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Estimating the van Genuchten retention curve parameters of undisturbed soil from a single upward infiltration measurement

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Abstract

Estimation of the soil-water retention curve, $\theta(h)$, on undisturbed soil samples is of paramount importance to characterise the hydraulic behaviour of soils. Moret-Fernández and Latorre (2016) presented a method to determine the parameters of the van Genuchten (1980) water retention cuve (α and n) from the saturated hydraulic conductivity (K_s), the sorptivity (S) and the β parameter of the Haverkamp et al. (1994) model, calculated S and β from the inverse analysis of an upward infiltration. Although this inexpensive, fast and simple to implement method was satisfactorily applied to sieved soil samples, its applicability on undisturbed soils has not been tested. The objective of this work is to show that the method can be applied to undisturbed soil cores representing a range of textures and structures. The undisturbed soil cores were collected with 5 cm-internal diameter -i.d.- by 5 cm-high stainless steel cylinders sampled on structured soils located in two different places: agricultural loam soil under conventional, reduced and no tillage systems, and a loam soil under grazed and ungrazed natural shrubland. The α and n values estimated for the different soils with the upward infiltration method (UI) were compared to corresponding values calculated with TDR-pressure cells (PC), for pressure heads of -0.5, -1.5, -3, -5, -10, -50 kPa. To compare both methods, the α values measured with UI were calculated to the drying branch of $\theta(h)$. Three replications of upward infiltration and PC were performed per treatment. The results demonstrated that the 5 cm-high cylinders used in all experiments provided accurate estimates of S and β. Overall, the α and n values estimated with UI were larger than those measured with PC. These differences could be attributed in part to limitations of the PC method. On average, the n values calculated from the optimized S and β data were 5% larger than those obtained with the TDR-pressure cell. A relationship with a slope close to one fitted the n values estimated with both methods ($n_{PC} = 0.73\ n_{UI} + 0.49$; $R^2 = 0.78$; $p < 0.05$). The results showed that this method can be a promising technique to estimate the hydraulic properties on undisturbed soil samples

Keywords: Hydraulic conductivity; Sorptivity, Soil tillage.

1.- INTRODUCTION

Water flow in the vadose zone is mainly regulated by the unsaturated hydraulic conductivity, K, which is related to the water retention curve, $\theta(h)$ (van Genuchten, 1980). Those parameters are indispensable to simulate soil water processes, such as water erosion, soil pollutant movement, or nutrient dynamics. While K reflects the ability of soil to transmit water when the soil is submitted to a hydraulic gradient, the water retention curve defines the relationship between the soil volumetric water content (θ) (L^3 L^{-3}) and the matric potential h (L). The unimodal van Genuchten (1980) equation relates θ and h through two empirical variables: n and α.

Laboratory methods used to characterize $\theta(h)$ can be classified into two categories, direct experimental and indirect inferential methods. The main direct laboratory methods are the pressure extractor (Klute, 1986), which estimates $\theta(h)$ from pairs of measured h and θ values, or the evaporative method, that calculates the K and $\theta(h)$ from the pressure head response of two tensiometers placed at different depths (Gardner and Miklich, 1962). Although these techniques can be applied on undisturbed soil cores, the tediousness of the experiments together with the specific equipment needed can limit its use. The indirect methods, which are increasingly employed and involve inverse solutions of the Richard's equation, estimate the soil hydraulic properties from the numerical analysis of measured transient soil properties (i.e., water flow, soil pressure head). The main advantage of these techniques is the ability to simultaneously estimate K and $\theta(h)$. To date, many different indirect procedures have been developed. Simunek et al. (1998) employed the evaporation method to estimate the drying branch of the soil hydraulic properties from simultaneous numerical analysis of measured soil water evaporation and soil pressure heads recorded at different depths. Hudson et al. (1996) suggested estimating the wetting branch of the soil hydraulic properties from the inverse analysis of an upward flow experiment under laboratory conditions using a constant flux of water at the bottom of the soil sample. Shao and Horton (1998) developed an integral method that allowed estimating the $\theta(h)$ van Genuchten model parameters from a simple horizontal infiltration experiment on a 20-cm length soil column, followed by measuring the saturated hydraulic conductivity. Young et al. (2002) employed a Mariotte system and tensiometers installed in a 15-cm-long soil column to estimate the wetting branch of the soil hydraulic properties. Moret-Fernández et al. (2016b) developed a tension sorptivimeter that allowed estimating the soil hydraulic parameters from the inverse analysis of a multiple tension upward infiltration curve, without using tensiometers. Taking into account the hysteresis phenomena, Peña-Sancho et al. (2017) estimated the soil hydraulic properties from a capillary wetting process at saturation followed by an evaporation process. Finally, Moret-Fernández and Latorre (2016) developed a simple procedure to calculate the parameters of the $\theta(h)$ van Genuchten model from a single upward infiltration curve followed by an overpressure step by applying the 1D downward Haverkamp et al. (1994) model adapted for an upward infiltration. In this case, a 5 cm-high cylinder filled with sieved soil was used.

Undisturbed soils in field conditions have some unique features in contrast with packed laboratory soils, such as the presence of roots or a complex porous system. Measurements of $\theta(h)$ on undisturbed soil samples are generally preferable to those made on disturbed samples. Current methods developed to estimate $\theta(h)$ have serious limitations when applied to undisturbed soil samples. This is the case of the methods based on the tension measurements, where installation of tensiometers in the undisturbed soil column is delicate and complex (Arya, 2002). Although Han et al. (2010) applied the integral method of Shao and Horton (1998) on undisturbed soil samples, the long soil columns (20 cm) used in the experiment and the need to use transparent cores, may limit its application for soils. In the method developed by Moret-Fernández et al. (2016b), the highly negative pressure head used at the beginning of the experiment, restricted the use to soil samples that had good contact between the nylon mesh of the sorptivimenter and the corresponding mesh located at the bottom of the soil cylinder (e.g. sieved soils). These authors suggested that this problem could be solved by starting the experiment at saturation conditions. This limitation could be solved by the Moret-Fernández and Latorre (2016) method, in which the bottom boundary of the upward infiltration experiments starts at saturation conditions.

