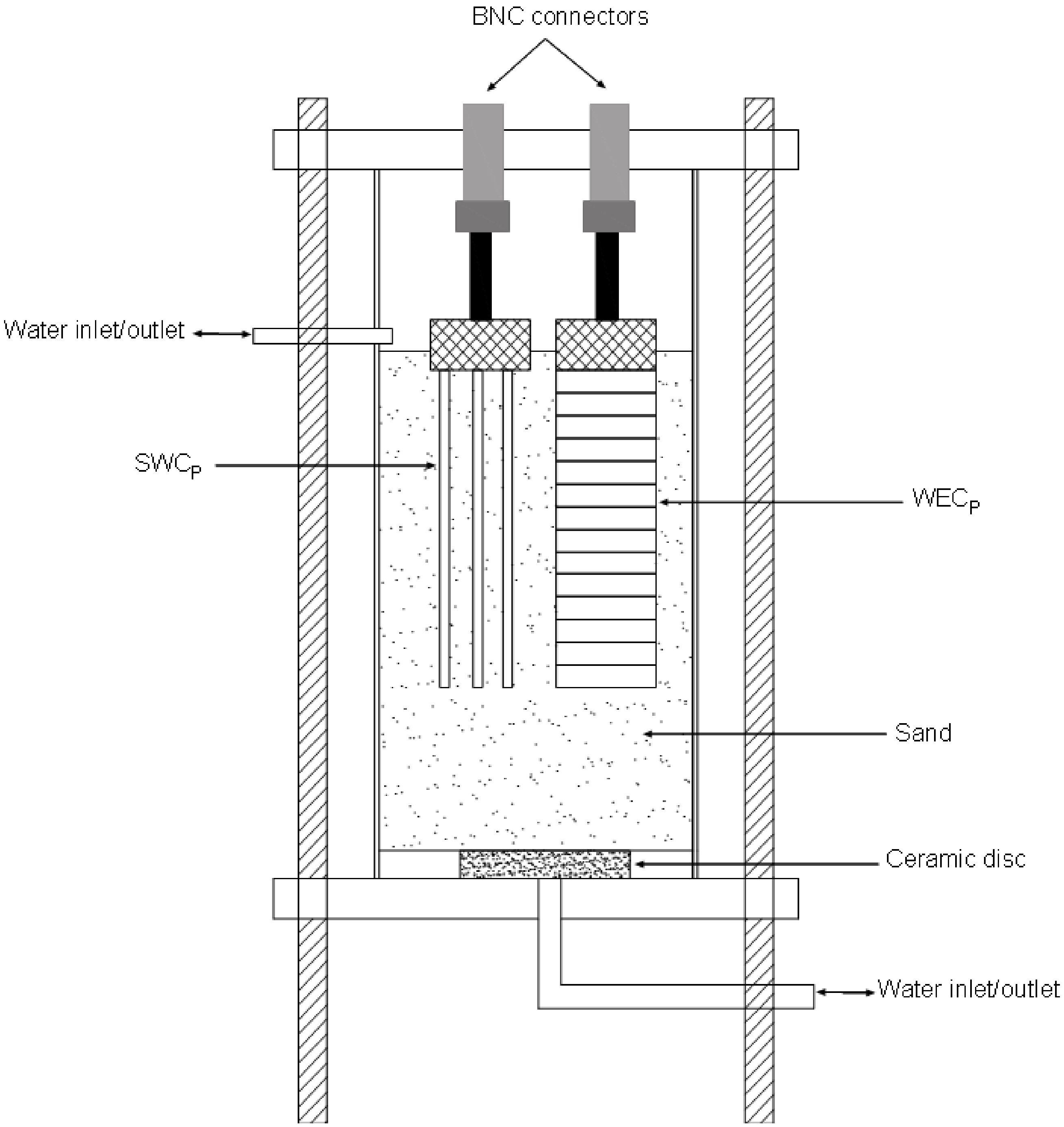
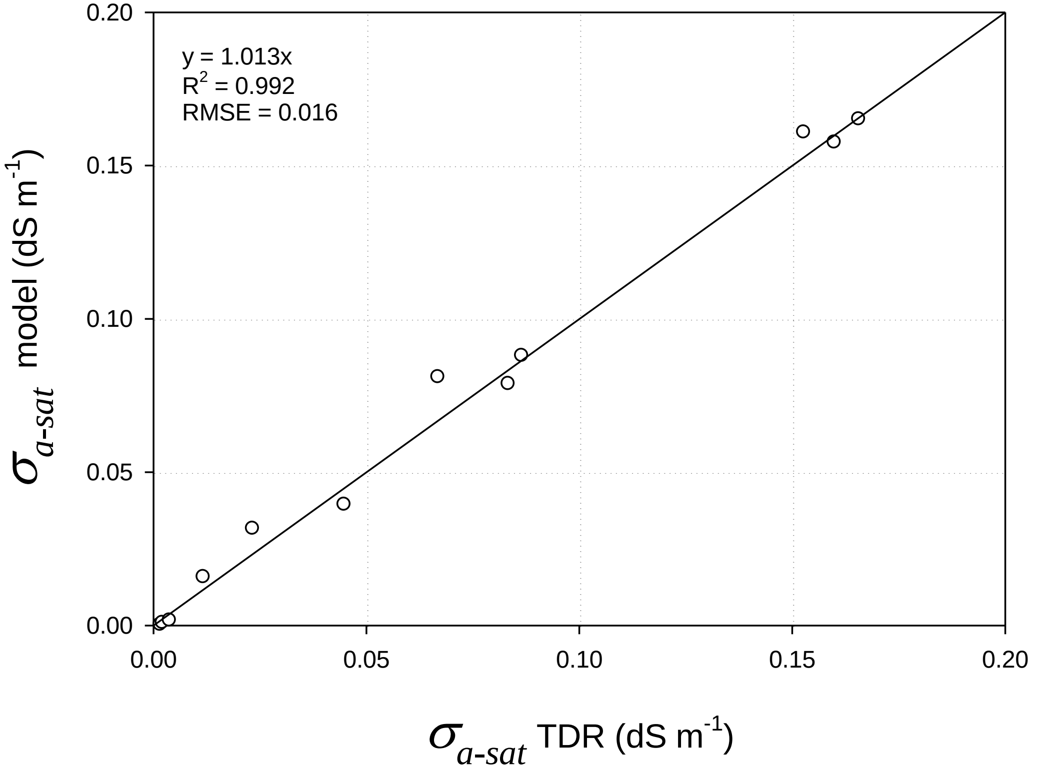

