Hydro-physical behaviour of gypseous soils under different soil management in a semiarid region of NE Spain

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Abstract

The hydro-physical properties of gypseous soils, which are commonly associated with dry climates, determine the productivity of rangelands and croplands. The objective of this paper is to study, in the semiarid central Ebro Basin, NE Spain, some hydro-physical properties of gypseous soils under five different contrasted soil managements: soils of ungrazed (N) and grazed (GR) uncultivated lands, and freshly mouldboard tilled (MB), cropped (C) and fallowed (F) agricultural soils. The gypsum content of the studied soils, which concentrations are natural, ranged from 50 to 92 %. The soil bulk density (ρ_b), saturated sorptivity (S_{10}) and hydraulic conductivity (K_{10}), and the water retention curve (WRC) of undisturbed soil samples from the 0-10 cm deep soil layer after removing the soil surface crust were calculated. Soil penetration resistance (SPR) for the upper 10 cm soil layer was also measured. Additional measurements of soil surface crust sorptivity (S_{crust}) and hydraulic conductivity (K_{crust}) were finally conducted. Livestock trampling in GR promoted the highest ρ_b and SPR values. The lack of soil disturbance in N caused that this treatment showed the lowest values of S_{crust} and K_{crust}, but the highest S_{10} and K_{10}. The specific behaviour of gypseous soils, whose loose aggregates easily collapse during the soil wetting process, promoted that the MB freshly tilled soil showed the lowest values of S_{10} and K_{10}. A typical bimodal function of the WRC was found. Pore size distribution was affected by the soil treatment, with the highest and lowest values under MB and GR treatments, respectively.

Keywords: Hydraulic conductivity; Water retention curve; Soil penetration resistance (SPR); Soil bulk density; Gypseous soils.

Introduction

Knowledge of hydro-physical properties of soils is crucial to evaluate, in the soils of semiarid regions, alternative management practices for soil and water conservation. Under a high annual water deficit, plant growth relies upon the quantity and timing of rainfall, as well as upon the soil's ability to retain and let water infiltrate (Austin et al. 1998). Plant growth and development is highly related to soil hydro-physical properties, which not only depend on soil intrinsic textural and chemical characteristics (Hamza and Anderson, 2005) but also on soil management. Overall, tillage alters the structure of the topsoil layers, increasing the total soil porosity (Green et al., 2003) and the saturated hydraulic conductivity (Moret and Arrúe, 2007). The subsequent impact of rain on the freshly tilled soil promotes a decrease in the hydraulic conductivity (Cameira et al., 2003; Moret and Arrúe, 2007) in conjunction with an increase in the bulk density (Mellis et al., 1996). Soil compaction due to animal trampling is one of the factors responsible for degradation of the physical quality of soils (da Silva et al., 2003; Hamza and Anderson, 2005; Kumar et al., 2010). Soil compaction by livestock trampling directly affects the penetration resistance (Hamza and Anderson, 2005), reduces the pore volume and the saturated hydraulic conductivity, and modifies the water-retention characteristics (Krummelbein et al., 2009, Moret-Fernández et al., 2011b).

Gypseous soils cover extensive areas around the world in zones with less than 400 mm annual rainfall (FAO, 1990). Eswaran and Zi-Tong (1991) estimated the extent of soils with Gypsic or Petrogypsic horizons in Africa, Asia, the Near East, Europe, and the United States to be 207 × 10^6 ha. Many gypseous lands are undergoing increasing human pressure, such as irrigation or other kinds of agricultural intensification (FAO, 1990). The gypsiferous materials cover about 7.2% of Spain surface extent, and 22% of the Ebro Basin (NE Spain) (Navas, 1983). Most of the 35000 km^2 of gypsiferous materials outcropping in the East of Spain occur in dry areas (Macau and Riba, 1965). In the central Ebro Basin, one of the most arid regions in Western Europe (Herrero and Snyder, 1997), gypsum-rich soils are quite common, because the moderate solubility of gypsum allows its permanent presence as a significant soil component in specific geomorphic positions.

Gypsum has largely been studied either as a fertilizer or as an amendment to improve the structure of sodic soils (Hamza and Anderson, 2002). However, little attention has been given so far to the soil physical fertility of naturally gypseous soils. Some of the physical limitations of this kind of soils for supporting plant life are due to their low water retention capacity and other hydric or mechanical characteristics. These include irregularities in the moisture distribution in the soil, increases in soil mechanical impedance, plasticity and cohesion in soils when the gypsum content is higher than 25% in non-cemented layers, or cementation of gypsum in layers within the root zone (Poch and Verplancke, 1997; Poch et al., 1998; Herrero and Boixadera, 2002). However, little quantitative information is available on the factors responsible for the low physical fertility of gypseous soils, and on how this is influenced by soil management. Experimental data on mechanical impedance, water retention or water infiltration in gypseous soils under different soil management systems are so far virtually nonexistent or are weakened by errors in analytical methods as reviewed by Herrero et al. (2009).