It is evident from the above literature that the current methods to estimate the water retention curve parameters presents several limitations when applied to undisturbed soil samples. Further efforts are needed to develop alternative methods to estimate the soil hydraulic properties on undisturbed soil samples. The objective of this paper is to test the applicability of the Moret-Fernández and Latorre (2016) method to estimate the soil hydraulic properties on undisturbed soil samples. Undisturbed cores (5 cm i.d. by 5cm-high) were collected in two different fields with different tillage (conventional, reduced and not tillage) and grazing (natural and grazed) managements, and the estimated hydraulic parameters were compared to those calculated with TDR- pressure cell (PC).

2. MATERIALS AND METHODS

2.1. Theory

For 1-D upward water flow, the cumulative infiltration, $I_{1D}(t)$ on a homogeneous, uniform initial water content and infinite length soil column, can be described by the quasi-exact equation derived from the Haverkamp et al. (1994) formulation (Moret-Fernádnez and Latorre, 2016)

$$\frac{2(1-\beta)\Delta K^2}{S_0^2}t = \frac{2\Delta K(I_{1D}+K_n t)}{S_0^2} - \ln\left\{\frac{1}{\beta}\exp\left[\frac{2\beta\Delta K(I_{1D}+K_n t)}{S_0^2}\right]+1-\frac{1}{\beta}\right\} \quad (1)$$

where t is time (T), θ (L^3 L^{-3}) is the volumetric water content, S_0 is the sorptivity (L $T^{-0.5}$) for θ_0; K_0 and K_n are the hydraulic conductivity values (L T^{-1}) corresponding to θ_0 and θ_n, respectively, $\Delta K=K_n-K_0$, and β is an integral shape parameter. This model is only suitable for those soils where the saturated-independent shape parameter β ranges between 0.3 and 1.7 (sand, loam and silt) (Lassabatere et al., 2009). The β shape function is defined as (Haverkamp et al., 1994)

$$\beta = 2 - 2\frac{\int_{\theta_n}^{\theta_0}(K - K_n / K_0 - K_n)(\theta_0 - \theta_n / \theta - \theta_n)D(\theta)d\theta}{\int_{\theta_n}^{\theta_0} D(\theta)d\theta} \tag{2}$$

For saturated soils, the steady state water flux density, q, into the soil (L T^{-1}) (Lichtner et al., 1996) can be expressed as

$$q = -K_s \frac{dH}{dz} \tag{3}$$

where and H=h+z (L) is the total head, and z is a vertical coordinate (L) positive upward.

The unsaturated soil hydraulic properties can be described according to (van Genuchten, 1980)

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^n\right)^m} \tag{4}$$

$$K(\theta) = K_s S_e^{0.5}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{5}$$

where S_e is the effective water content, K_s is the saturated hydraulic conductivity, θ_s and θ_r denote the saturated and residual volumetric water content, respectively, and α (L^{-1}), n, and m=(1-$1/n$) are empirical parameters. Under this formulation, van Genuchten (1980) found that the soil diffusivity, D, could be expressed as.

$$D(S_e) = \frac{(1-m)K_s}{\alpha m(\theta_s - \theta_r)} S_e^{1/2 - 1/m}\left[\left(1 - S_e^{1/m}\right)^{-m} + \left(1 - S_e^{1/m}\right)^m - 2\right] \tag{6}$$

Parlange (1975) demonstrated that, for homogeneous, uniform initial water content and infinite length soil column, S could be defined as

$$S^2(\theta_s, \theta_0) = \int_{\theta_i}^{\theta_s} D(\theta)[\theta_s + \theta - 2\theta_i]d\theta \tag{7}$$

where θ_i is the initial volumetric water content.

Combining Eq. (6) and (7), we obtain

$$S^2 = \frac{(1-m)K_s}{\alpha m(\theta_s - \theta_r)}\int_{\theta_i}^{\theta_s}[\theta_s + \theta - 2\theta_i]S_e^{1/2 - 1/m}\left[\left(1 - S_e^{1/m}\right)^{-m} + \left(1 - S_e^{1/m}\right) - 2\right]d\theta \qquad (8)$$

2.2. Estimation of the water retention curve parameters

The estimation of the van Genuchten (1980) soil water retention parameters (α and n) from a single upward infiltration curve measured on a finite soil column required the following steps (Moret-Fernández and Latorre, 2016).

- Homogeneous, uniform initial water content close to θ_r and finite soil core was considered.
- An upward infiltration curve made by saturation conditions at the bottom of the soil sample, followed by an overpressure step at the end of the water absorption process, was measured. Because Eq. (1) requires infinite soil columns, only infiltration times between t = 0 and the time just before the wetting front arrives at the top of the soil column were considered.
- The K_s was calculated by applying Eq. (3) to the overpressure step measured at the end of the soil wetting process.
- By introducing the calculated K_s in Eq. (1), S and β were numerically estimated by minimizing the objective function, Q, that represents the difference between Eq.(1) and the experimental upward infiltration (I) data (Moret-Fernández and Latorre, 2016):

$$Q = \sum_{i=1}^{N}\left(\left(I_i - I(S, \beta, t_i)\right)\Delta t_i\right)^2 \qquad (9)$$

where N is the number of measured (I t) values. To this end, a global optimization search (Pardalos and Romeijn, 2002) was employed. The objective function was summarized as contours (response surfaces) for the S-β and t-β combinations. The parameter combinations for the response surface were calculated on a rectangular grid, with S, β values ranging from 0.1

to 2.5 and 0.3 to 1.7, respectively and t between t = 0 and the time just before the wetting front arrive to the top of the soil column, respectively.

