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Effects of tillage on the soil water retention curve during a fallow period of a semiarid dryland

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Abstract

Tillage practices have a significant influence on the soil hydro physical properties. The objective of this work is to evaluate the effect of tillage on the α and n van Genuchten soil water retention curve parameters during a 18 month long fallow period in a semiarid dryland. Three different tillage systems employed during 23 years of trials were compared: conventional (CT), reduced (RT) and no-tillage (NT) systems. Measurements of soil bulk density (ρ_b) and soil water retention curve $\theta(\psi)$ were performed at 0-10, 10-20 and 20-30 cm of soil depths. The $\theta(\psi)$ was determined with the TDR-pressure cells at the following pressure heads: 0.5, 1.5, 3, 10, 50, 100, 500 and 1500 kPa. From these data, the α and n parameters and the S_{Dexter} index were evaluated. The 0-40 cm depth soil volumetric water content, θ, was also measured in the field using the TDR technique. Compared to CT and RT, NT presented along all the fallow period the highest values of θ. No significant influence of soil depth on $\theta(\psi)$ was observed in all tillage treatments at each sampling dates. Although under consolidated soil conditions no statistical differences in ρ_b and the water content at saturation (θ_s) were observed among tillage treatments, NT presented the highest and lowest values of ρ_b and θ_s, respectively. The loosening of soil due to tillage practices in CT and RT significantly decreased ρ_b and increased θ at the wet end section of $\theta(\psi)$. Post-tillage rainfalls resulted in a significant decrease in θ_s, the α parameter of $\theta(\psi)$ and in the maximum value of the pore size distribution (PSD_{max}). The different soil structure created by mouldboard ploughing (CT) and chiselling (RT) explained that higher PSD_{max} under RT than under CT. The most important changes in $\theta(\psi)$ were reported after the firsts copious effective rainfall events (>10 mm) recorded after tillage. These facts made that the soil recovered the pre-tillage water retention curve shapes. Effective rainfalls in the late fallow had a minor effect on the water retention curve. Although tillage tended to increase the n parameter, this change

was not significant. The S_{Dexter} index, which was also affected by tillage, was > 0.035 during all the fallow period, indicating a good soil physical quality.

1. Introduction

The soil water flow is regulated by the soil hydraulic properties, namely the hydraulic conductivity ($K(\theta)$), and the water retention curve ($\theta(\psi)$). While $K(\theta)$describes the ease with which a fluid can move through a porous space, $\theta(\psi)$ is defined as the relationship between the soil volumetric water content (θ) and the matric potential (ψ). The shape of this last function depends on the particle size distribution and the arrangement of the soil aggregates. According to Dexter (2004a), physical quality of soils can be described by the S_{Dexter} index, that corresponds to the angular coefficient (slope of the tangent) at the inflection point of the $\theta(\psi)$ defined by the Van Genuchten (1980) model. This index is consistent with observations of soil compaction, organic matter content and root growth, and provides a scale that can be used to compare easily the effects of different management practices. According to (Dexter, 2004a), a soil with a good physical quality is that in which $S_{Dexter} > 0.035$.

In Aragón (NE Spain), where the rainfed cropping system represents the 75 % of the total cropped surface (Gobierno de Aragón, 2012), most of the arable crops are located in arid or semi-arid lands, where the average annual precipitation, lower than 400 mm, has a not well-defined rainy season (McAneney and Arrúe, 1993). In this region, the traditional fallow-cereal rotation is the most common cropping system. This includes a period of 16-18 months where the soil is maintained free of plant growth, eliminating weeds by tillage (cultivated fallow) or herbicides (López et al., 1996).

The soil tillage systems have a significant influence on the soil the soil bulk density (ρ_b) (Logsdon et al., 1990; Tebrügge and During 1999; Green et al., 2003; Moret and Arrúe 2007b; Guedes Filho et al., 2013, among others). Under structured soil conditions Spongrova et al. (2010) did not observed significant differences in ρ_b between conventional (CT) and no-tillage (NT) systems. Overall, the greater ρ_b under NT should be attributed to the absence of soil disturbance in NT systems (Tëbrugge et al., 1999; Green et al., 2003; Bescansa et al., 2006; Moret and Arrúe 2007b; Guedes Filho et al., 2013). In spite of the large number of field researches conducted to study the effect of tillage on the soil hydraulic conductivity, the information available about tillage influence on $\theta(\psi)$ and related indexes (S_{Dexter}) is very scarce. Under structured soils conditions, Evett et al. (1999) and Schwartz et al. (2003) observed that $\theta(\psi)$ under NT presented a more gradual reduction in water content as tension increases and lower water contents close to saturation. Kodesova et al. (2011) found that the retention ability under grassland cover was higher than under a CT system. Daragmeh et al. (2008) compared CT versus RT, and observed that soil moisture at any pressure head under RT was higher than under CT. Similar results were obtained by Bescansa (2006). These differences can be due to the incorporation of crop residues and the higher content of soil organic matter (SOM) under RT (Bescansa, 2006). Cunha et al. (2011) calculated the S_{Dexter} index under CT and NT, and found that this index under both treatments was lower than 0.035. In contrast, Calonego and Rosolem (2011), in a similar work, working with RT and NT systems, obtained S_{Dexter} values higher than 0.035.

Tillage practices alter the soil structure and consequently their hydraulic properties. Loosening of surface soil by tillage tends to increase the total soil porosity and $K(\theta)$, and modifies the shape of $\theta(\psi)$ (Green et al., 2003; Moret and Arrúe, 2007; Strudley et al., 2008). These changes result in an increase in the pore volume at the wet end section of $\theta(\psi)$, a decrease in the pore fractions corresponding to lower (more negative) pressure heads, and an increase in the slope of the $\theta(\psi)$ (Mapa, 1986; Ahuja et al., 1998, Schwartz et al., 2003; Schwärzel et al., 2011). Tillage operations, however, have a transitory effect on $\theta(\psi)$ because of rain impacts on the freshly tilled soil, which promotes a steady breakdown of soil structure (Mapa, 1986; Green et al., 2003; Daragmeh et al., 2008). The soil structure changes due to the rainfall events and the associated wetting and drying cycles lead to a collapse of the largest pores while keeps constant and sometimes even increases the frequency of the smallest ones (Mapa, 1986; Rousseva et al., 2002). Schwen et al. (2011b, 2011a) studied the soil reconsolidation under CT and RT, and found that while the $\theta(\psi)$ slope presented small temporal alterations, considerable changes were observed at the wet end of $\theta(\psi)$. These changes were in the order of CT < RT. These results, however, contrast with those obtained by Jirku et al. (2013) in a CT experiment, who observed that both the slope and the near saturation section of $\theta(\psi)$ were highly variable in time.

Very limited information about the influence of soil depth on ρ_b and $\theta(\psi)$ is so far available. Kodesova et al. (2011) reported that soil porosity under CT tends to decrease with depth. In other works, Vizitiu et al. (2011) observed, working in a loam soil, that the topsoil layers presented higher water contents at near saturation conditions, however, an opposite behaviour was reported on clayey soils.

This research is part of a long-term conservation tillage experiment initiated in 1989 to assess soil and crop responses under different tillage systems in a dryland semiarid cereal-growing area of Central Aragon (NE Spain). Due to the gap in the knowledge about the dynamic of $\theta(\psi)$ under different tillage systems, the objective of this work is to study, under conventional and reduced tillage systems, the effect of tillage on the dynamics of the soil bulk density and the water retention curve parameters at three different soil depths (0-10, 10-20 and 20-30 cm) during a 18-months long fallow period.

2. Material and methods

2.1. Study site and experimental set-up

The site is located at the dryland research farm of the Aula Dei Experimental Station (EEAD-CSIC) in the province of Zaragoza (latitude 41º44’N; longitude 0º46’W; altitude 276 m), Spain, where a long-term conservation tillage experiment was initiated in 1989. Details about site and soil characteristics, crop management practices and experimental design have been previously given (López et al., 1996); therefore, only relevant aspects are repeated here. The climate is semiarid with average annual precipitation of 390 mm and an average annual air temperature of 14.5 ºC. The soil at the research site has a loam texture (fine-loamy) and is classified as Hypercalcic Calcisol, according to the FAO soil classification system (WRB, 2007). Particle size distribution and soil chemical data of the different treatments are summarized in Table 1.