In spite of the large number of field studies conducted to evaluate the management effects on the hydraulic functioning of soils, the information about the influence of management on the hydro-physical properties of gypseous soils is nearly non-existent. The low water holding capacity of gypseous soils makes their ability to support crops and other plants much more dependent on adequate management than of soils with higher clay contents. This is more evident in dry areas, where water availability is the main limitation for plant development. Today, the soil management in the central Ebro Basin is mainly governed by the empirical traditional knowledge. Our research can improve this management, and will be increasingly valuable because of the disappearance of rural population and the vanishing of folk knowledge. Moreover, the agricultural intensification can produce undesirable effects due to the lack of management guidelines adapted to gypseous soils. This is especially true for the ongoing transformations to sprinkler irrigated lands in the central Ebro Basin. The purpose of this research was to study the hydro-physical properties of gypseous soils of the central Ebro Basin (NE Spain) with several contrasting aggregation status due to different soil managements. Soil bulk density, soil penetration resistance, water retention and infiltration parameters in the 0-10 cm deep were measured in five different soil aggregation conditions: ungrazed [N] and grazed [GR] uncultivated lands, as well as in freshly mouldboard tilled [MB], cropped [C] and fallowed [F] agricultural soils.

Material and methods

Sites description and history

The experiments were conducted in the semiarid dry lands of the central Ebro Basin (north-eastern Spain; Fig. 1). The average annual precipitation ranges between 313 and 350 mm and the average annual air temperature ranges between 13.3 and 14.5 ºC. Evapotranspiration, calculated from Penman-Monteith method, ranges between 1190 and 1312 mm in the studied sites (Table 1). According to the Thornthwaite climatic classification, the climatic conditions of the studied region is Semirarid-Mesothermic II (Liso and Ascaso, 1969). The soil moisture regime is aridic, and the studied soils are Aridisols (Table 1) according to Soil Taxonomy (Soil Survey Staff, 1999). The experimental sites range in elevation from 331 m to 550 m a.s.l., and are located in the municipalities of Belchite, Leciñena and Bujaraloz (Fig. 1). The lithology of these areas is gypsum alternating with marls, limestone, and clays (Quirantes, 1978). Uncultivated areas are mainly shrublands of *Rosmarinus officinalis* L. (Rosemary) in the hills, and steppes of *Lygeum spartum* L. (Albardine) and *Salsola vermiculata* L. ("Sisallo"), in the bottom flat valleys (Braun-Blanquet and Bolós, 1957). Vegetation cover is discontinuous, in a typical patchy spatial pattern with vegetation patches alternating with bare soil. Bare soil is often covered by lichens and mosses, forming a biological soil crust. A physical soil crust is often present where biological soil crust is not developed. Bare soil is not usually occupied by litter, which is often restricted to the soil underneath the perennial plants. The traditional land use in the region is an agro-pastoral system involving rainfed agriculture and extensive sheep grazing. The cropping system in these semi-arid dry lands is a traditional cereal–fallow rotation, which involves a long-fallow period of 16–18 months running from harvest (June-July) of the first year to sowing (November-December) the following year. Winter cereals obtain no yield in many years, with a mean annual yield of 900 kg ha^{-1} (McAneney and Arrúe, 1993). Soil tillage during the cereal-fallow rotation includes a pass with a mouldboard plough (down to 40 cm depth) in the spring of the fallow period plus repeated secondary tillage cultivations for weed control during the long fallow period. An additional pass with a mouldboard plough plus secondary tillage cultivations are usually repeated before seeding.

Experimental design

The N and GR treatments were located at Leciñena (500 m a.s.l.) and Belchite (400 m a.s.l.) (Fig. 1), on uncultivated soil without and with sheep grazing, respectively. The grazing intensity in the GR fields was < 1 livestock units ha^{-1} $year^{-1}$. Natural vegetation cover in the Middle Ebro Valley is spatially discontinuous where vegetation is distributed in patches with wide open inter-patch areas. Measurements were performed on the bare soil of the inter-patch areas. Soils under N and GR treatments were identified at Leciñena and Belchite (Table 1). N and GR fields were selected in each village. Within each field, eight sampling points regularly distributed along a 50 m transects were selected (Table 2). The distance between fields was about 850 m in Leciñena and 2000 m in Belchite.

Measurements in the MB, C, and F soil treatments were performed in a flat agricultural landscape at Bujaraloz (340 m a.s.l.) (Fig. 1). Four sampling points for MB and C treatments and six for F (Table 2) were selected on commercial agricultural plots where the sowing and ploughing decisions were made by the farmers. The distances between fields ranged from ~100 m to 2000 m. MB treatment were performed on freshly tilled soils just after a pass with a mouldboard plough (in the spring of the 18-months fallow period) and before any rainfall event. The C treatment corresponded to soils in the aggregation status corresponding to the last stages of winter cereal development (May-June) and the F treatments consisted of soils in the aggregation status after six to eight months of fallow, prior to any primary tillage operations. The soil under the fallow treatment did not present adventitious plants and was partially covered (> 20%) with winter cereal crop residues.

Measurements in C and F were performed between crop lines on a soil surface free of crop residues. All measurements were conducted between February 2009 and October 2010.

Soil texture, chemical properties and organic matter

All soil samplings (for soil texture, chemical properties and organic matter content) per experimental field were taken from the 0-10 cm depth soil layer and stored in a single bag. The samples, one replication per field, were homogenised and sieved to less than or equal to 2 mm for the subsequent laboratory analyses. The gypsum content was titrated by the loss of crystal water of gypsum (Artieda et al., 2006). The calcium carbonate equivalent (CCE) was measured by gasometry. The soil texture was measured using the laser diffraction technique (COULTER® LS230). The organic carbon was determined by an improved chromic-acid digestion and spectrophotometric procedure (Heanes, 1984), and the results were transformed into organic matter by multiplying by the factor 1.724 (Burt, 2004).