- By introducing the calculated K_s, S and β values in Eqs. (2) and (8), we obtained a system of two equations with two unknown variables (α and n). This system of equations was numerically solved with the R V. 3.3.1 software (The R Foundation for Statistica Computing).

2.3. Field experiments

2.3.1. Sorptivimeter

The upward infiltration curve was measured with a sorptivimeter (Moret-Fernández et al., 2016). This consists in a saturated perforated base of 5 cm-diameter, that accommodates a 5 cm i.d by 5 cm-high stainless steel cylinder containing the undisturbed soil sample (Fig. 1). The bottom of the perforated base is connected to a Mariotte water-supply reservoir (30 cm high and 2.0 cm i.d.). A ± 3.44 kPa differential pressure transducer (PT) (Microswitch, Honeywell), connected to a datalogger (CR1000, Campbell Scientist Inc.), was installed at the bottom of the water-supply reservoir (Casey and Derby, 2002).

The sorptivimeter implementation required that the perforated plus the nylon mesh base were previously saturated. The measurement started when the cylinder containing the undisturbed soil sample was placed on the saturated base, and finished when the wetting front arrived at the soil surface. At this time, an overpressure step, ranging between 2 and 12 cm of pressure head from the soil surface, was introduced by raising the water reservoir to a desired height. The saturated hydraulic conductivity was calculated from the overpressure section of the cumulative absorption curve according to Eq.(3). The initial and final water content were gravimetrically measured. Additionally, the final water content was also calculated as the sum of the initial water content plus the water absorbed by the soil at the time that a water sheet is observed on the soil surface. More details of the sorptivmeter design and its implementation are summarized in Moret-Fernández et al. (2016)

2.3.2. Field sampling and method testing

The undisturbed cores were collected from consolidated soils located in two different places. The first field (EEAD) is located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (41°44′N, 0°46′W, altitude 270 m). The climate is semiarid with an average annual precipitation of 390 mm and an average annual air temperature of 14.5°C. Soil at the research site is a loam (fine-loamy, mixed, thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Selected physical and chemical properties of the soil are given in Blanco-Moure et al. (2012). The study was conducted in a block with three plots (30 x 10 m^2 per plot), which were set up on a low angle slope area (slope 0–2%) of land in 1991 within a long-term conservation tillage experiment. The field was in winter barley (Hordeum vulgare L.)–fallow rotation, and the sampling were performed conducted when the field was in the 16- to 18-mo-long fallow phase of this rotation, which extends from harvest (June–July) to sowing (November–December) the following year. Three different tillage management treatments, one per plot, were compared: CT, RT, and NT. The CT treatment consisted of mouldboard ploughing of fallow plots to a depth of 30 to 40 cm in late winter or early spring, followed by secondary tillage with a sweep cultivator to a depth of 10 to 15 cm in late spring. In the RT treatment, the primary tillage was chisel ploughing to a depth of 25 to 30 cm (non-inverting action), followed as in CT by a pass of the sweep cultivator in late spring. The NT treatment used exclusively herbicides (glyphosate [N-(phosphorous methyl)glycine]) for weed control throughout the fallow season.

The second field was located in the Belchite municipality (Zaragoza), also in the Middle Ebro Valley (NE, Spain; 41º30’N, 0º15’W), and at 250 m above the sea level. The climate is semi-arid Mediterranean, the mean rainfall is 353 mm/year (average of 50 years at 250 m above sea level), and the mean annual temperature is 14.9 ◦C (M.A.P.A., 1987) (Table 1). Soil at the research site is a loam (Calcic Petrogypsids) according to the USDA soil classification (Soil Survey Staff, 2010). The lithology is a gypsum substratum alternating with carbonate units (marls and limestone) and clays (Quirantes, 1978). The landscape is characterized by low hills and flat-bottomed valleys with altitudes ranging from 127 to around 800 m a.s.l. Hills are occupied mainly by dwarf-scrubs of *Rosmarinus officinali*s L., while uncultivated valley bottoms are occupied by *Lygeum spartum* L. steppe and scarce scrub of *Salsola vermiculata* L. and *Artemisia herba-alba* Asso (Braun-Blanquet and Bolòs, 1957). Land use in the area is based on a traditional agropastoral system involving dry cereal croplands and extensive sheep production. Two different soil management types were considered: ungrazed natural shrubland, N; and grazed shrubland, GR. The grazing treatment consisted of a moderate grazing intensity (<1 head ha^{-1} $year^{-1}$) according to the traditional use in the area (Pueyo, 2005). The treatments were located in two nearly flat experimental fields, separated 1 km one from other. Characteristics of the soils employed in the experiments are summarized in Table 1.

In all cases, the sampling points, which were located on bare soil, were uniformly distributed in the plots. Six undisturbed soil cores were sampled per plot using the core method, with core dimensions of 50 mm internal diameter and 50 mm-high. In the laboratory, soil cores were air dried over several weeks. Once the soil samples were air dried, three replications per soil type and treatment were employed to estimate the α and n with the UP method. The remaining three replications were subsequently employed to estimate the van Genuchten (1980) parameters using TDR-pressure cells (PC) (Moret-Fernández et. al, 2012). The volumetric water content (θ) in the pressure cell was measured by TDR in the air dry soil, which corresponds to a pressure head (h) of about -166 MPa (Munkolm and Kay, 2002), at soil water saturation and at pressure heads of -0.5, -1.5, 3-, -10 and -50, kPa. In our case, the θ_r and θ_{sat} corresponded to the air dry soil water content and the water content at saturation measured TDR. The measured pairs of values θ and h were numerically fitted with the R V.3.1.1 (The R Foundation dor Statistical Computing) software to the van Genuchten (1980) model (Eq. 1). To this end, θ_{sat} and θ_r were considered as known values and the α and n were estimated by minimizing an objective function, $T(\alpha,n)$ that represents the difference between the simulated and the experimental data