Three tillage treatments were compared under the traditional cereal-fallow rotation in the study area: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of mouldboard ploughing of fallow plots to a depth of 30-40 cm. The RT treatment consisted on a chisel ploughing to a depth of 25-30 cm (non-inverting action). The tillage operations for both CT and RT systems were done on 28 March 2012. NT used exclusively herbicides for weed control throughout the fallow season. The study was conducted when the field was in the long fallow phase of this rotation, which extends from harvest (June-July) to sowing (November-December) the following year. Field measurements were made during one fallow season: from November 2011 through November 2012.

Tillage treatments were arranged in a complete block design (López and Arrúe, 1995) with three replicates for each treatment (Fig. 1). The size of the basic plot was 33.5 m x 10 m, with a separation of 1 m between plots. Two measurement points were considered for each plot, accounting for a total of 18 measurements (6 measurement points or sampling sites per tillage treatment). All measurements were included within an area of ≈ 2 m^2 defined in each sampling site (Fig. 1).

2.2. Field and laboratory measurements

Daily rainfall data during fallow was continuously registered (at one hour interval) with a datalogger (model CR10, Campbell Scientific Inc.) from an automatic weather station located at the experimental site. Only precipitation events larger than 10 mm were considered as effective rainfall events (Moret and Arrúe 2007b). Soil volumetric water content (θ) within the 0-40 cm soil depth was monitored from November 2011 through November 2012 using the TDR technique (Time Domain Reflectometry). To this end, in each sampling site a two wires TDR probe was installed. The TDR probes consisted on a two parallel stainless steel rods (4 mm diameter, 450 mm length and 40 mm spacing between rods centres) vertically inserted down to 40 cm depth. More details of the TDR probe setup can be found in Moret et al. (2006). The protruding TDR electrode pair were connected to a TDR100 (Campbell Scientific) cable tester by means of a 50 cm length and 50 Ω coaxial cable. The TDR waveforms were transferred to a laptop and analysed using the software TDR-Lab (Moret-Fernández et al., 2010). The Topp et al. (1980) model, which resulted to be suitable for our soil (Moret et al., 2006) was used to estimate the water content. A total of 6 measurements of soil moisture were made per tillage treatment (Fig. 1) and observation date. The frequency of the soil water content measurements depended on the time from the last rainfall event: daily during the first week after rainfall and more spaced in time for the following weeks.

Given that ρ_b is assumed to not change under NT in this long term field experiment, as also reported by Moret and Arrúe (2007b), a single sampling for ρ_b and $\theta(\psi)$ at the beginning of the experiment (*pre-tillage,* S_1) was taken in NT. Five different soil samplings during the fallow period were performed in CT and RT (Fig. 1): (a) before primary tillage (*pre-tillage,* S_1); (b) after primary tillage but before any post-tillage rainfall events had occurred (*post-tillage,* S_2); (c) after primary tillage but following a period of intermittent rainfall events (*post-tillage + rain,* S_3); (d) during the late phase of fallow (*late fallow,* S_4); and (e) just before primary tillage operations (*end-fallow,* S_5). Three soil depths were considered: 1-10 cm, 10-20 cm and 20-30 cm. A total of 6 soil samples per soil depth, tillage treatment, and sampling date were collected.

The soil bulk density was determined by the core method (Grossman and Reinch, 2002) with core dimensions of 50 mm diameter x 50 mm height. The same soil cores used to measure ρ_b were employed to determine $\theta(\psi)$ of undisturbed samples. The soil cores were air dried during 10 days and the $\theta(\psi)$ were determined using TDR-pressure cells (Moret-Fernández et al., 2012). The soil samples were saturated by capillary rise until a water sheet was observed on the surface core. Once the soil sample was saturated, the following pressure heads were sequentially applied: 0.5, 1.5, 3, 10, 50, 100, 500 and 1500 kPa. The θ at each pressure step was measured by TDR using a 1502C Tektronix cable tester. TDR waveforms were transferred to a computer and analysed with the software TDR-Lab (Moret-Fernández et al., 2010). To this end, the model proposed by Topp et al. (1980) was employed. At the end of the experiment, the soil samples were dried at 105ºC for 24h, weighed, and the ρ_b calculated. The $\theta(\psi)$ was fitted to the unimodal van Genuchten (1980) model using the SWRC Fit Version 2.3 software (Seki, 2007).

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

where S_e is the effective saturation, α is a scaling factor (kPa^{-1}), n is the pore size distribution parameter and $m = 1-1/n$. The residual water content (θ_r) was automatically estimated by the SWRC Fit program. Due to the fact that a more unstable soil structure at water saturation conditions can collapse, mainly in freshly tilled soils (Moret-Fernández et al., 2016), the soil volumetric water content at saturation, assuming no trapped air, θ_s, was calculated from bulk density (ρ_b) according to

$$\theta_s = 1 - \frac{\rho_b}{\rho_r} \tag{2}$$

where ρ_r (2.62 g cm^{-3}) is the particle soil density.

The soil physical quality index S_{Dexter} (Dexter, 2004a), derived from $\theta(\psi)$, was calculated as

$$S_{Dexter} = -n(\theta_s - \theta_r)\left[1 + \frac{1}{m}\right]^{-(1+m)} \quad (3)$$

The pore size distribution (*PSD*) was calculated in a similar way than that described in Pires et al. (2008) as follows:

$$PSD = \frac{dS_e(\psi)}{d\psi} \quad (4)$$

Water pressure heads were transformed into pore radius (r) using the Laplace relation $r = 1490/\psi$, with r and ψ given in μm and cm, respectively (Kutílek and Nielsen, 1994). Although *PSD* does not provide direct information about the porosity, it gives a measure of the relative abundance of pore size (Or et al., 2000).

To compare the effects of tillage treatments on ρ_b and $\theta(\psi)$, an analysis of variance (ANOVA) for a randomized complete block design was used. A one-way ANOVA was used to evaluate the effect of the sampling depth and sampling date in the hydro-physical parameters. Duncan's multiple range test was used to compare treatment means ($p < 0.05$). All analyses were accomplished using the R (version 3.1.1) software.

3. Results

Rainfall distribution and the 0-40 cm soil depth water content during the fallow period are shown in Figure 2. The total rainfall and the total effective rainfalls events (P > 10 mm) during this period were 314.3, and 195.1 mm, respectively. From tillage to the end of fallow, three important sets of effective rainfall events were recorded: just after S_2 (23.63 mm) and S_3 (42.22 mm), and just before S_5 (96.77 mm) (Fig. 2). Overall, the soil water content under NT was higher than that observed in CT and RT. The water content in the soil after important copious rainfall (i.e. November 2012) ranged between 0.30 $m^3 m^{-3}$ (NT) and 0.20 $m^3 m^{-3}$ (CT and RT).

Although the results did not show a significant effect of the soil depth on ρ_b, this parameter tended to increase with depth (Fig. 3). The ρ_b under NT was, for all soil depths, higher than that of CT and RT (Fig.2). Compared to CT, a significantly ($p < 0.001$) lower ρ_b was observed under RT, especially in the 0-10 cm profile (Fig. 3). Soil loosening after primary tillage decreased ρ_b, however, these changes were only significant under RT. An increase ρ_b was observed after the post-tillage rainfalls. The non-significant differences in ρ_b between S_2 and S_3 indicate that the effective rainfall recorded between these two samplings (23.63 mm) was not enough to completely reconsolidate the soil. In contrast, the copious total rainfall (96.77 mm) recorded during the late fallow period (S_4 and S_5) was enough to drive the soil under CT and RT to the pre-tillage ρ_b values.