Field measurements and laboratory analysis of soil hydro-physical properties

The soil dry bulk density (ρ_b), measured within the 2-7 cm depth soil layer after removing the soil surface crust, was determined by the core method (Grossman and Reinsch, 2002) (50 mm diameter and 50 mm height). Replication of ρ_b per field and sampling point are summarized in Table 2. The soil was dried at 50 ºC for 48 h. The ρ_b samplings were subsequently used to determine the prior volumetric water content, used to calculate the soil hydraulic coductivity, and to interpret the soil penetration resistance values.

The soil hydraulic conductivity, K, and sorptivity, S, at saturation were measured in situ at each sampling point on the soil surface crust (K_{crust} and S_{crust}) and on the 0-10 cm depth soil layer after removing the soil surface crust (K_{10} and S_{10}). To this end, a tension disc infiltrometer (Perroux and White, 1988) with a base radius of 50 mm was used. The K and S were calculated from the transient cumulative infiltration using the Vandervaere et al. (2000) method. The final soil water content was sampled from the upper centimetres of the soil just after removing the disc infiltrometer from the soil surface. Replications of water infiltration per field and sampling point are summarized in Table 2. No measurements of K_{crust} and S_{crust} were possible in the freshly tilled soil of the MB treatment due to surface crust was broken down by tillage.

The soil penetration resistance (SPR) for the 0-10 cm depth soil was measured *in situ* with a commercial penetrometer (CP40II® Penetrometer), which automatically measured the profile of the resistance to penetration. Five replications, close to the infiltration measurements, were performed per sampling point (Table 2).

The subsurface water retention curves (WRC) for undisturbed soil samples were measured in the laboratory using a pressure head TDR-cell (Moret-Fernández et al., 2011a). The undisturbed soil samples were taken from the 0-10 cm depth soil layer after removing the soil surface crust using the core method. A first measurement of θ was taken in air-dry soil conditions (166,000 kPa; Munkholm and Kay, 2002). Additional measurements of θ were taken at soil water saturation and at eight different pressure heads from -1.7, to -1500 kPa. The WRC were fitted to a bimodal function (Durner, 1994) using the SWRC Fit Version 1.2 software (Seki, 2007) (http://seki.webmasters.gr.jp/swrc/). Replications of WRC per field and sampling point are summarized in Table 2. The same soil cores used to calculate the WRC were subsequently dried at 50 ºC for 48 h and employed to calculate an additional value of ρ_b.

To compare the effects of the soil management system on the soil hydro-physical properties, an analysis of variance (ANOVA) for a completely randomized design was carried out using SPSS® (V. 13.0) statistical software. The PR, S_{crust} and θ_{sat}, variables needed to be normalized using the root square function, K_{10} and n_1 with an inverse transformation, and ρ_b using a quadratic function. The treatment means were compared using the Duncan's multiple range test.

Results and discussion

The gypsum content in the studied soils, which are natural concentrations where stated, ranged from 50 to 92 %, and the CCE content from 5 to 57% (Table 3). The soil texture in the different fields ranged from sandy loam to silt loam (Table 3). The organic matter content (OM) ranged from 0.7 to 2.5%, with the lowest averaged values in the GR treatment. This last result agrees with those observed by Mills and Fey (2003) and du Preez et al. (2011) in South Africa, who pointed that removal of a cover of vegetation by grazing tends to reduce OM due to reduced inputs of organic matter and enhanced activity of soil microbes. The volumetric soil water content at the sampling time measured in the different fields ranged between 0.04 and 0.13 m^3 m^{-3} (Table 3).

The soil bulk density (ρ_b) and soil penetration resistance (SPR), which values are related to soil compaction, were significantly affected by soil treatment. As cited in literature for non-gypseous soils (Sauer et al., 1990; Logsdon et al., 1999; Moret and Arrúe, 2007, among others), disruption and destabilization of soil structure by tillage increases the soil porosity, which promotes a significant reduction of the upper layer ρ_b and SPR (Fig. 2a and b). The increase of ρ_b and SPR in C and F compared to MB is due to soil settlements and filling of pore space instigated by the mechanical compaction, the wetting and drying cycles and the biological activity of soil after tillage (Leij et al., 2002). Maximal values of ρ_b and SPR corresponded to GR treatment. These values should be attributed, as cited in studies in non-gypseous soils (Hamza and Anderson, 2005; Zhao et al., 2007; Krummelbein et al., 2009; Price et al., 2010; Piñeiro et al., 2010) to the livestock trampling, which compacts the upper soil layer.

Although no statistical difference in S_{10} and K_{10} ($p < 0.05$) was observed between uncultivated soils (N and GR) and agricultural soils either cropped (C) or with fallow (F), the N treatment showed the highest values of S_{10} and K_{10} (Fig. 2c and d). This could be due to the more stable preferential channels in the N soil (Sidle et al., 2001), which may better persist after soil wetting. The lowest values of S_{10} and K_{10} corresponded to the loosened MB soil. These results contrast with those found in the literature for non-gypseous soils (Messing and Jarvis, 1993; Moret and Arrúe, 2007), in which soil hydraulic conductivity significantly increases after tillage. The different behaviour shown by gypseous soils has been attributed by Poch and Verplancke (1997) to the gypsum properties, which dissolves during soil wetting and subsequently grows in new crystals that obstruct pre-existing conductive pores. These effects may be amplified in freshly tilled soils, where soil collapses and gypsum dissolves more easily. Field observations showed that the saturated gypseous soil under MB treatment formed a kind of sticky paste that restricts the infiltration. This sticky paste in the first centimetres or millimeters of the gypseous soils, with very abrupt contact with the underlying dry soil, is well known by farmers, and designated with local names like “chabisque”. A slight shower, or even dew, produces this sealing paste. Taking into account all soil managements, a significant correlation ($P < 0.05$, $R^2 = 0.32$; $y = 0.012x + 0.009$) was found between K_{10} and OM. Within each treatment, this correlation was only significant in the F management ($P < 0.05$, $R^2 = 0.81$). These results indicate that increasing values OM in gypseous soil has a positive effect on K_{10}. No significant relationship was found between the sand/clay content and the soil hydraulic parameters.