BNC connectors
Water inlet/outlet
SWC$_P$
WEC$_P$
Sand
Ceramic disc
Water inlet/outlet

Figure 1.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R² = 0.992
RMSE = 0.016
0.00
0.05
0.10
0.15
0.20
$\sigma_{a\text{-}sat}$ model (dS m^{-1})
$\sigma_{a\text{-}sat}$ TDR (dS m^{-1})

Figure 2.

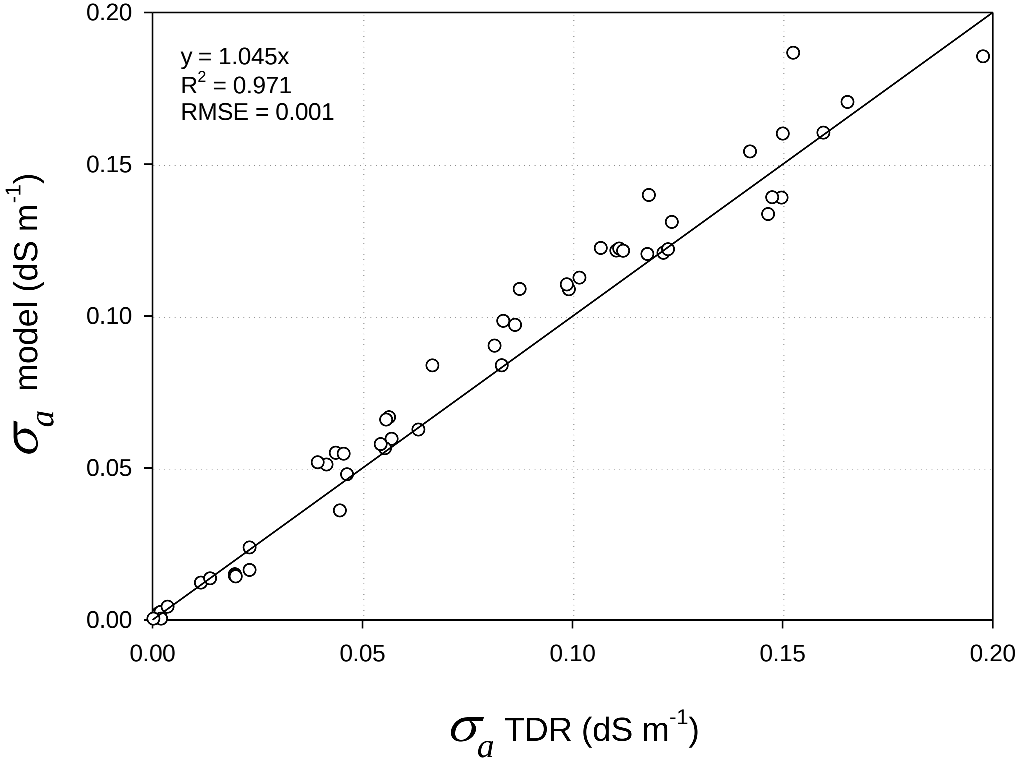