The $\theta(\psi)$ and the corresponding water retention curve parameters measured for the different tillage treatments, soil depths and sampling dates, are shown in Figure 4 and Table 2, respectively. Overall, no significant effect ($p > 0.05$) of soil depth on $\theta(\psi)$ and the van Genuchten (1980) parameters was found in all treatments and sampling dates. Given these results, from now on, the influence of the sampling date on the water retention curve will be focused on the 0-10 cm soil layer. Although under consolidated soil conditions (S_1), no statistical differences ($p > 0.05$) among the $\theta(\psi)$ measured for the different tillage treatments were observed (Fig. 4), the n and θ_s measured under NT tend to be lower than those observed in CT and RT. The higher θ under NT for lower pressure heads agrees with the higher θ measured under this treatment in the field experiment (Fig. 2). A S_{Dexter} value higher than 0.035 was found in all treatments (Fig. 5). Overall, the S_{Dexter} followed the trend CT ≈ RT > NT (Fig. 5). Tillage operations and the subsequent soil reconsolidation processes had an important effect on the soil water retention curve (Fig. 4). After tillage (S_2), no significant differences ($p < 0.05$) between CT and RT treatments were found in the water retention curve parameters (Table 2). Compared to the pre-tillage sampling (S_1), the loosening of the soil surface (S_2) significantly ($p < 0.05$) increased the pore volume at the wet end section of $\theta(\psi)$, which resulted in an increase in θ_s and α (Table 2). These effects were more evident when analyzing the soil pore size distribution (PSD) The maximum value in the *PSD* function (PSD_{max}) calculated for the different soil managements followed the gradient $S_3 > S_2 > S_4 > S_5 > S_1$ (Fig. 6). Compared to S_2, an unexpected higher θ_s , α , PSD_{max} and S_{Dexter} values were found in the S_3 water retention curves (Table 2 and Figures 5 and 6). These differences can be attributed to the soil wetting process used to measure the water retention curve: the waterlogging of freshly tilled soil may induce the collapse of the more unstable macropores ($\psi < -0.5$ kPa) and keep constant and sometimes even increase the frequency of smallest ones ($\psi > -0.5$ kPa) (Moret-Fernández et al., 2016). Post-tillage effective rainfalls (162.62 mm from S_2 to S_5) modified again the water retention curve (Fig. 4; Fig. 6) and the related parameters (Table 2). These changes, which depend on the amount and intensity of rainfall events recorded after tillage, resulted in a significant ($p < 0.05$) decrease of θ_s, α (Table 2 and Fig. 6) and PSD_{max} (Fig. 5).

4. Discussion

Overall, the increase of ρ_b with depth (Fig. 3) is consistent with those results reported by Bescansa et al. (2006) and Guedes Filho et al. (2013). The highest ρ_b values under NT (Fig. 3) are in agreement with those results observed by other authors (Logsdon et al., 1990; Evett et al., 1999; Tebrügge and During 1999; Hernanz et al., 2002; Schwartz et al., 2003; Lampurlanés and Cantero-Martínez, 2003; Moret and Arrúe 2007b; Guedes Filho et al., 2013). This fact is commonly associated with the gradual consolidation of the soil matrix over time owing to rainfall and the absence of annual tillage-induced loosening (Moret and Arrúe, 2007b). Compared to CT, the lower ρ_b under RT could be related with the higher persistence of the soil loosening after chiseling, when compared with moldboard ploughing (Cassel et al., 1978; Sommer and Zach, 1992; López et al.,1996). The decrease of ρ_b after primary tillage operations agrees with those results obtained by Logsdon et al. (1999), Green et al. (2003), Moret and Arrúe (2007b) or Strudley et al. (2008), among others. However, this soil status was only temporary, since the post-tillage rainfalls and the associated wetting-drying cycles promoted the soil reconsolidation, which results in an increase of ρ_b (Fig. 3) (Strudley et al., 2008).

Unlike to the results reported by Vizitiu et al. (2011) in clay soils, no significant effect of the soil depth on the $\theta(\psi)$ and the van Genuchten (1980) parameters was observed. These results would indicate that soil reconsolidation was similar along the 0-30 cm depth soil profile. The lower θ_s observed in the topsoil layer under NT and under consolidated soil conditions is in agreement with the higher soil compaction observed in this treatment (Fig. 4 and Table 2) (Moret and Arrúe, 2007b). The smaller n value under NT resulted in a more gradual reduction in water content with increasing soil tension (Fig. 4) (Evett et al., 1999; Schwartz et al., 2003). Similar results were reported similarly by Datiri and Lowery (1991) and Arshad et al. (1999), who observed higher water contents under NT for soil pressure head ranges of 0-40 and 0-400 kPa, respectively. Overall, the S_{Dexter} value, which was higher than 0.05, indicated good soil quality conditions.

After tillage, the increase of the pore volume at the wet end section of $\theta(\psi)$, which resulted in an increase in θ_s and α (Table 1), are in agreement with the results reported by Hamblin and Tennant (1981), Lindstrom and Onstad (1984) and Schwen et al. (2011a, 2011b). As observed by Schwen et al. (2011a, b) in a similar experiment, tillage operations had not a significant influence on n. This behavior could be due to the fact that the n parameter is more related to the soil texture (Jirku et al., 2013), while θ_s and α are more associated to the soil structure. This hypothesis agrees with Schwen et al. (2011c), who found that α was significantly affected by soil compaction. The increase of PSD_{max} due to tillage operations

(Fig. 6) should be attributed to the soil breakdown by tillage, which makes larger interaggregate pore spaces (Leij et al., 2002; Moret-Fernández et al., 2013). Compared to CT, the higher PSD_{max} under RT (Fig. 6) may be related to the different soil structure created by mouldboard ploughing and chiselling: the cutting action under RT preserves better cracks and channels between soil aggregates, creating a porosity consisting of inter-connected packing voids with large equivalent diameters (Kribaa et al., 2001; Leão et al., 2014). This results agrees with the lower ρ_b observed in RT (Fig. 3). Similarly to that reported by Calonego and Rosolem (2011), an increase of the S_{Dexter} index was observed after tillage (0.072 and 0.0776 for CT and RT, respectively). This change could be related with the decrease of ρ_b (Tormena et al., 2008; Cavalieri et al., 2009).

As reported by several authors (Schwen et al., 2011a, 2011b; Or et al., 2000; Leij et al., 2002; Moret-Fernández et al., 2013), the rainfall was the main factor that conditions the changes in the $\theta(\psi)$ parameters (Table 2, figures 5 and 7). These changes should be related to the wetting process of the freshly tilled soil that promotes the disintegration and deformation of the more unstable soil aggregates (Shiel et al., 1988; Day and Holmgren, 1952). Overall, the most important changes in θ_s and α (Fig. 7b and c) occurred between S_3 and S_4, where total cumulative effective rainfall was of 42.22 mm (Fig. 7a). However, no significant influence of the late fallow rainfalls (between S_4 and S_5) on the water retention curve was observed. These results would indicate that the first effective rainfalls after tillage are the main responsible factor that modifies and brings the water retention curve to its pre-tillage values (Fig. 2 and 7). No significant influence of rainfall on n was observed (Fig. 7d).

5. Conclusions

This work evaluates the effect of tillage practices on the soil water retention curve measured at different soil depths during an 18-months long fallow period after 23 years of trials in a semiarid dryland in central Aragón (NE Spain). Three different tillage systems were compared: conventional (CT), reduced (RT) and no tillage (NT). The results showed that $\theta(\psi)$ was not influenced by the soil depth. However, tillage had a significant effect on the $\theta(\psi)$ shape and related parameters. That is to say, tillage operations caused a decrease in ρ_b and an increase in α, S_{Dexter} and the maximum value of the pore size distribution function. No clear influence of tillage on n water retention curve parameter was observed. Wetting and drying cycles associated to post-tillage rainfall events made the soil recovered the pre-tillage water retention curve shapes. These changes mainly occurred after post-tillage copious rainfall events. Thus, the results indicate that the firsts effective rainfalls recorded after tillage are the main factor that regulates the reconsolidation of freshly tilled soils. However, more effort should be done to better characterize the reconsolidation processes of tilled soils. For this purpose, more intensive measurements of water retention curve and the saturated soil hydraulic properties should be done after tillage.

References

Ahuja, L.R., Fiedler, F., Dunn, G,H., Benjamin, J.G., Garrison, A. 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Sci. Soc. Am. J. 62**:** 1228-1233.

Arshad, M.A., Franzluebbers, A.J., Azooz, R.H. 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Till. Res. 53: 41-47.