The soil surface crust sorptivity (S_{crust}) and hydraulic conductivity (K_{crust}) at saturation were also strongly affected by soil management. The lowest values of S_{crust} and K_{crust} corresponded to the N soil, followed by GR and agricultural soils, respectively (Fig. 3). The lowest infiltration parameters under N should be related to the consolidation of the surface crust on the undisturbed soil surface. Other factors affecting lower water infiltration under N may be related to the formation of a biological soil crust on the soil surface that has proven to be important in many arid and semiarid ecosystems for their abilities to stabilize the soil surface (Liu et al., 2009). Light stocking rate could be beneficial for increasing the infiltration capacity of the soil, due to the topsoil crust removal by livestock trampling (du Toit et al., 2009).

Assuming a residual volumetric water content equal to zero, the water retention curve measured in all treatments showed a clear bimodal form, which indicates that the soils display a patent double porosity system (Fig. 4a). Taking into account all soil treatments, a unique significant correlation ($P < 0.05$, $R^2 = 0.26$) was found between OM and the α_1 coefficient. No significant relationship was found between the sand/clay content and the WRC coefficients. Significant effects of soil management on the WRC parameters were observed. The soils under MB presented the highest values of θ_{sat}, α_1 and w (Table 4), which indicates a higher total porosity and a larger volume of macropores. These results agree with Ahuja et al. (1998), who observed that tillage changes primarily the “effective pore space” within the 0-33 kPa water retention range. Appreciable differences among the different soil treatments were observed in the effective saturation curves, $S_e(\psi)$ (Eq. 2), for the water retention parameters of Table 4 (Fig. 4b). The pore system of a soil can also be characterized by its equivalent pore-size density (C*), which is expressed as $C^* = {dS_e}/{d\psi}$ (Durner, 1994). Although C* does not provide direct information about the porosity, it gives a measure of the relative abundance of pore size (Or et al., 2000). According to Laplace’s law, the ψ at which a water-filled pore starts to drain is inversely proportional to the equivalent radius of the pore necks (r_p), and can be approximately computed as $r_p = \frac{0.15}{\psi}$ (cm). The analysis of C^* as function of r_p (C^*_r), calculated for the WRC parameters shown in Table 4, gives more evident differences among the soil treatments (Fig. 4c). The pore system can be divided into textural and structural components, the latter being far more susceptible to changes due to either wetting and drying processes or external loading (Ahuja et al., 1998). Since all compared soils did not show important differences in composition and textural characteristics, differences in the C^*_r curves would be mainly attributed to the structural component of the pore system. No apparent differences among soil managements were observed in C^*_r for pressure heads corresponding to the textural soil component ($\psi > 100$ kPa; $r_p < 1.5$ μm). The maximum in the C^*_r function (C^*_{Mx}) calculated for the different soil management, which values gives a measure of the relative maximal abundance of pore size, followed the gradient MB > C > F > N > GR (Fig. 4c). This decreasing gradient should be related to the effect of the different treatments on the soil porosity. Soil breakdown by tillage forms large interaggregate pore space (Or et al., 2000; Green et al., 2003), which results in the highest values of C^*_{Mx}. These new large pores are structurally unstable and, due to either wetting-drying processes (Cameira et al., 2003; Moret and

Arrúe, 2007) or external loadings (Or et al., 2000), their sizes tend to evolve to a more stable forms. The soil pore closure makes decreasing C^*_{Mx}, which values gets lower by the time elapsed since the tillage operations increases. External soil impacts due to animals trampling, which tend to compact the top soil layers (Fig. 2a and b), reduced the soil porosity and consequently the C^*_{Mx} values (Fig. 4c). Overall, a good agreement was found between C^*_{Mx} and the ρ_b and SPR values measured in the different treatment. For the particular case of SPR, a consistent relationship ($C^*_{Mx} = -0.08 \, \mathrm{Ln(SPR)} + 0.69$; $R^2 = 0.98$) was found between the estimated C^*_{Mx} and the averaged SRP values measured for the different soil treatments.

Conclusions

This work compares, in a semiarid region of NE Spain, the soil hydro-physical properties of gypseous soils under different aggregation conditions due to different soil management: soils of ungrazed (N) and grazed (GR) uncultivated lands, mouldboard tillage (MB), cropped (C) and fallowed (F) agricultural soils. The ρ_b and SPR were the highest and lowest in the GR and MB treatments, respectively. The N treatment, with intact upper soil horizons, showed the lowest and highest values of infiltration parameters for the surface crust and for the 0-10 cm soil layer after removing the soil surface crust, respectively. The lowest values of S_{10} and K_{10} corresponded to the MB treatment. A clear bimodal water retention curve was found in all soil treatments with the highest values of θ_{sat} and w in the MB soils. The equivalent pore-size density as a function of the pore radius was maximal under MB and minimal under GR. The results show that gypseous soils have a different infiltration behaviour from that commonly reported in the literature for non-gypseous soils, a fact which should be taken into account in order to improve soil management and cropland productivity. However, further research, including micromorphological analysis, is required to understand this specific behaviour of gypseous soils.