y = 1.045x
R^2 = 0.971
RMSE = 0.001
0.00
0.05
0.10
0.15
0.20
0.00
0.05
0.10
0.15
0.20
σ_a model (dS m^{-1})
σ_a TDR (dS m^{-1})

Figure 3.

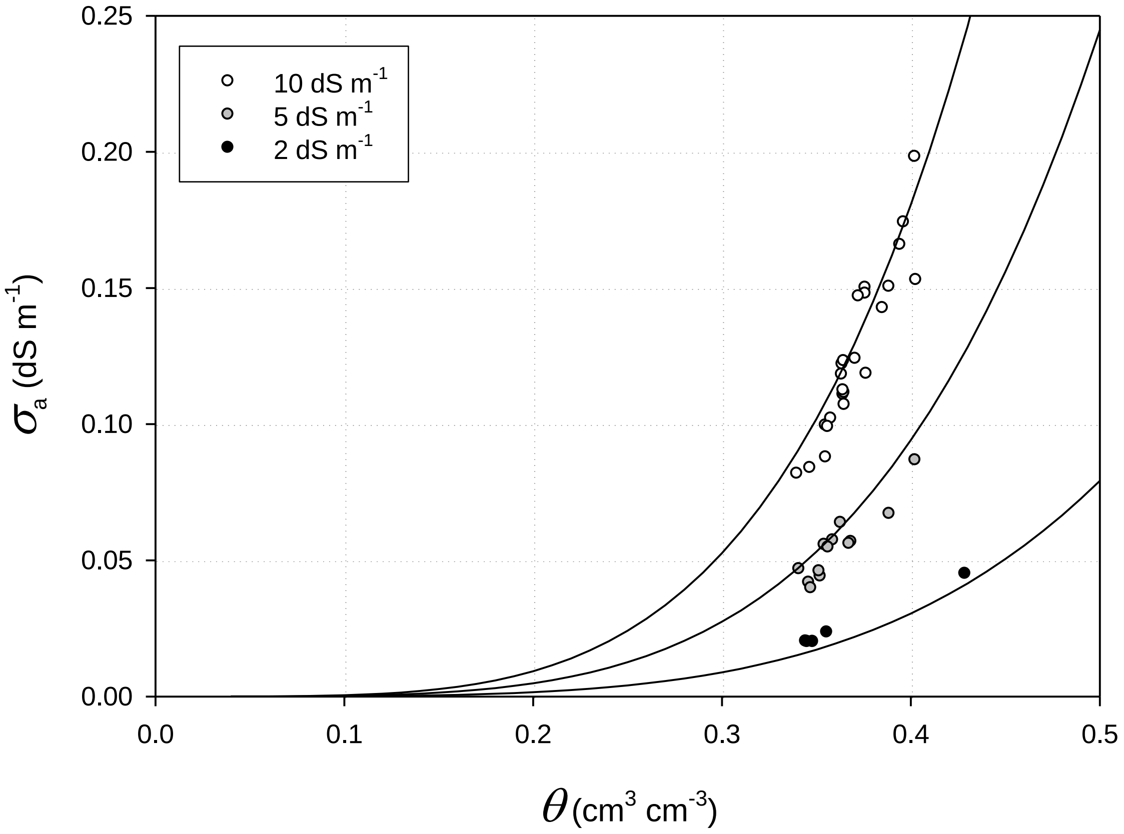
0.25
0.20
0.15
0.10
0.05
0.00
σ_a (dS m^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
θ (cm^3 cm^{-3})
○ 10 dS m^{-1}
● 5 dS m^{-1}
● 2 dS m^{-1}