Blanco-Moure, N., Gracia, R., Bielsa, A.C., López, M.V. 2016. Soil organic matter fractions as affected by tillage and soil texture under semiarid Mediterranean conditions. Soil Till. Res. 155: 381-389.

Bescansa, P., Imaz, M.J., Virto, I., Enrique, A., Hoogmoed, W.B. 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Till. Res. 87: 19-27.

Calonego, J.C., Rosolem, C.A. 2011. Soil water retention and s index after crop rotation and chiselling. Rev. Bras. Ciênc. Solo 35: 1927-1937.

Cavalieri, K.M.V., da Silva, A.P., Tormena, C.A., Leão, T.P., Dexter, A.R., Hakansson, I. 2009. Long-term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferrasol in Paraná, Brazil. Soil Till. Res. 103: 158-164.

Cassel, D.K., Bowen, H.D., Nelson, L.A. 1978. An evaluation of mechanical impedance for three tillage treatments on Norfolk sandy loam. Soil Sci. Soc. Am. J. 42: 116-120.

Cunha, E.Q., Stone, L.F., Moreira, J.A.A., Ferreira, E.P.B., Didonet, A.D., Leandro, W.M. 2011. Sistemas de preparo do solo e culturas de cobertura na produçao orgânica de feijao e milho. I – Atributos físicos do sol. Rev. Bras. Ciênc. Solo 35: 589-602.

Day, P.R., Holmgren, G.G. 1952. Microscopic changes in soil structure during compression. Soil Sci. Soc. Am. J. Pro. 16: 73-77.

Daraghmeh, O.A., Jensen, J.R., Petersen, C.T. 2008. Near-Saturated Hydraulic Properties in the Surface Layer of a Sandy Loam Soil Under Conventional and Reduced Tillage. Soil Sci. Soc. Am. J. 72: 1728-1737.

Datiri, B.C., Lowery, B. 1991. Effects of conservation tillage on hydraulic properties of a Griswold silt loam soil. Soil Till. Res. 21: 257-271.

Dexter, A.R. 2004a. Soil physical quality – Part I. Theory, effects on soil texture, density, and organic matter, and effects on root growth. Geoderma 120: 201-214.

Dexter, A.R., Bird, N.R.A. 2001. Methods for predicting the optimum and the range of soil water content for tillage based on the water retention curve. Soil Till. Res. 57: 203-212.

Ferré, P.A., Topp, G.C. 2002. Time Domain Reflectometry. In: Dane J.H., J.H., Topp, G.C. (Eds). Methods of Soil Analysis. Part 4-Physical Methods. (SSSA Book Series No. 5, Madison, USA), pp. 434-446.

Gobierno de Aragón. 2012. Anuario Estadístico Agrario de Aragón, 2012. (Departamento de Agricultura, Ganadería y Medio Ambiente (Zaragoza, Spain).

Green, R.T., Ahuja, L.R., Benjamin, J.G. 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 116: 3-27.

Grossman, R.B., Reinsch, T. 2002. Bulk density and linear extensibility. In: Dane J.H., J.H., Topp, G.C. (Eds). Methods of Soil Analysis. Part 4-Physical Methods. (SSSA Book Series No. 5, Madison, USA), pp. 201-228.

Evett, S.R., Peters, F.H, Jones, O.R., Unger, P.W. 1999. Soil hydraulic conductivity and retention curves from tension infiltrometer and laboratory data. In: Leij, F.J., Wu, L. (Eds). Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media. Part 1 (USDA, Riverside, USA), pp. 541-551.

Guedes-Filho, O., Blanco-Canqui, H., da Silva, A.P. 2013. Least limiting water range of the soil seedbed for long-term tillage and cropping systems in the central Great Plains, USA. Geoderma 207: 99-110.

Hamblin, A., Tennant, D. 1981. The influence of tillage on soil-water behavior. Soil Sci. 132: 233-239.

Hernanz, J.L., López, R., Navarrete, L., Sánchez-Girón, V. 2002. Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil Till. Res. 66: 129-141.

Jirku, V., Kodesová, R., Nikodem, A., Mühlhanselová, M., Zigová, A. 2013. Temporal variability of structure and hydraulic properties of topsoil of three soil types. Geoderma 204: 43-58.

Kodesová, R., Jirku, V., Kodes, V., Mühlhanselová,, M., Nikodem, A. 2011. Soil structure and soil hydraulic properties of Haplic Luvisol used as arable land and grassland. Soil Till. Res. 111: 154-161.

Kribaa, M., Hallaire, V., Curmi, P., Lahmar, R. 2001. Effect of various cultivation methods on the structure and hydraulic properties of a soil in a semi-arid climate. Soil Till. Res. 60: 43-53.

Kutílek, M., Nielsen, D.R. 1994. Soil water retention curve. In: Soil Hydrology. Catena Verlag (Germany) p. 81.

Lampurlanés, J., Cantero-Martínez, C. 2003. Soil bulk density and penetration resistance under different tillage and crop management systems and their relationships with barley root growth. Agron. J. 95: 526-536.

Leão, T.P., da Silva, A.P., Tormena, C.A., Giarola, N.F., Figueiredo, G.C. 2014. Assessing the immediate and residual effect s of chiselling for ameliorating soil compaction under long-term no-tillage. J. *S*oil Water Conserv. 69: 431-438.

Leij, F.J., Ghezzehei, T.A., Or, D. 2002. Modeling the dynamics of the soil pore-size distribution. Soil Till. Res. 64: 61-78.

Lindstrom, M.J., Onstad, C.A. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. J. *S*oil Water Conserv. 39: 149-152.

Logsdon, S.D., Allmaras, R.R., Wu, L., Swan, J.B., Randall, G.W. 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. Soil Sci. Soc. Am. J. 54: 1096-1101.

Logsdon, S.D., Kaspar, T.C., Cambardella, C.A. 1999. Depth-incremental soil properties under no-till or chisel management. Soil Sci. Soc. Am. J. 63: 197-200.

López, M.V., Arrúe, J.L., Sánchez-Girón, V. 1996. A comparison between seasonal changes in soil water storage and penetration resistance under conventional and conservation tillage systems in Aragón. Soil and Tillage Research 37: 251-271.

López, M.V., Arrúe, J.L. 1995. Efficiency of an Incomplete Block design Based on Geostatistics for Tillage Experiments. Soil Sci. Soc. Am. J. 59: 1104-1111.

Mapa, R.B., Green, R.E., Santo, L. 1986. Temporal variability of soil hydraulic properties with wetting and drying subsequent to tillage. Soil Sci. Soc. Am. J. 50: 1133-1138.

McAneney, K.J., Arrúe, J.L. 1993. A wheat-fallow rotation in north-eastern Spain: water balance-yield considerations. Agronomie 13: 481-490.

Moret Fernández, D., Peña, C., López, M.V. 2016. Influence of wetting process on the estimation of water retention curve of tilled soils. Soil Res. http://dx.doi.org/10.1071/SR15274.

Moret-Fernández, D., Castañeda, C., Pueyo, Y., Bueno, C.G., Herrero, J. 2013. Hydro-Physical Behavior of Gypseous Soils Under Different Soil Management in a Semiarid Region of NE Spain. Arid Land Res and Manag 27: 1-16.

Moret-Fernández, D., Vicente, J., Latorre, B., Herrero, J., Castañeda, C., López, M.V. 2012. TDR pressure cell for monitoring water content retention and bulk electrical conductivity curves in undisturbed soil samples. Hydrol. Process. 26: 246–254.

Moret-Fernández, D., Vicente, J., Lera, F., Latorre, B., López, M.V., Blanco, N., González-Cebollada, C., Gracia, R., Salvador, M.J., Bielsa, A., Arrúe, J.L. 2010. TDR-Lab Version 1.2 User's Guide. 2010.

Moret, D., Braud, I., Arrúe, J.L. 2007a. Water balance simulation of a dryland soil during fallow under conventional and conservation tillage in semiarid Aragon, Northeast Spain. Soil Till. Res. 92: 251-263.

Moret, D., Arrúe, J.L. 2007b. Dynamics of soil hydraulic properties during fallow as affected by tillage. Soil Till. Res. 96: 103-113.

Moret, D., Arrúe, J.L., López, M.V., Gracia, R. 2006. Influence of fallowing practices on soil water and precipitation storage efficiency in semiarid Aragon (NE Spain). Agric. Water Manage. 82: 161–17.