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Figure captions

Figure 1. Sampling fields at the central Ebro Basin, superimposed to the Landsat image (Band 5) from 8 August 2000. Dry farmed areas on gypseous soils are in white and bright tones. Irrigated areas and lands with xerophytic vegetation are in dark tones.

Figure 2. Average (a) soil bulk density, (b) penetration resistance, and (c) sorptivity ($S_{1\text{-}10}$) and (d) hydraulic conductivity ($K_{1\text{-}10}$) at saturation measured on the 0-10 cm depth soil layer for the ungrazed (N), grazed (GR), mouldboard ploughing (MB), cropped (C), and fallowed (F) soils. Columns with the same letter indicate no significant differences ($p < 0.05$) between treatments. Vertical lines indicate standard deviation within each treatment.

Figure 3. Average (a) sorptivity (S_{crust}) and (b) hydraulic conductivity (K_{crsut}) at saturation measured on the soil surface crust layers for the ungrazed (N), grazed (GR), cropped (C), and fallowed (F) soils. Columns with the same letter indicate no significant differences ($p < 0.05$) between treatments. Vertical lines indicate standard deviation within each treatment.

Figure 4. (a) Averaged measured (circles) and average modelled (line) water retention curves, (b) effective saturation curves modelled for the water retention parameters of Table 4, and (c) the corresponding equivalent pore-size distribution (C^*_r) as function of the equivalent radius of the pore necks from for the ungrazed (N), grazed (GR), mouldboard ploughing (MB), cropped (C), and fallowed (F) treatments.

Table 1. Types of soil management in the sampling sites, location, average annual precipitation (P), evapotranspitaion (ET_0), calculated from Penman-Monteith method, and temperature (T), and classification (Soil Survey Staff, 1999) of the studied soils.

Soil management	Sites	Location	Annual average *			Soil classification
			P (mm)	ET_0 (mm)	T (ºC)	
Ungrazed (N) Grazed (GR)	Belchite	41º23’N, 0º42’W	313.7	1311.9	14.5	Typic Haplogypsids
Ungrazed (N) Grazed (GR)	Leciñena	41º46'N, 0º35'W	350.4	1189.9	13.3	Gypsic Haplosalids
Mouldboard tillage (MB) Cropped (C) Six months fallow (F)	Bujaraloz	41º26’N, 0º10’W	332.0	1306.1	13.5	Typic Calcigypsids

* Data from SIAR (Sistema de Información Agroclimática para el Regadío) network of meteorological stations (Ministerio de Agricultura, Alimentación y Medio Ambiente, Spain) from 2005 to 2011

Table 3. Initial volumetric soil water content (θ_i), chemical and USDA texture of the studied soils under ungrazed (N), grazed (GR), mouldboard ploughing (MB), cropped (C), and fallowed (F) treatments.

Soil Management	Site	Field	θ_i	Gypsum	CCE[1]	Organic matter	Sand	Silt	Clay	Soil texture (USDA)
			m^3m^{-3}				%			
N	Belchite	Lomaza	0.09	64.1	5.4	1.4	57.3	32.2	10.5	Sandy loam
	Leciñena	F-1	0.08	56.6	34.3	1.6	55.0	27.4	17.6	Sandy loam
GR	Belchite	Granja	0.07	49.6	17.3	0.8	56.3	32.1	11.6	Sandy loam
	Leciñena	F-2	0.08	54.0	22.3	0.9	68.5	24.4	7.1	Sandy loam
MB	Bujaraloz	BL-41	0.09	78.0	14.1	1.2	13.5	71.5	15.0	Silt loam
		BL-39	0.05	82.6	8.8	0.7	32.2	58.4	9.4	Silt loam
		BL-45	0.12	72.7	17.6	0.9	55.3	39.0	5.7	Sandy loam
		BL-50	0.05	91.8	6.2	0.9	68.4	28.0	3.6	Sandy loam
C	Bujaraloz	BL-31	0.08	57.5	19.9	1.7	25.0	61.0	14.0	Silt loam
		BU-1	0.12	68.4	17.4	1.0	35.7	53.6	10.7	Silt loam
		BL-46	0.05	49.8	24.6	2.5	23.2	64.0	12.8	Silt loam
		BL-48	0.05	85.7	8.7	1.0	33.2	57.7	9.1	Silt loam
F	Bujaraloz	BL-18	0.05	90.1	8.3	0.9	41.7	52.2	6.1	Silt loam
		BL-16	0.07	62.9	57.2	2.0	47.2	40.1	12.7	Loam
		BL-9	0.04	60.1	25.4	2.2	53.5	35.9	10.6	Sandy loam
		BL-14	0.06	71.8	11.6	1.7	29.5	62.6	7.9	Silt loam
		BU-5	0.13	82.3	9.0	0.9	50.0	44.1	5.9	Sandy loam
		BL-21	0.11	70.1	26.4	1.4	28.3	62.3	9.4	Silt loam

[1] CCE: calcium carbonate equivalent

Table 2. Experimental design, number of sampling points and replications sampled in the different experimental fields.