Figure 4.

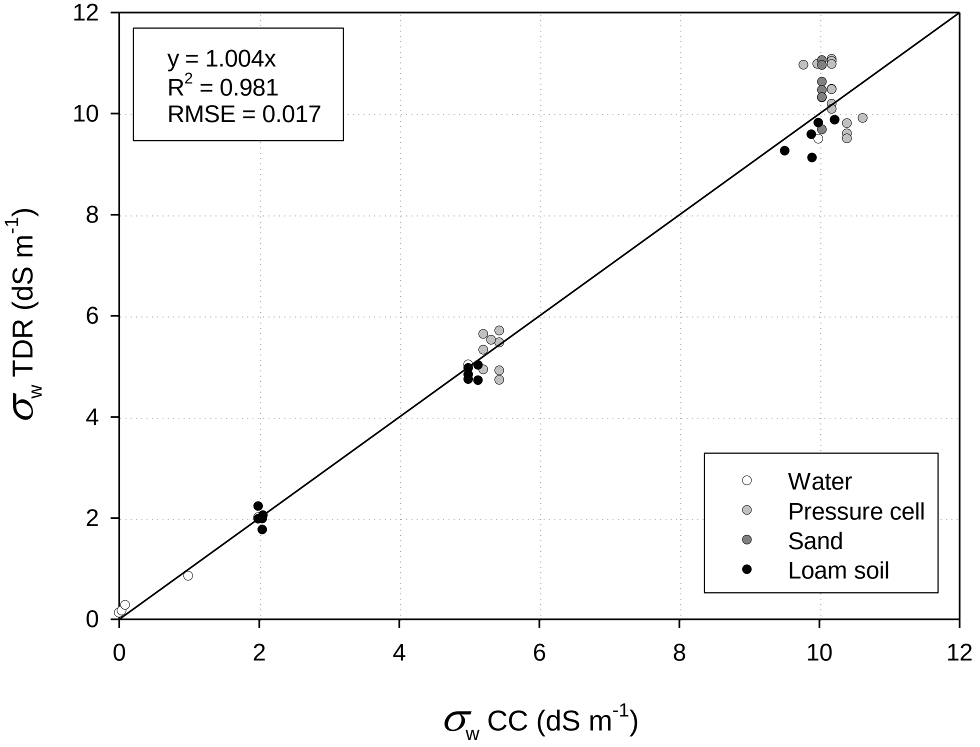
y = 1.004x
R^2 = 0.981
RMSE = 0.017
Water
Pressure cell
Sand
Loam soil
σ_w TDR (dS m^{-1})
σ_w CC (dS m^{-1})
0
2
4
6
8
10
12

Figure 5.