Or, D., Leij, F.J., Ghezzehei, T.A. 2000. Stochastic model for post-tillage soil pore evolution. Water Resour. Res. 36: 1641-1652.

Peng, X., Horn, R., Smucker, A. 2007. Pore shrinkage dependency of inorganic and organic soils on wetting and drying cycles. Soil Sci. Soc. Am. J. 71: 1095-1104.

Pires, L.F., Cássaro, F.A.M., Reichardt, K., Bacchi, O.O.S. 2008. Soil porous system changes quantified by analyzing soil water retention curve modifications. Soil Till. Res. 100: 72-72.

Rousseva, S., Torri, D., Pagliai, M. 2002. Effect of rain on the macroporosity at the soil surface. Eur. J. Soil Sci. 53: 83-94.

Schwartz, R.C., Evett, S.R., Unger, P.W. 2003. Soil hydraulic properties of cropland compared with reestablished and native grassland. Geoderma 116: 47-60.

Schwärzel, K., Carrick, S., Wahren, A., Feger, K.H., Bodner, G., Buchan, G. 2011. Soil hydraulic properties of recently tilled soil under cropping rotation compared with two-year pasture. Vadose Zone J 10: 354-366.

Schwen, A., Bodner, G., Scholl, P., Buchan, G., Loiskandl, W. 2011a. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. Soil Till. Res. 113: 89-98.

Schwen, A., Bodner, G., Loiskandl, W. 2011b. Time-variable soil hydraulic properties in near-surface soil water simulations for different tillage methods. Agric. Water Manage. 99: 42-50.

Schwen, A., Hernández-Ramírez, G., Lawrence-Smith, E.J., Sinton, S., Carrick, S., Clothier, B.E., Buchan, D.G., Loiskandl, W. 2011c. Hydraulic Properties and the Water-Conducting Porosity as Affected by Subsurface Compaction using Tension Infiltrometers. Soil Sci. Soc. Am. J. 75: 822-831.

Seki, K. 2007. SWRC fit – a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. Hydrol. Earth Syst. Sci. 4: 407-437.

Shiel, R., Adey, M.A., Lodder, M. 1988. The effect of successive wet/dry cycles on aggregate size distribution in a clay texture soil. J.Soil Sci. 39, 71-80.

Sommer C, Zach M. 1992. Managing traffic-induced soil compaction by using conservation tillage. Soil Till. Res. 24: 319-336.

Spongrova, K., Matula, S., Kechavarzi, C., Dresser, M. 2010. Differences in topsoil properties of a sandy loam soil under different tillage treatments. 19th World Congress of Soil Science, Soil Solutions for a Changing World. 1-6 Augut 2010. Brisbane, Australia.

Strudley, M.W., Green, T.R, Ascough, J.C. 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil Till. Res. 99: 4-48.

Tebrügge F., Düring R.A. 1999. Reducing tillage intensity - a review of results from a long-term study in Germany. Soil Till. Res. 53: 15-28.

Topp, G.C., Davis, J.L., Annan, A.P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 16: 574-582.

Tormena, C.A., da Silva, A.P., Imhoff, S.D.C., Dexter, A.R . 2008. Quantification of the soil physical quality of a tropical Oxisol using the S index. Sci. Agric. 65: 56-60.

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic properties of unsaturated soils. Soil Sci. Soc. Am. J. 44: 892-898.

Vizitiu, O., Calciu, I., Panoiu, I., Simota, C. 2011. Soil physical quality as quantified by S index and hidrophysical indices of some soils from Arges hydrographic basin. Res. J. Agr. Sci. 43: 249-256.

FAO. 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil Resources Reports No. 103. Rome.

Figure captions

Figure 1. Experimental design for the tillage experiment (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). The squares indicate the areas where soil measurements were made.

Figure 2. Time course of (a) Rainfall (P) and (b) averaged soil volumetric water content (θ) in the 0-40 cm layer during the experimental fallow period under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Figure 3. Soil bulk density (ρ_b) measured during the fallow period under conventional (CT), reduced (RT) and no-tillage (NT) treatments systems in pre-tillage (S_1), post-tillage (S_2), post-tillage + rain (S_3), late fallow (S_4) and end-fallow (S_5) and 0-10, 10-20 and 20-30 cm of soil depths. 'T' denotes tillage'. * indicates significant differences among tillage treatments at $p < 0.05$. ** indicates significant differences among tillage treatments at $p < 0.01$. Symbols denote average ρ_b per tillage treatment. Error bars denote calculated standard deviation.

Figure 4. Soil water retention curves $\theta(\psi)$ measured under conventional (CT), reduced (RT) and no-tillage (NT) systems in pre-tillage (S_1), post-tillage (S_2), post-tillage + rain (S_3), late fallow (S_4) and end-fallow (S_5) at 0-10, 10-20 and 20-30 cm of soil depths. *, ** and *** indicate significant differences among tillage treatments at $p < 0.05$, 0.01 and 0.001, respectively. The modelled pre-tillage NT $\theta(\psi)$ curve is plotted in al sampling dates. Symbols denote average (ψ, θ) points per tillage treatment. Error bars denote the calculated standard deviation. The modelled $\theta(\psi)$ curves were calculated with the average (ψ, θ) points.

Figure 5. S_{Dexter} parameter calculated during the fallow period under conventional (CT), reduced (RT) and no-tillage (NT) treatments in pre-tillage (S_1), post-tillage (S_2), post-tillage + rain (S_3), late fallow (S_4) and end-fallow (S_5) for the 0-10 cm of soil depth. 'T' denotes "tillage practices". Symbols denote average S_{Dexter} values per tillage treatment. Error bars denote the calculated standard deviation.

Figure 6. Pore size distribution (PSD) (Eq. 4) calculated for conventional (CT), reduced (RT) and no-tillage (NT) systems in the pre-tillage (S_1), post-tillage (S_2), post-tillage + rain (S_3), late fallow (S_4) and end-fallow (S_5) sampling dates on the 0-10 cm depth.

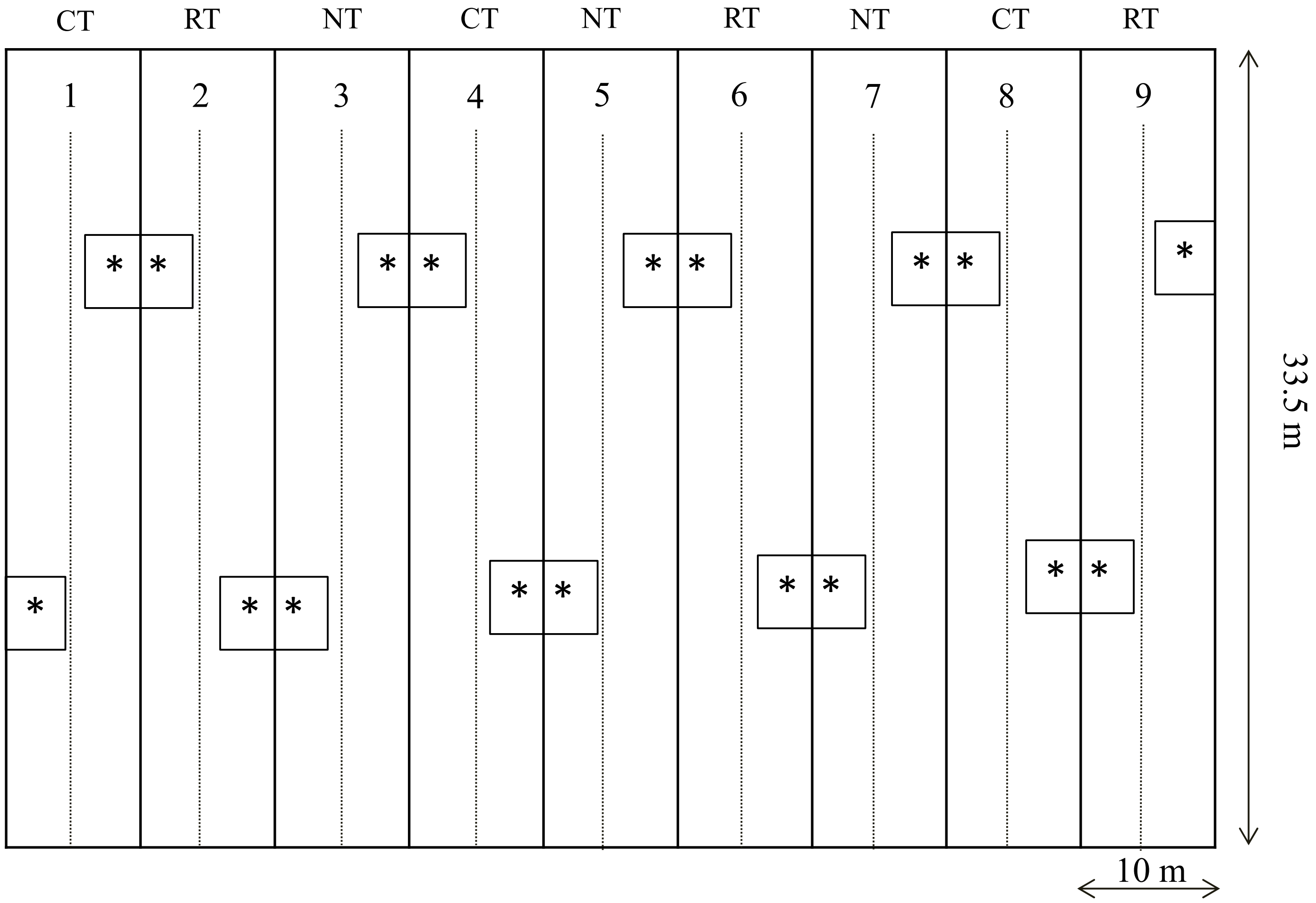
Figure 7. (a) Cumulative effective rainfall (P), and dynamics of the (b) saturated water content (θ_s) (c), α and (c) n parameters of the water retention curve measured under conventional (CT) and reduced (RT) tillage treatments from tillage operation to late fallow. Continuous and dashed lines denote the corresponding pre-tillage stage values for CT and RT, respectively. Capital and lowercase letters denote significant differences ($p < 0.05$) between sampling dates for RT and CT, respectively.