Soil management	Village	Field	50 m transect	Sampling points	ρ_b [1]	*K/S* [2]	*WRC* [3]	*SPR* [4]
					Replications / sampling point			
N	Belchite	Lomaza	Yes	8	1	1	1	5
	Leciñena	F-1	Yes	8	1	1	1	5
GR	Belchite	Granja	Yes	8	1	1	1	5
	Leciñena	F-2	Yes	8	1	1	1	5
MB	Bujaraloz	BL-41	No	1	1	2	2	5
		BL-39	No	1	1	2	2	5
		BL-45	No	1	1	2	2	5
		BL-50	No	1	1	2	2	5
C	Bujaraloz	BL-31	No	1	1	2	2	5
		BU-1	No	1	1	2	2	5
		BL-46	No	1	1	2	2	5
		BL-48	No	1	1	2	2	5
F	Bujaraloz	BL-18	No	1	1	2	2	5
		BL-16	No	1	1	2	2	5
		BL-9	No	1	1	2	2	5
		BL-14	No	1	1	2	2	5
		BU-5	No	1	1	2	2	5
		BL-21	No	1	1	2	2	5

[1] Soil bulk density
[2] Saturated hydraulic conductivity and sorptivity
[3] Water retention curve
[4] Soil penetration resistance

Table 4. Average and standard deviation (within parenthesis) values for the parameters of the Durner et al. (1994) water retention curves [a] estimated for the different soil managements, and coefficient of determination (R^2) for best fit between the measured and modelled water retention curves. Within the same column, different letters indicate significant differences among soil treatments ($p < 0.05$).

Soil management	θ_{sat} [b] ($m^3\ m^{-3}$)	W [c]	α_1 [d]	n_1 [e]	α_2	n_2	R^2
Ungrazed	0.43 (0.04) **cd**	0.55 (0.14) **ab**	0.48 (0.34) **b**	1.81 (1.02) **a**	$2.1\ 10^{-4}$ ($4.9\ 10^{-4}$) **a**	1.47 (0.23) **a**	0.99
Grazed	0.41 (0.04) **d**	0.36 (0.19) **c**	0.37 (0.30) **b**	1.60 (1.53) **a**	$3.0\ 10^{-4}$ ($7.8\ 10^{-4}$) **a**	1.49 (0.19) **a**	0.99
Mouldboard tillage	0.48 (0.02) **a**	0.59 (0.11) **a**	1.65 (0.57) **a**	1.74 (0.51) **a**	$6.9\ 10^{-4}$ ($6.0\ 10^{-4}$) **a**	1.45 (0.22) **a**	0.99
Cropped	0.47 (0.02) **ab**	0.44 (0.14) **abc**	0.91 (0.68) **b**	1.69 (0.68) **a**	$3.8\ 10^{-4}$ ($2.5\ 10^{-4}$) **a**	1.41 (0.12) **a**	0.99
Fallow	0.44 (0.02) **bc**	0.41 (0.16) **bc**	0.61 (0.35) **b**	1.92 (0.35) **a**	$3.9\ 10^{-4}$ ($2.8\ 10^{-4}$) **a**	1.51 (0.11) **a**	0.99

[a] $\theta = (\theta_{sat} - \theta_r)\left[w\left[\frac{1}{1+(\alpha_1\psi)^{n2}}\right]^{m_1} + (1-w)\left[\frac{1}{1+(\alpha_2\psi)^{n2}}\right]^{m_2} \right] - \theta_r$

[b] θ_{sat}: saturated volumetric water content

[c] w: weighting factor for the subcurves.

[d] α_i: scale factor (kPa)

[e] n_i: pore-size distribution parameter

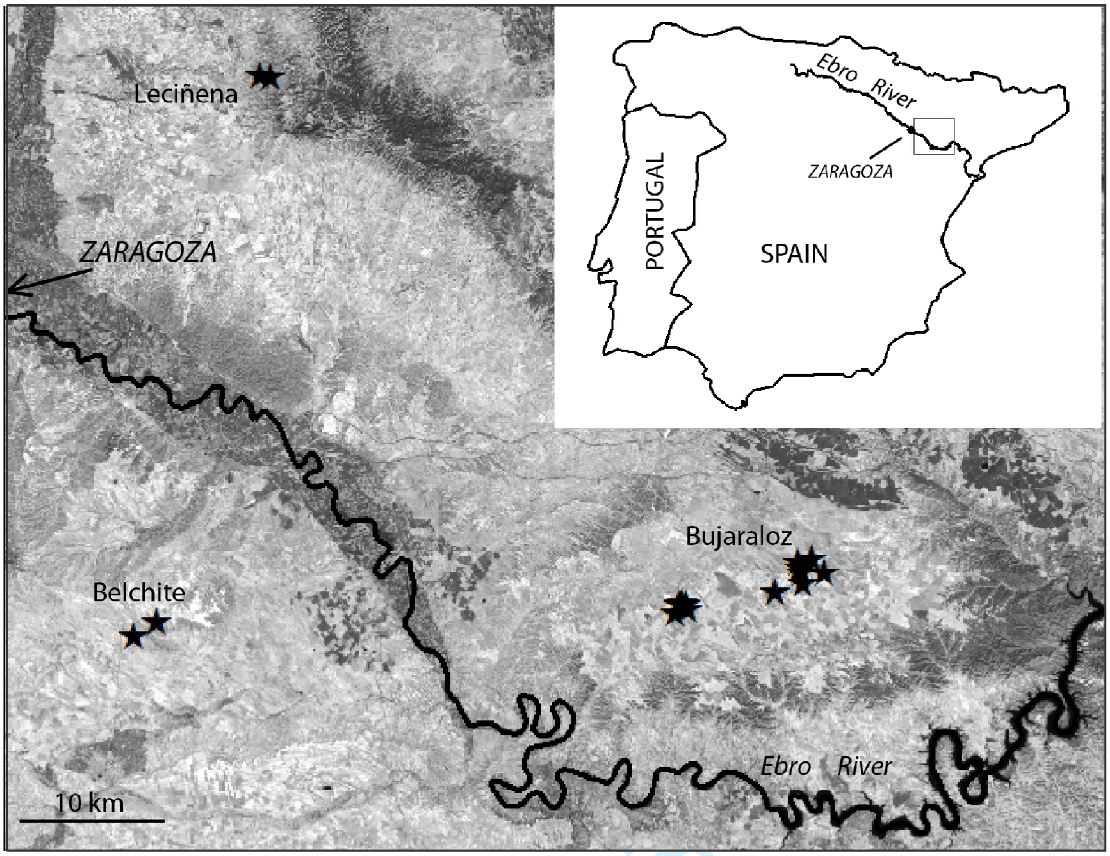
Leciñena
ZARAGOZA
Belchite
Bujaraloz
Ebro River
10 km
Ebro River
ZARAGOZA
PORTUGAL
SPAIN