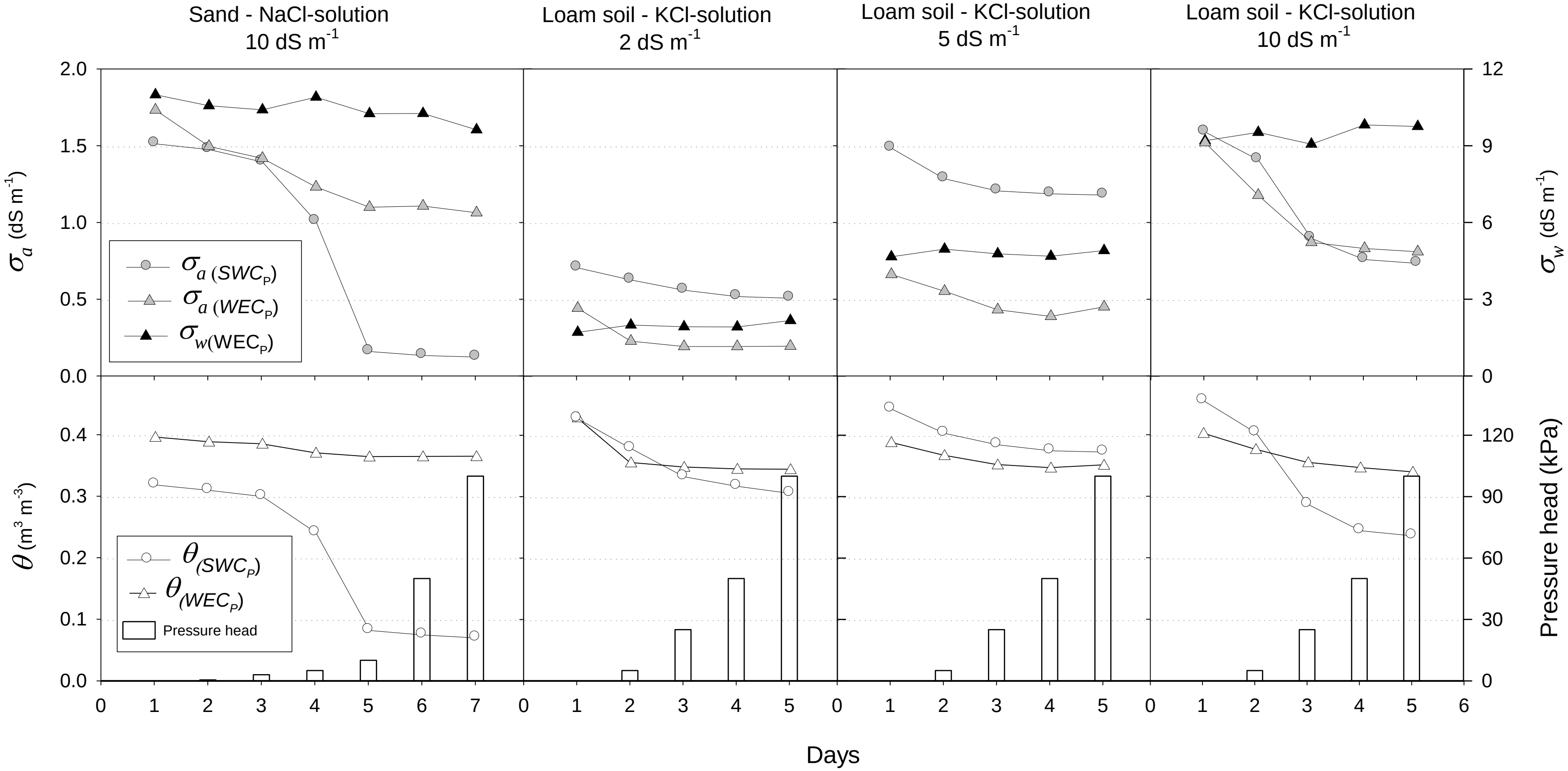
Sand - NaCl-solution
10 dS m-1
Loam soil - KCl-solution
2 dS m-1
Loam soil - KCl-solution
5 dS m-1
Loam soil - KCl-solution
10 dS m-1
σa (dS m-1)
σw (dS m-1)
σa (SWCP)
σa (WECP)
σw(WECP)
θ (m3 m-3)
Pressure head (kPa)
θ(SWCP)
θ(WECP)
Pressure head
2.0
1.5
1.0
0.5
0.0
0.4
0.3
0.2
0.1
0.0
12
9
6
3
0
120
90
60
30
0
0
1
2
3
4
5
6
7
Days

Figure 6.