Table 1. Particle size distribution, pH, electrical conductivity (EC), CaCO3, gypsum and organic carbon (OC) contents of the studied soil in the 0-40 cm depth (CT, conventional tillage; RT, reduced tillage; NT, no tillage) (Blanco-Moure et al. 2016).

Treatment	pH (H_2O1:2.5)	EC (1:5) dS m^{-1}	$CaCO_3$ g kg^{-1}	Gypsum g kg^{-1}	Organic carbon g kg^{-1}	Sand %	Silt %	Clay %
CT	8.4	0.18	471	46	10.6	33.3	43.3	23.4
RT	8.4	0.16	482	46	10.2	31.6	44.5	23.9
NT	8.4	0.18	485	47	10.5	31.8	44.5	23.7

Table 2. Average parameters of the van Genuchten water retention curve for the different sampling dates, depths and tillage treatments (conventional (CT), reduced (RT) and no-tillage (NT)). Different letter within each tillage treatment denote significant differences ($p < 0.05$) between sampling dates.

Tillage	Sampling	0-10 cm				10-20 cm				20-30 cm			
		θ_s	θ_r	α	n	θ_s	θ_r	α	n	θ_s	θ_r	α	n
		$cm^3 \, cm^{-3}$		kPa^{-1}		$cm^3 \, cm^{-3}$		kPa^{-1}		$cm^3 \, cm^{-3}$		kPa^{-1}	
CT	S1	0.46 (0.03) ^{a}	0.25 (0.07) ^{a}	0.35 (0.08) ^{a}	1.82 (0.58) ^{a}	0.44 (0.02) ^{b}	0.24 (0.03) ^{a}	0.41 (0.42) ^{b}	1.76 (0.49) ^{a}	0.46 (0.03) ^{bc}	0.29 (0.03) ^{a}	0.27 (0.07) ^{b}	1.94 (0.33) ^{a}
	S2	0.48 (0.01) ^{a}	0.23 (0.07) ^{a}	0.54 (0.41) ^{a}	1.80 (0.67) ^{a}	0.49 (0.03) ^{a}	0.20 (0.07) ^{a}	1.08 (0.76) ^{a}	1.95 (1.05) ^{a}	0.49 (0.03) ^{ab}	0.25 (0.03) ^{ab}	0.47 (0.24) ^{ab}	1.72 (0.17) ^{a}
	S3	0.48 (0.04) ^{a}	0.21 (0.03) ^{a}	0.67 (0.55) ^{a}	1.81 (0.31) ^{a}	0.50 (0.02) ^{a}	0.21 (0.04) ^{a}	0.74 (0.44) ^{ab}	1.58 (0.17) ^{a}	0.51 (0.02) ^{a}	0.19 (0.05) ^{b}	0.96 (0.48) ^{a}	1.52 (0.11) ^{a}
	S4	0.45 (0.03) ^{a}	0.23 (0.02) ^{a}	0.23 (0.12) ^{a}	1.87 (0.17) ^{a}	0.46 (0.03) ^{ab}	0.21 (0.10) ^{a}	0.28 (0.17) ^{b}	1.63 (030) ^{a}	0.45 (0.04) ^{bc}	0.23 (0.04) ^{ab}	0.55 (0.73) ^{ab}	1.72 (0.23) ^{a}
	S5	0.45 (0.03) ^{a}	0.29 (0.05) ^{a}	0.32 (0.31) ^{a}	1.79 (0.20) ^{a}	0.44 (0.02) ^{b}	0.27 (0.03) ^{a}	0.23 (0.12) ^{b}	1.87 (0.37) ^{a}	0.44 (0.03) ^{c}	0.29 (0.09) ^{a}	0.23 (0.13) ^{b}	1.73 (0.42) ^{a}
RT	S1	0.48 (0.03) ^{ab}	0.24 (0.05) ^{a}	0.47 (0.40) ^{b}	1.68 (0.35) ^{a}	0.45 (0.14) ^{bc}	0.21 (0.25) ^{b}	0.43 (0.29) ^{ab}	1.63 (0.71) ^{a}	0.45 (0.02) ^{b}	0.22 (0.09) ^{b}	0.25 (0.06) ^{b}	1.48 (0.24) ^{c}
	S2	0.50 (0.02) ^{a}	0.24 (0.04) ^{a}	0.86 (0.40) ^{ab}	1.64 (0.26) ^{a}	0.51 (0.03) ^{a}	0.20 (0.06) ^{b}	0.96 (0.73) ^{ab}	1.73 (0.49) ^{a}	0.52 (0.03) ^{a}	0.20 (0.05) ^{b}	1.77 (2.21) ^{a}	1.39 (0.07) ^{c}
	S3	0.50 (0.03) ^{a}	0.19 (0.02) ^{a}	1.39 (1.18) ^{a}	1.56 (0.30) ^{a}	0.48 (0.03) ^{ab}	0.23 (0.04) ^{ab}	1.06 (1.15) ^{a}	1.62 (0.30) ^{a}	0.49 (0.03) ^{ab}	0.21 (0.03) ^{b}	0.94 (0.51) ^{a}	1.54 (0.15) ^{bc}
	S4	0.49 (0.04) ^{ab}	0.25 (0.06) ^{a}	0.52 (0.2) ^{b}	1.71 (0.27) ^{a}	0.48 (0.04) ^{abc}	0.24 (0.08) ^{ab}	1.89 (3.33) ^{ab}	1.67 (0.34) ^{a}	0.48 (0.01) ^{ab}	0.26 (0.03) ^{ab}	0.47 (0.37) ^{ab}	1.93 (0.58) ^{ab}
	S5	0.46 (0.02) ^{b}	0.21 (0.04) ^{a}	0.45 (0.17) ^{b}	1.72 (0.23) ^{a}	0.44 (0.02) ^{c}	0.29 (0.06) ^{a}	0.22 (0.22) ^{b}	1.92 (0.39) ^{a}	0.44 (0.03) ^{b}	0.31 (0.04) ^{a}	0.28 (0.29) ^{b}	1.99 (0.38) ^{a}
NT	S1	0.43 (0.04)	0.16 (0.13)	0.36 (0.35)	1.38 (0.22)	0.40 (0.02)	0.22 (0.09)	0.26 (0.09)	1.54 (1.03)	0.42 (0.01)	0.26 (0.09)	0.32 (0.59)	1.92 (1.08)