Figure 1.

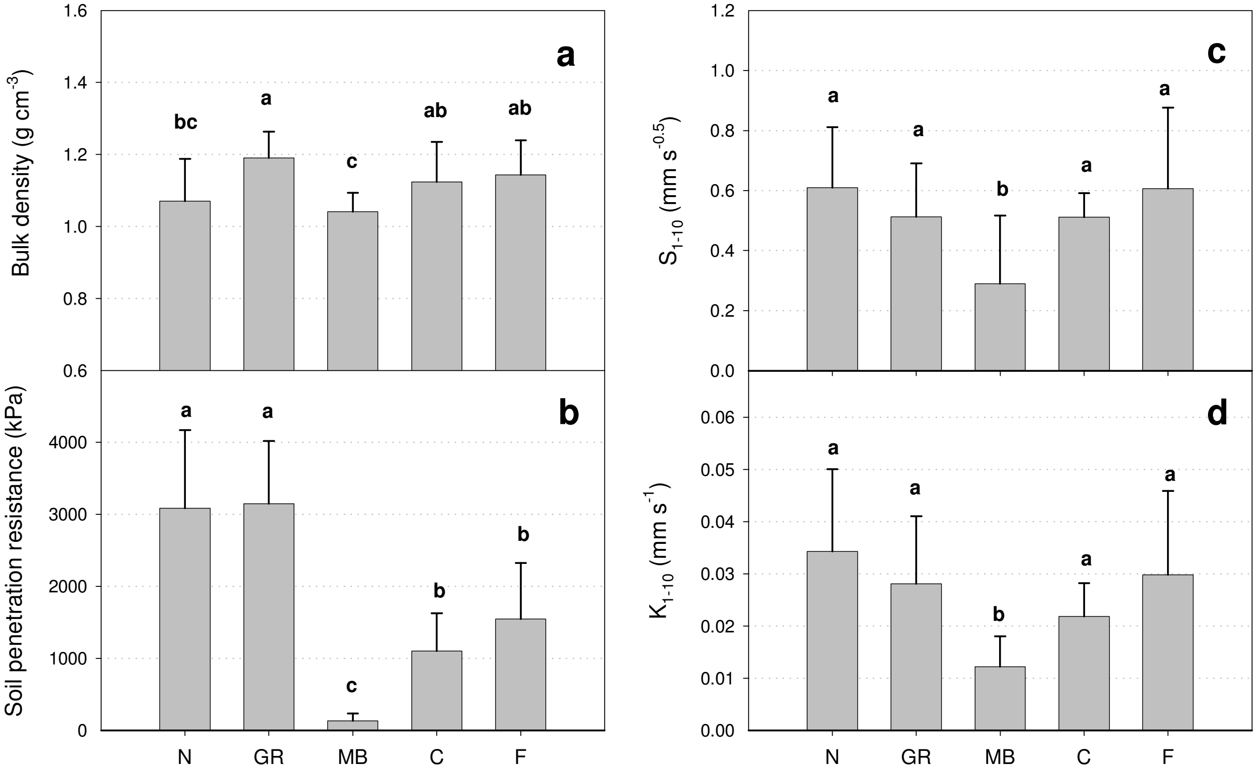
a
b
c
d
Bulk density (g cm^{-3})
Soil penetration resistance (kPa)
S_{1-10} (mm s$^{-0.5}$)
K_{1-10} (mm s^{-1})
1.6
1.4
1.2
1.0
0.8
0.6
4000
3000
2000
1000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.00
0.01
0.02
0.03
0.04
0.05
0.06
bc
a
c
ab
ab
a
a
c
b
b
a
a
b
a
a
a
a
b
a
a
N
GR
MB
C
F

Figure 2.