$$T=\sum_{i=1}^{N}\left(\left(\theta(h)_i-\theta(h)(\alpha,n)\right)\right)^2 \tag{10}$$

where N is the number of measured (θ,h) values. A brute-force search was used on the optimization. Given the two unknown variables, α and n, the values of the objective functions were summarized as contours (response surfaces) for the α-n combination. The resultant response surface was calculated on a rectangular grid, with α and n values ranging from 0.01 to 10 and 1.2 to 2.2, respectively. The water retention parameters calculated with the UP method were compared to the corresponding values estimated with the TDR-pressure cell. Because UP and TDR-cell methods calculate the opposite branches of the water retention curve, the α parameters obtained from the upward infiltration measurements were converted to the corresponding drying branch using the I hysteresis index developed by Gebrenegus and Ghezzehei (2011)

$$I=\left(\frac{r^n-1}{r^{\frac{n(n-1)}{2n-1}}-1}\right)^{\frac{1}{n}-1}-\left(\frac{r^n-1}{r^n-r^{\frac{n^2}{2n-1}}}\right)^{\frac{1}{n}-1} \tag{11}$$

where $r = \alpha_d / \alpha_w$; and the subscripts d and w, denote drying- and wetting-curve, respectively. In the absence of measured wetting and drying water retention data, the I index was calculated as Gebrenegus and Ghezzehei (2011)

$$I = 0.378 ln\,(n) \tag{12}$$

As reported by Likos et al. (2014), no significant influence of the wetting-drying process on the n parameter was considered.

The same soil cores used to calculate the soil hydraulic properties were finally dried at 50 ºC for 72 h and employed to calculate the soil bulk density. Since gypsum content was relevant in the studied soils, the 50 °C temperature was used to avoid the constitutional water release by the gypsum crystal because of the transformation of gypsum into bassanite or anhydrite at temperatures >50 °C (Herrero et al., 2009).

To compare the effects of the soil type and treatment on the soil hydro-physical properties, analysis of one-way variance (ANOVA) for a completely randomized design was conducted using SPSS (V. 13.0) statistical software. The K_s, α and n variable measured from the upward infiltration needed to be normalized with the $\log_{10}$ transformation. All treatment means were compared using Duncan's multiple range test.

3.- RESULTS AND DISCUSSION

The head losses due to the water flow from the water reservoir to the soprtivimeter calculated according to the sorptivimeter pipes dimensions were negligible (< 0.1 mm). As example, Figure 2 shows, for one of the three replications measured in each soil and treatment, the best fitting between experimental and simulated upward infiltration curves and the error maps for the S-β and β-t combinations. In all cases, the results showed an excellent fitting between experimental and simulated upward infiltration curves ($R^2 > 0.98$), and S-β response surfaces with a unique and well defined minimum. This indicated the upward infiltration times used in the experiments gave accurate estimations of S and β. Similar conclusions were achieved when analysing the t-β response surfaces, where the β value tended to asymptotically coalesce to a unique and well defined value. These results suggested that the 5 cm-high cylinder used in the experiment was long enough for accurate estimates of β. Because the S parameter is accurately derived from the early-time of the upward infiltration (Moret-Fernández and Latorre, 2016), the response surfaces for the t-S combination were not considered in the analysis. The β value was, in all cases, lower than 1.7, which denoted that the model could satisfactorily be used to estimate the soil hydraulic properties (Lassavatere et al., 2009). Except for the θ_r, β and n parameters, significant differences between the five different soils were observed for K_s, S, α and θ_s (Table 2). Overall, the K_s and S values measured from the upward infiltration were within the same order of magnitude as those measured in situ and in the same fields and treatments with the disc infiltrometer (Moret-Fernández et al., 2011, 2013).

The unique minimum observed in the $T(\alpha,n)$ response surface calculated from the water retention curves measured with the TDR-pressure cell indicated that total number of pairs of h-θ values used in the experiments was enough to provide accurate estimates of α and n (Fig. 3). Overall, a good fitting between experimental and simulated water retention curves was obtained. Significant differences for the comparison between the θ_s, α and n values calculated from the TDR-pressure cell measurements were observed among all treatments (Table 3).

A significant relationship, with a slope close to one, was observed between the n values estimated with the TDR-pressure cell and the corresponding values estimated from the upward infiltration curves (Fig. 4a). On average, the n values calculated from the optimized S and β data were 4.8% larger than those obtained with the TDR-pressure cell. This means that the $\theta(h)$ measured with the TDR-cell presented a smoother slope, which involved larger water content at more negative pressure heads. As reported by Solone et al. (2012), this difference could be due to limitations of the pressure plate apparatus, when the θ was measured at high pressure heads. For instance, if the time needed to stabilize the water flow inside the pressure cell was not long enough, the θ measured by the pressure cell at the end of the pressure step would be larger than the actual value. On the other hand, the lack of data between the lowest applied pressure head (-50 kPa) and the pressure head for θ_r, could give more weight to the dry end of the water retention function, making softer slopes and consequently lower n values. While significant differences in n values among the different soil treatments were observed in the PC (Table 2), these differences vanished in UP (Table 3). This different behaviour between both methods could be explained by the higher standard deviation observed in UP, which indicated that PC was less sensitive to the soil variability. This could be explained by the soil flooding conditions imposed in the pressure cells that may collapse the more unstable soil aggregates, (Moret-Fernández et al., 2016a), homogenize the soil porosity, and consequently, decrease the standard deviation of the calculated *n* values. All these problems probably vanished with the upward infiltration method, where the bulk soil was not waterlogged and the wetting process included all soil pressure heads from the residual to the saturated water content.