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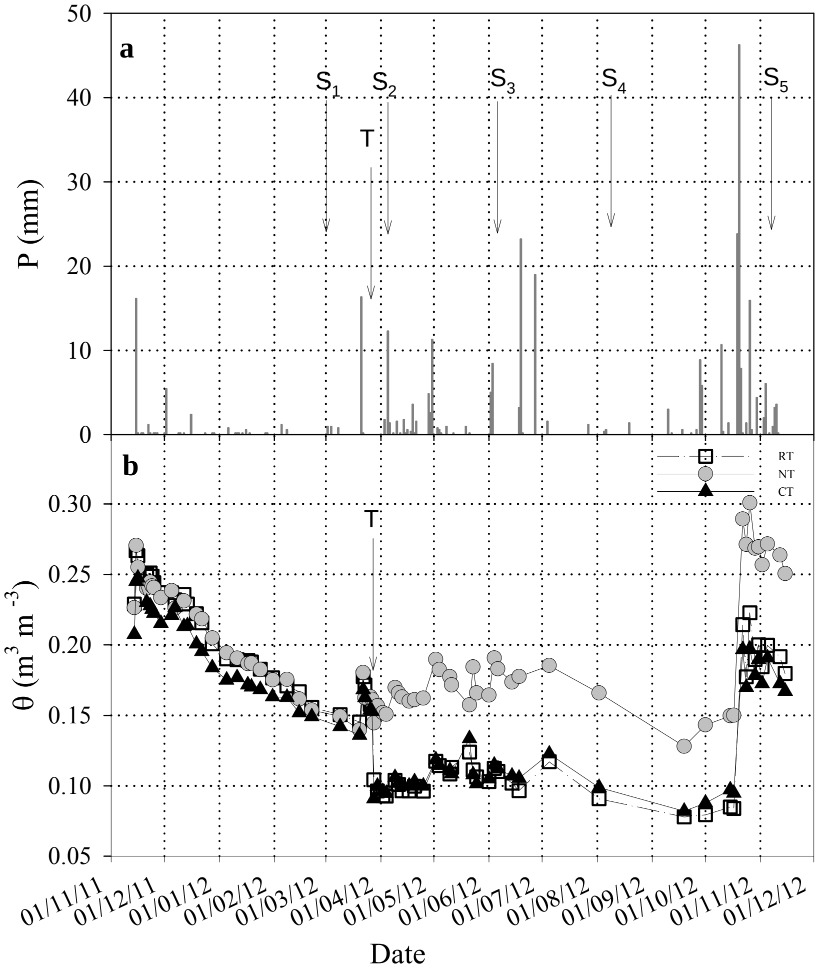
a
b
P (mm)
50
40
30
20
10
0
S1
S2
S3
S4
S5
T
RT
NT
CT
θ (m3 m-3)
0.30
0.25
0.20
0.15
0.10
0.05
01/11/11
01/12/11
01/01/12
01/02/12
01/03/12
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Date

Figure 2.

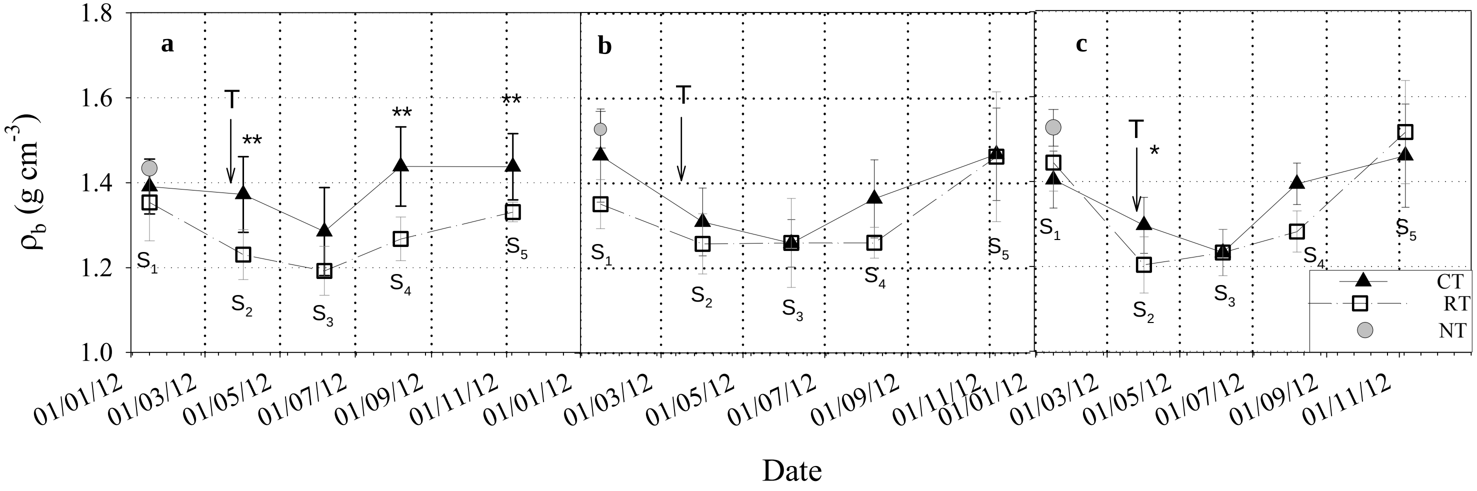

ρb (g cm-3)
1.8
1.6
1.4
1.2
1.0
a
b
c
T
**
**
**
*
S1
S2
S3
S4
S5
CT
RT
NT
01/01/12
01/03/12
01/05/12
01/07/12
01/09/12
01/11/12
Date

Figure 3.