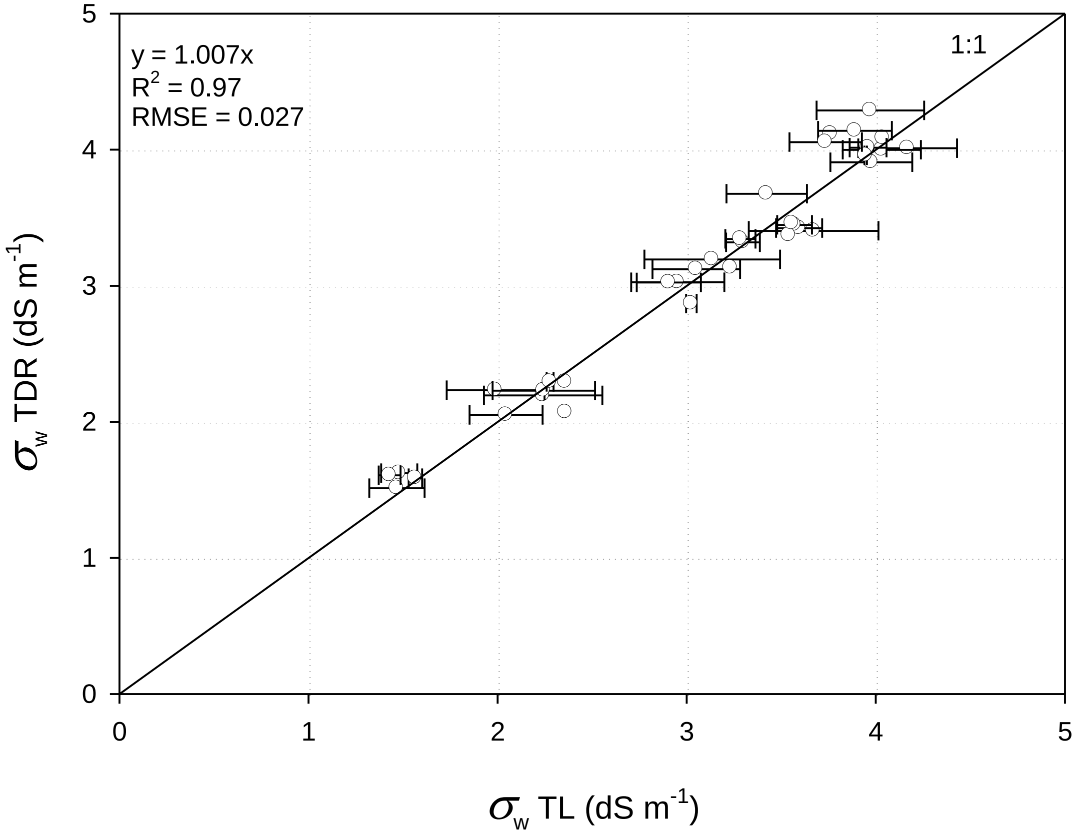
y = 1.007x
R^2 = 0.97
RMSE = 0.027
1:1
σ_w TDR (dS m^{-1})
σ_w TL (dS m^{-1})
0
1
2
3
4
5
0
1
2
3
4
5

Figure 7.