Overall, the α values for the drying branch of $\theta(h)$ calculated from the upward infiltration measurements were larger than those calculated with the TDR-pressure cell (Fig. 4b). This means that the soil with UP showed higher pore volume at the wet end of the soil water retention curve (Ahuja et al., 1998) (Fig. 5). The difference between the maximum and minimum average α values measured for the five soils with the PC and the UP method were 0.021 and 0.14 cm^{-1}, respectively. These results indicate that the UP method was more sensitive to detect differences in the α parameter. This differential behaviour between both methods could be again explained by the wetting process up to saturation used in the TDR-pressure cell, which may have an important influence on the structural component of the soil, and consequently on the α parameter. As reported by Moret-Fernández et al. (2016a), the soil waterlogged conditions in the pressure cell can collapse the more unstable macropores and increase the volume of the smaller ones, causing a decrease and a homogenization of the α value. Although these authors observed that this effect was more significant in freshly tilled soils, this phenomenon was also evident in consolidated soils. These soil dynamics may be minimized by the upward infiltration technique, where the S and β are estimated from the upward infiltration curve, before the soil is saturated. This process may prevent collapsing the more unstable soil pores, which resulted in increasing α values. This lack of correlation may be also due to the different process considered for measuring α (wetting vs. draining), where an indirect confirmation for this is given by the good correlation found for *n* that, as commonly known, is less affected by hysteresis. The larger hysteresis index obtained in the experimental soils might also be related with the cracks that can appear after air drying the soil or the preferential channels of the undisturbed soil samples, which are not taken into account in the hysteresis models.

4.-CONCLUSIONS

This work shows that the method recently developed by Moret-Fernández and Latorre (2016), which determines the α and n parameters from the S and the β values calculated from the inverse analysis of an upward infiltration curve, can be satisfactorily applied to undisturbed soil cores of 5 cm height. The differences in the α and n values observed between both methods could be attributed to limitations of the PC method, in which the soil flooding process used in the pressure cells, together with the limited soil pressure heads employed in this method, could result in an underestimation of the α and n value. In conclusion, this work used an inexpensive, fast and simple to implement method that, unlike to the current techniques, allows estimating the hydraulic properties of undisturbed soil samples using the 5 cm-high cylinders commonly used to measure the soil bulk density. A free application to apply this method will be available in the Soil and Water Infiltration web site (http://swi.csic.es).

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Figure captions

Figure 1. Sorptivimeter scheme

Figure 2. Experimental (cycles) and best optimization (line) of the upward infiltration curves, and the error maps for the *S*-β and β-*t* combinations estimated from minimization of the *Q* function for one of the four replications measured in each soil and treatment. CT, conventional tillage; RT, reduce tillage, NT, no tillage; natural shrubland, N; and grazed shrubland, GR. Red line in β-*t* combinations denotes the 0.02 contour line.

Figure 3. Experimental (cycles) and best optimization (line) of the water retention curves and error maps for the α-*n* combination estimated from minimization of the *T* function for one of the four replications measured in each soil and treatment. CT, conventional tillage; RT, reduce tillage, NT, no tillage; natural shrubland, N; and grazed shrubland, GR.

Figure 4. Relationship between the *n* (a) and α (b) values estimated with upward infiltration for the drying branch of the water retention curve and the corresponding values measured with TDR-pressure cell method.

Figure 5. Averaged water retention curve estimated with the pressure cell (PC) and upward infiltration (UP) methods on conventional tillage (CT), reduce tillage (RT), no tillage (NT), natural shrubland (N) and grazed shrubland (GR) treatments.