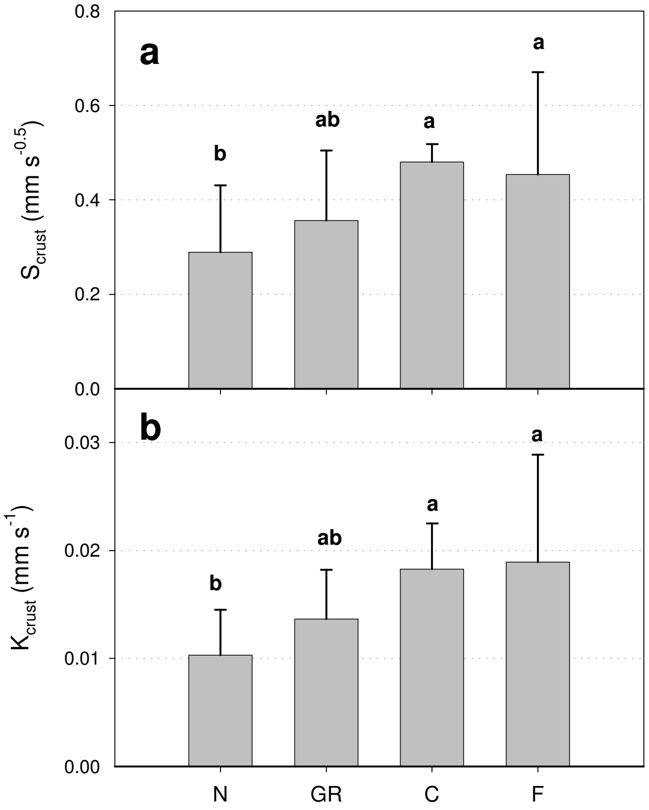
a
b
0.8
0.6
0.4
0.2
0.0
S_{crust} (mm $s^{-0.5}$)
b
ab
a
a
0.03
0.02
0.01
0.00
K_{crust} (mm s^{-1})
b
ab
a
a
N
GR
C
F

Figure 3.

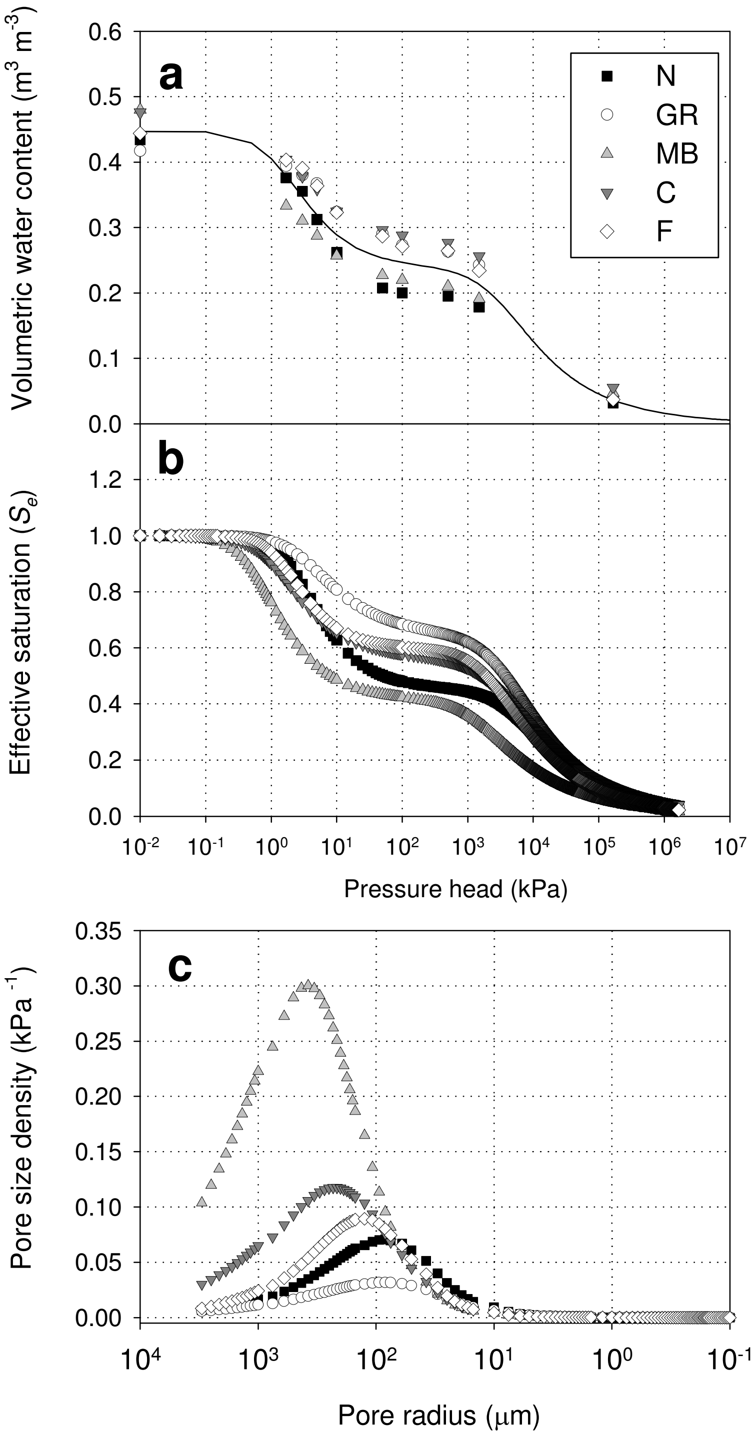
a
Volumetric water content (m3 m-3)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
N
GR
MB
C
F
b
Effective saturation (Se)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10-2
10-1
100
101
102
103
104
105
106
107
Pressure head (kPa)
c
Pore size density (kPa-1)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
104
103
102
101
100
10-1
Pore radius (μm)

Figure 4