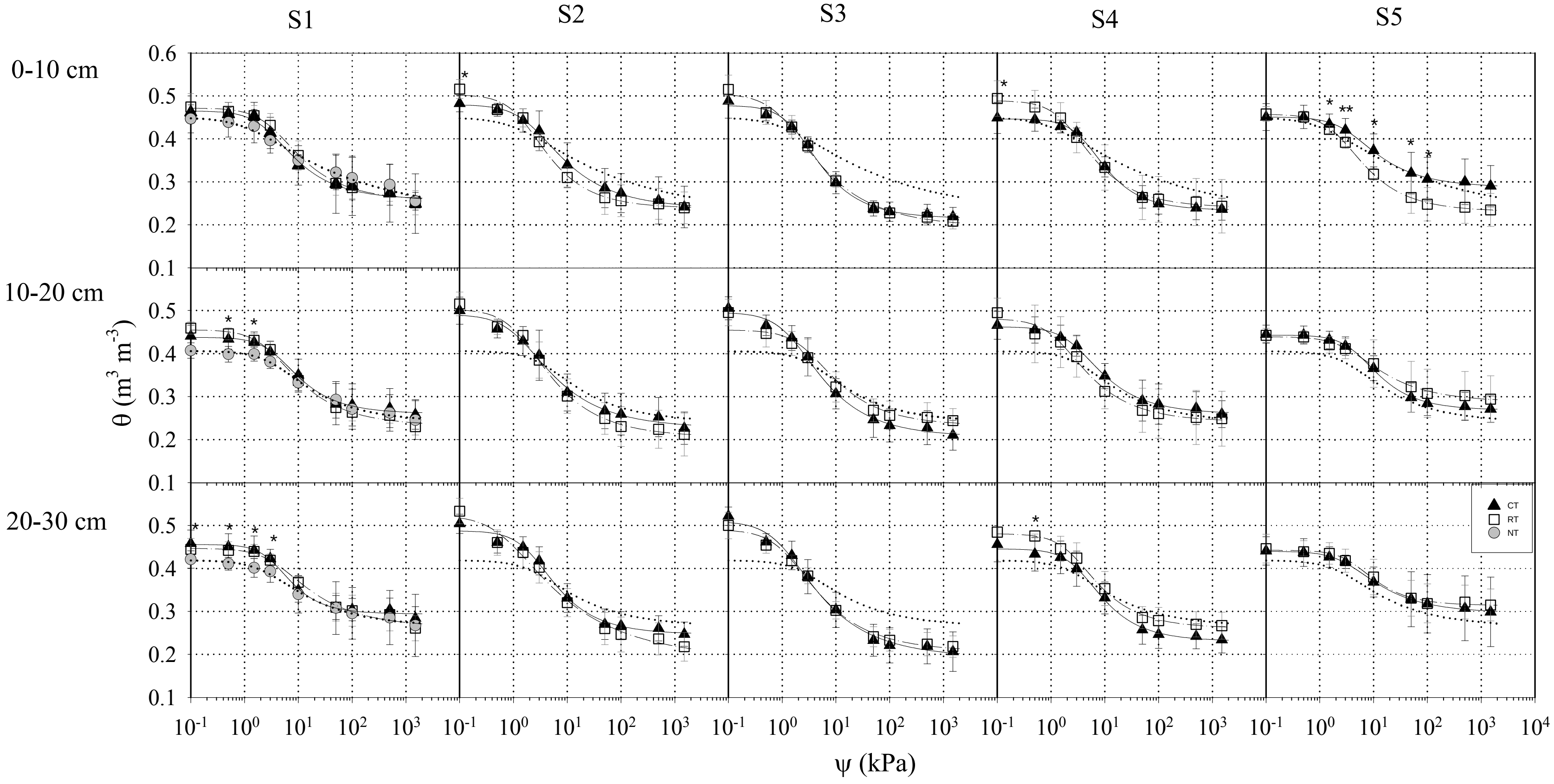
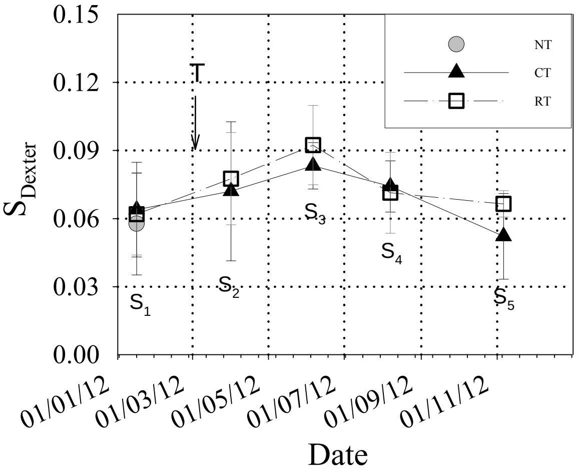

S1
S2
S3
S4
S5
0-10 cm
10-20 cm
20-30 cm
θ (m3 m-3)
0.6
0.5
0.4
0.3
0.2
0.1
10-1
100
101
102
103
104
ψ (kPa)
CT
RT
NT
*
**

Figure 4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0.12
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0.03
0.00
S_Dexter
T
S1
S2
S3
S4
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NT
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01/01/12
01/03/12
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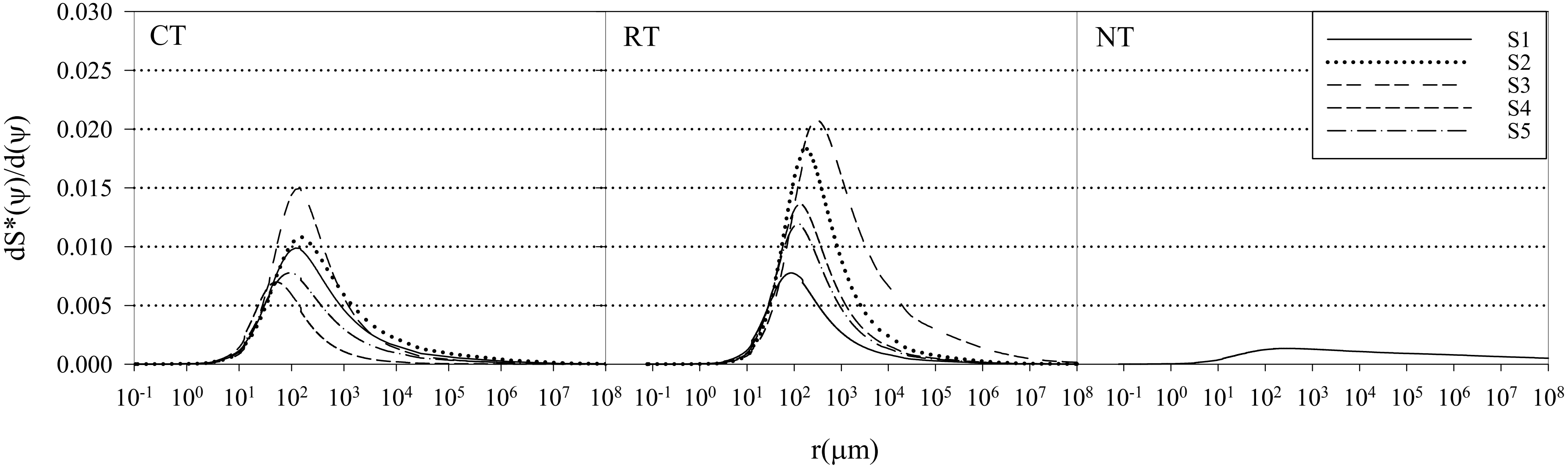
01/07/12
01/09/12
01/11/12
Date

Figure 5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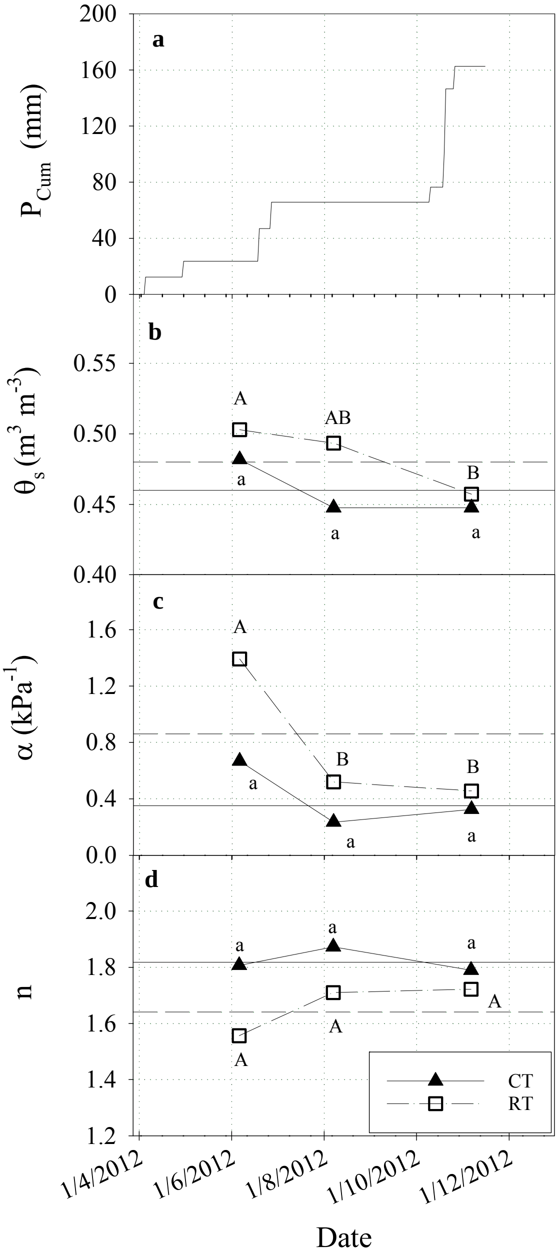
0.025
0.020
0.015
0.010
0.005
0.000
dS*(ψ)/d(ψ)
CT
RT
NT
S1
S2
S3
S4
S5
10-1
100
101
102
103
104
105
106
107
108
r(μm)

Figure 6


a
b
c
d
P_{Cum} (mm)
θ_s (m^3 m^{-3})
α (kPa^{-1})
n
200
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120
80
40
0
0.55
0.50
0.45
0.40
1.6
1.2
0.8
0.4
0.0
2.0
1.8
1.6
1.4
1.2
A
AB
B
a
CT
RT
1/4/2012
1/6/2012
1/8/2012
1/10/2012
1/12/2012
Date

Figure 7