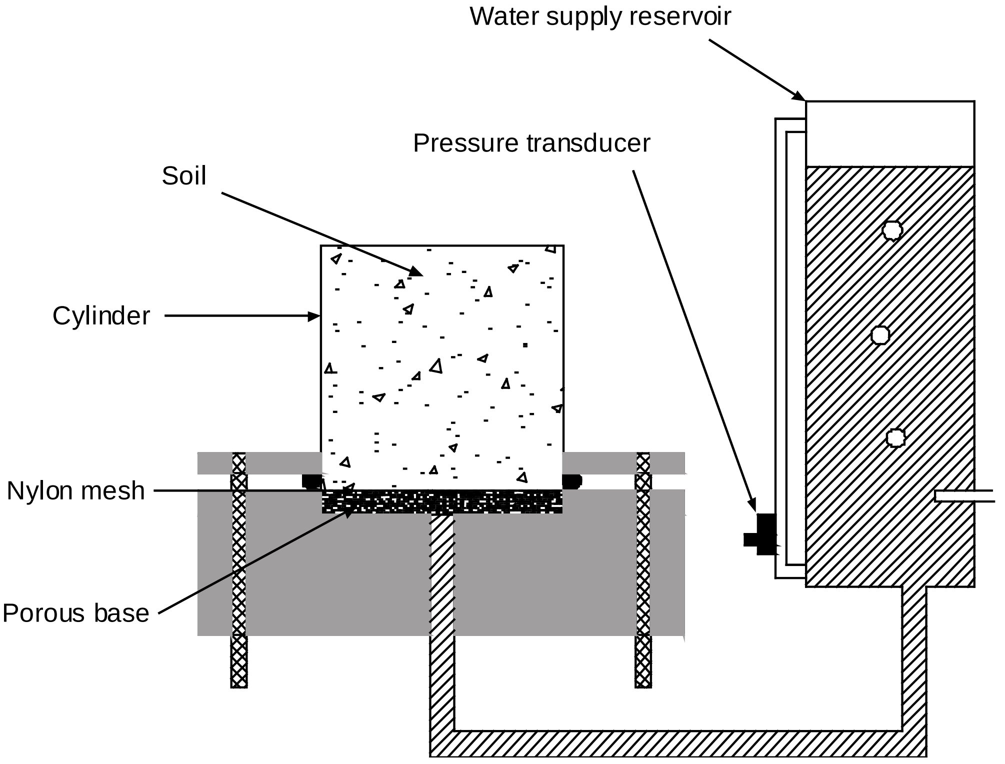


Figure 1. Sorptivimeter scheme

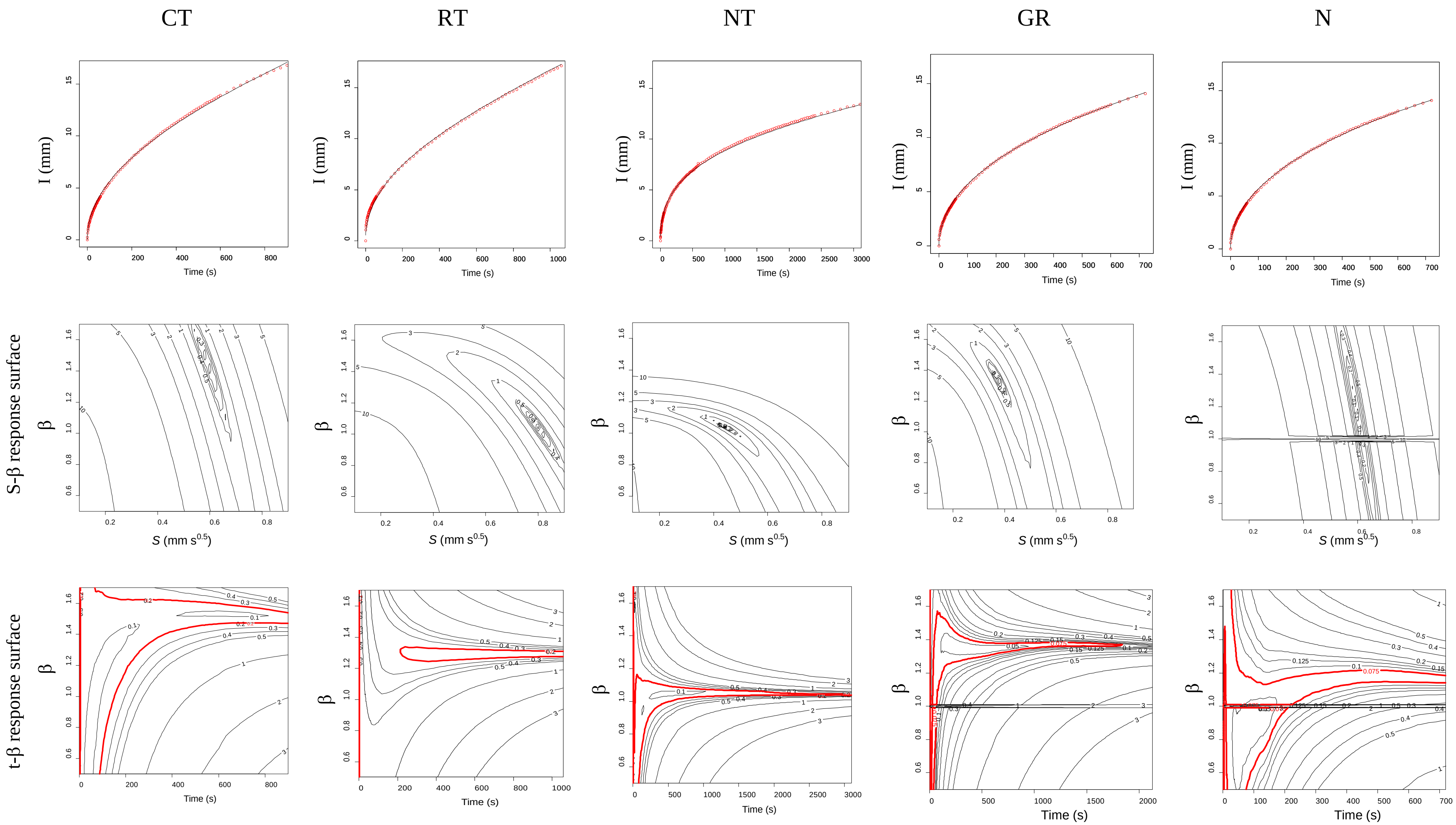


Figure 2. Experimental (cycles) and best optimization (line) of the upward infiltration curves, and the error maps for the *S*-*β* and *β*-*t* combinations estimated from minimization of the *Q* function for one of the four replications measured in each soil and treatment. CT, conventional tillage; RT, reduce tillage, NT, no tillage; natural shrubland, N; and grazed shrubland, GR. Red line in *β*-*t* combinations denotes the 0.02 contour line.