Figure 8_Moret-Fernández et al JH

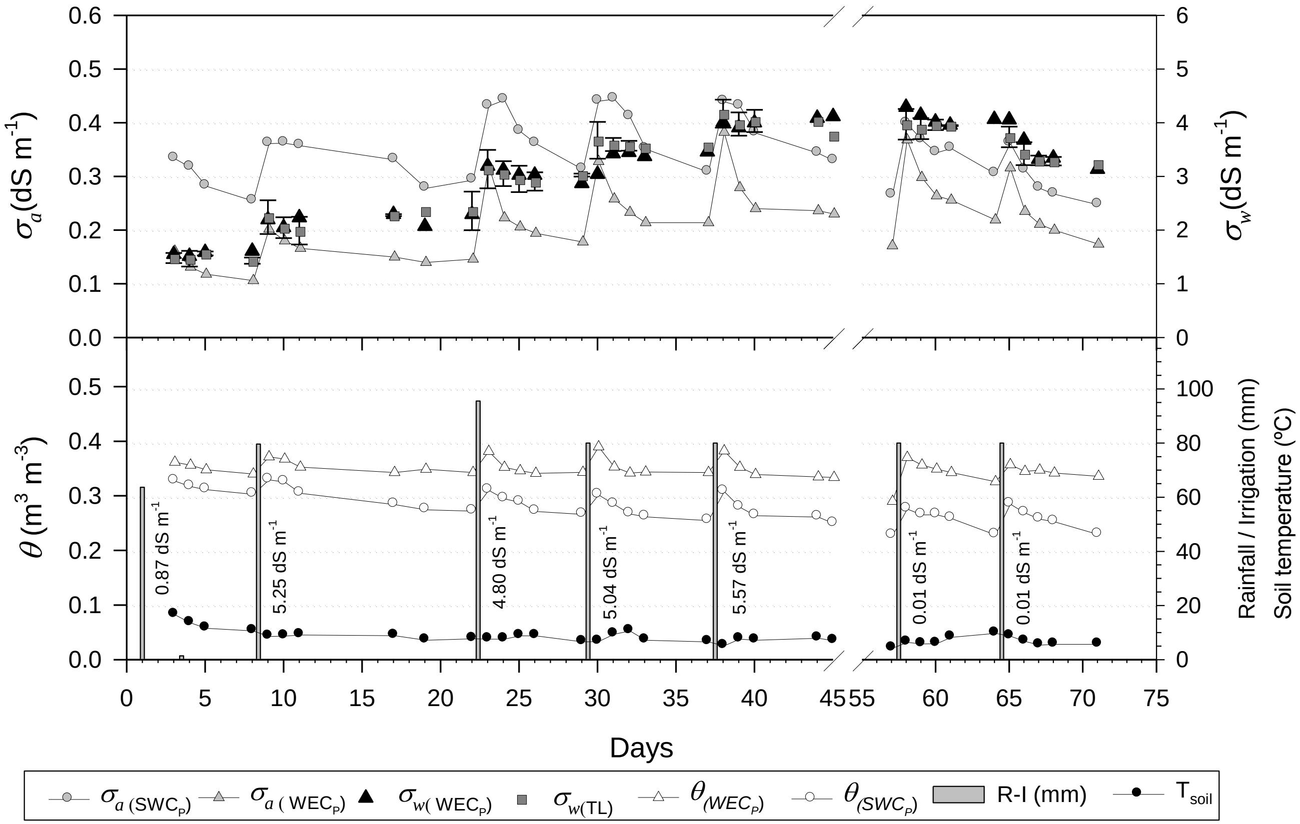

Figure 8.

Table 1. Soil wetting cycles with distilled water and different KCl-water solutions applied on the field experimental plot.

Date	Observation	Day	Infiltration (mm)	Electrical conductivity (dS m^{-1})
21-11-11	Irrigation	1	64	0.86
23-11-11	Rainfall	3	1.4	-
29-11-11	Irrigation	9	80	5.25
13-12-11	Irrigation	22	96	4.78
19-12-11	Irrigation	29	80	5.02
27-12-11	Irrigation	37	80	5.57
17-01-12	Irrigation	58	80	0.001
24-01-12	Irrigation	65	80	0.001