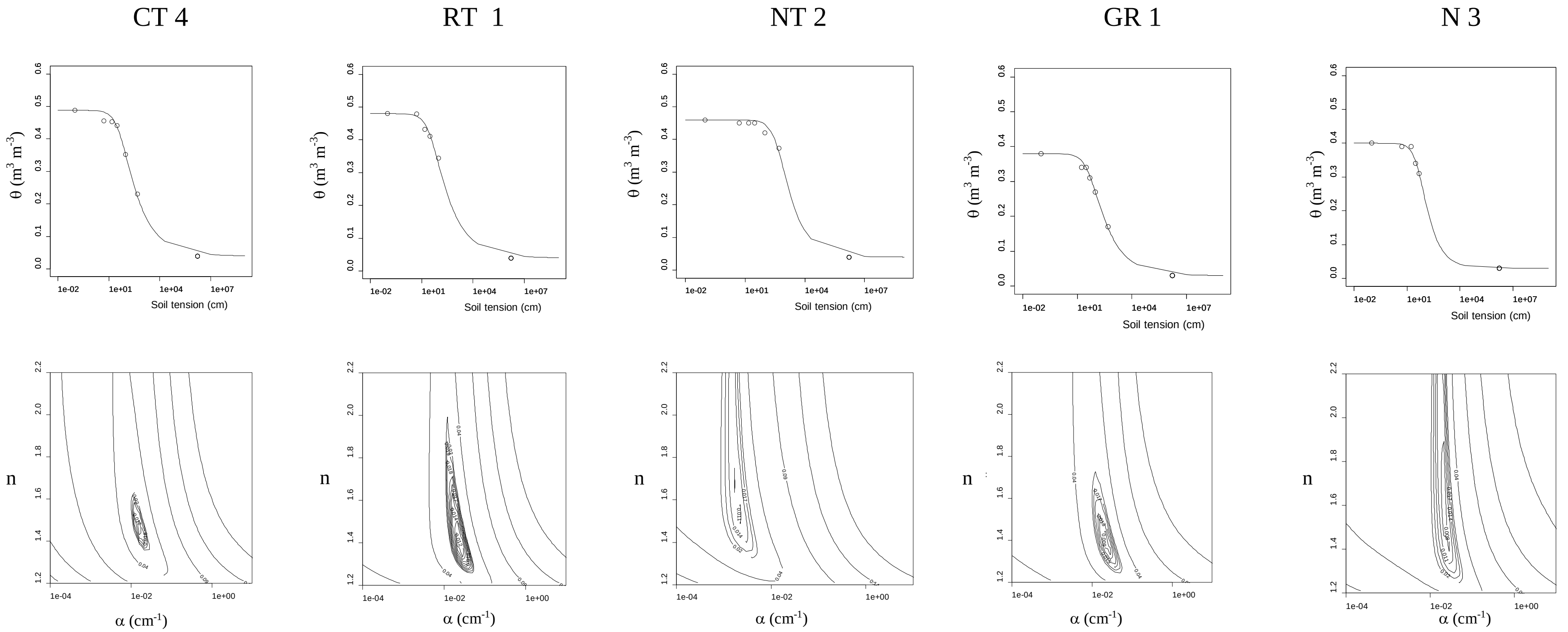
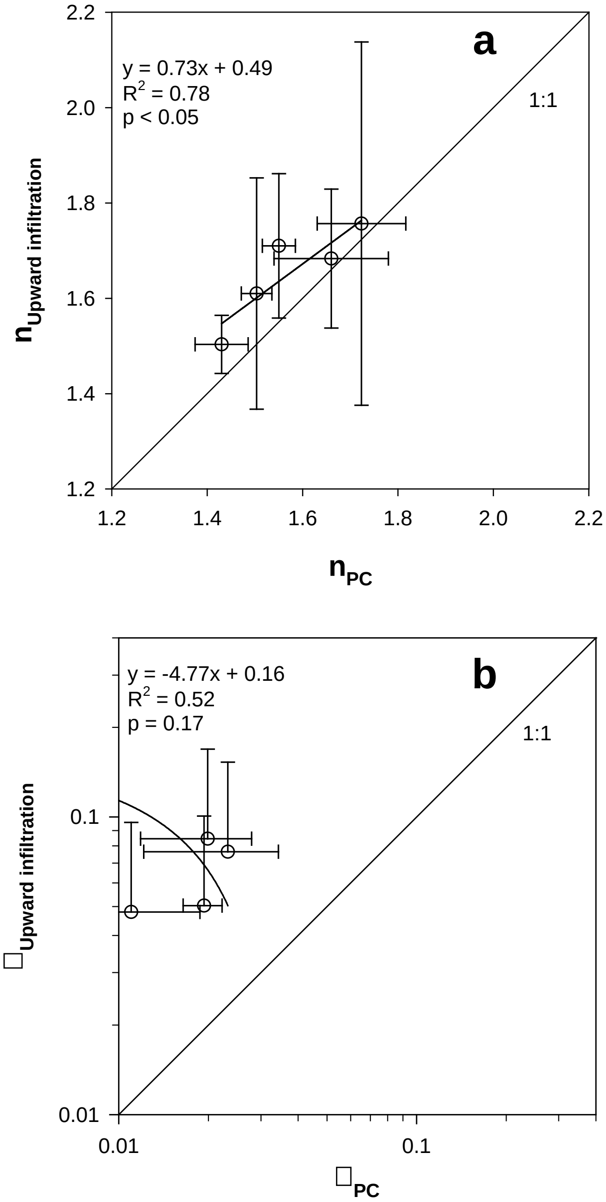


Figure 3. Experimental (cycles) and best optimization (line) of the water retention curves and error maps for the α-*n* combination estimated from minimization of the *T* function for one of the four replications measured in each soil and treatment. CT, conventional tillage; RT, reduce tillage, NT, no tillage; natural shrubland, N; and grazed shrubland, GR.



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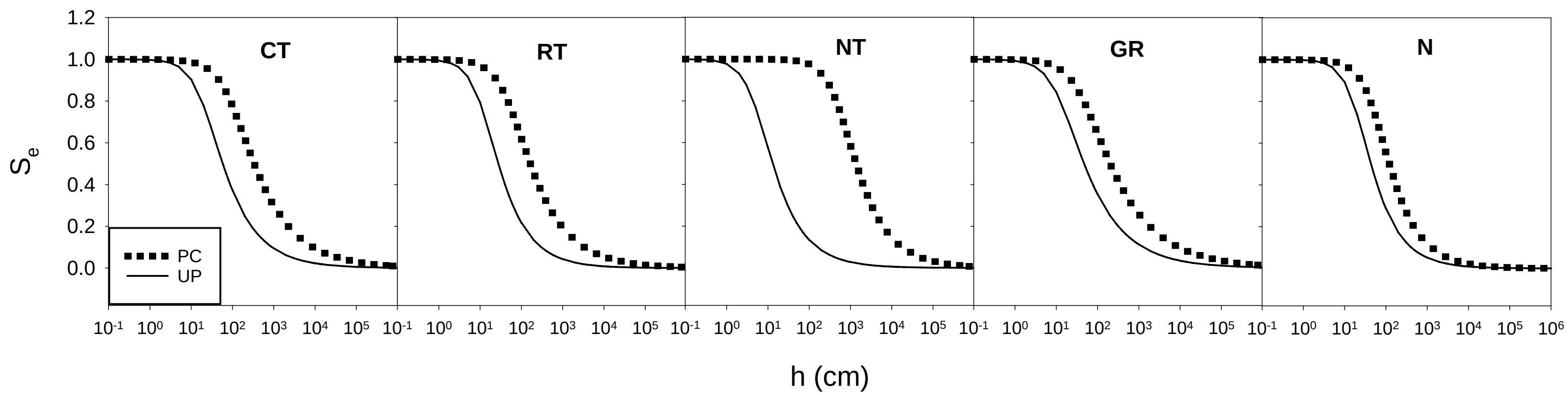

Figure 5. Averaged water retention curves estimated with the pressure cell (PC) and upward infiltration (UP) methods on conventional tillage (CT), reduce tillage (RT), no tillage (NT), natural shrubland (N) and grazed shrubland (GR) treatments.

Table 1. Gypsum, $CaCO_3$, organic carbon (OC) contents, averaged soil bulk density (ρ_b) and textural characteristics of the studied soils (0-5 cm depth).

Location	Management	Gypsum	$CaCO_3$	OC	ρ_b	Sand	Silt	Clay	Textural classification [1]
		%			g cm^{-3}	%			
EEAD	CT	4.87	46.2	1.07	1.31	28.7	46.3	25.0	Loam
	RT	4.14	46.6	1.11	1.32	31.8	43.9	24.3	Loam
	NT	4.43	47.3	1.33	1.37	31.3	45.1	23.6	Loam
Codo	Grazed	43.78	7.07	0.46	1.46	42.8	43.4	13.8	Loam
	Ungrazed	40.28	9.23	0.43	1.44	42.2	40.9	16.9	Loam

[1] USDA classification

Table 2. Average and standard deviation (within parenthesis) values of the saturated hydraulic conductivity (K_s), sorptivity (S), β parameter, and saturated (θ_s) and residual (θ_r) volumetric water content measured form the upward infiltration experiments, and the α value for a wetting (α_w) and drying (α_d) process and n parameters of the van Genuchten (1980) model calculated from K_s, S and β measured for the different treatments: CT, conventional tillage; RT, reduce tillage, NT, no tillage; ngrazed natural shrubland, N; and grazed shrubland, GR. Within the same column, different letters indicate significant differences among soil treatments (p <0.05).

Treatments	K_s	S	β	θ_s	θ_r	α_w	α_d	n
	mm s^{-1}	mm $s^{-0.5}$		m^3 m^{-3}		cm^{-1}		
CT	0.019 (0.005) **a**	0.69 (0.10) **a**	1.25 (0.24) **a**	0.51 (0.03) **a**	0.04 (0.001) **a**	0.09 (0.02) **b**	0.05 (0.01) **b**	1.61 (0.24) **a**
RT	0.029 (0.008) **a**	0.68 (0.11) **a**	1.14 (0.14) **a**	0.50 (0.01) **a**	0.04 (0.001) **a**	0.17 (0.02) **b**	0.08 (0.01) **b**	1.71 (0.15) **a**
NT	0.023 (0.008) **a**	0.37 (0.04) **bc**	1.17 (0.14) **a**	0.45 (0.02) **b**	0.03 (0.001) **a**	0.37 (0.17) **a**	0.19 (0.08) **a**	1.68 (0.15) **a**
GR	0.006 (0.004) **b**	0.27 (0.09) **c**	1.34 (0.07) **a**	0.40 (0.02) **c**	0.04 (0.001) **a**	0.15 (0.02) **b**	0.08 (0.01) **b**	1.50 (0.06) **a**
N	0.032 (0.039) **a**	0.53 (0.18) **ab**	1.14 (0.31) **a**	0.41 (0.03) **c**	0.03 (0.001) **a**	0.10 (0.04) **b**	0.05 (0.02) **b**	1.76 (0.38) **a**

Table 3. Average and standard deviation (within parenthesis) values of the saturated (θ_s)and residual (θ_r) volumetric water content, α and n parameter of the water retention curve calculated from the TDR-pressure cell data measured for the different treatments: CT, conventional tillage; RT, reduce tillage, NT, no tillage; grazed natural shrubland, N; and grazed shrubland, GR. Within the same column, different letters indicate significant differences among soil treatments ($p < 0.05$).

Treatments	θ_s	θ_r	α	n
	$m^3\ m^{-3}$	$m^3\ m^{-3}$	cm^{-1}	$mm\ s^{-1}$
CT	0.47 (0.03) **b**	0.04 (0.001) **a**	0.011 (0.008) **ab**	1.50 (0.03) **c**
RT	0.50 (0.01) **a**	0.04 (0.001) **a**	0.020 (0.008) **a**	1.55 (0.01) **bc**
NT	0.47 (0.01) **b**	0.03 (0.001) **a**	0.002 (0.001) **b**	1.66 (0.12) **ab**
GR	0.36 (0.01) **c**	0.04 (0.001) **a**	0.023 (0.011) **a**	1.43 (0.06) **c**
N	0.38 (0.01) **c**	0.03 (0.001) **a**	0.019 (0.003) **a**	1.72 (0.09) **a**