**Hydro-physical characterization of contrasting soils in a semiarid zone of
the Ebro river valley (NE Spain)**

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Abstract

The arid agricultural lands of the Monegros Desert, in the central Ebro Basin (NE Spain), show contrasting white patches (WP) and dark patches (DP), evidencing their different soil composition. The white patches have shallow soils with low or nil crop development in most years. Soil at the dark patches uses to be deeper, and winter cereal attains better development. This paper analyzes soil hydro-physical features in order to identify differences in soil physical properties between white and dark soils. For this purpose, twenty pairs of WP/DP soils were studied on several agricultural plots. Each sampled pair was under the same soil condition. Three soil treatment (ST) were studied: freshly tilled soil (MB), cropped (C), and fallowed soil (F). The gypsum and calcium carbonate content, organic matter (OM) content, and particle size distribution for the 0-10 cm depth soil were determined. Field measurements for the 1-10 cm depth soil layer were soil bulk density (ρ_b), soil penetration resistance (SPR), saturated hydraulic conductivity (K_{1-10}) and sorptivity (S_{1-10}). The water retention curve (WRC) was determined in the lab on undisturbed soil cores for the 1-10 cm depth soil layer. Additional field measurements of soil surface crust sorptivity (S_{crust}) and hydraulic conductivity (K_{crust}) at saturation were also performed. The results show that WP soils have significantly ($p < 0.05$) higher contents of gypsum, lower contents of calcium carbonate and OM, and a coarser texture than DP soils. Compared to DP, the WP soils have higher values of SPR but lower ρ_b , K and S values in both the surface crust and the 0-10 cm depth soil layer. On average, K_{1-10} in DP was 1.4 times higher than that measured in WP. DP showed a better-defined microstructure and retained more water retention at near saturation conditions than WP. Soil treatments have a significant effect on ρ_b , SPR, S_{1-10} , K_{1-10} and on the WRC parameters. Overall, ρ_b and SPR was the lowest under MB, with maximal S_{1-10} and K_{1-10} values

under C. Compared to C and F, MB presented the highest volume of structural porosity and the lowest water retention at near saturation conditions.

Keywords: Gypsum soil; Bulk density (ρ_b); Soil penetration Resistance (SPR); Soil hydraulic conductivity (K); Sorptivity (S); Water retention curve (WRC).

Introduction

Crop growth and development is highly related to soil hydro-physical properties, which depend on soil management, and on the soil's intrinsic textural and chemical characteristics. Under a high annual water deficit, the cereal yield 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). Infiltration and evaporation, that are the most significant soil-controlled processes determining soil water storage, are mainly driven by the soil hydro-physical properties. Overall, fine textures in soils with similar soil agricultural treatments reduce the soil hydraulic conductivity. Tillage alters the structure of the topsoil layers, increasing the total soil porosity (Green et al., 2003; Moret and Arrúe, 2007) and the saturated hydraulic conductivity (Messing and Jarvis, 1993; 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) due in part to crusting in conjunction with an increase in the bulk density (Mellis et al., 1996).

The agricultural management of the arid lands of Central Ebro Valley, NE Spain, is driven by the scarcity and irregularity of rains and the high evapotranspiration. A limiting factor of plant growth in this region is the shallow occurrence of the bedrock, mainly horizontal strata of gyprock and limestone. The only feasible crops under dry-farming are winter cereals, which remain unprofitable in many years (McAneney and Arrúe, 1993). An outstanding feature of

the Central Ebro Valley agricultural landscape is the contrasting colored areas (from tens to hundreds of meters and irregularly shaped) commonly named *blanqueros* (white patches, WP) and *fosqueros* (dark patches, DP), in which cereals are observed to have different growing. The poor chemical fertility, low water-holding capacity and other constraints on agriculture associated with gypsic soils have been reviewed by Herrero and Boixadera (2002). High gypsum content causes poor aggregation and structure and has a significant effect on plant development and the soil's physical fertility (van Alphen and Ríos, 1971; Poch and Verplancke, 1997); it reduces the soil water infiltration (Poch et al., 1998) and the available water for plants; and it can make horizons impenetrable for roots. The quantification of hydrological properties is lacking for most gypsic soils, as is the case in our study area. Appreciable effects on cereals yields due to the high calcium carbonate content of soils have not been so far reported.

The Central Ebro Valley region lacks of soil maps. Under these circumstances, we adopted the short-cut "DP vs. WP" to generate information useful for agriculture and environment (Castañeda et al., 2010; Castañeda and Moret-Fernández, in press). After our field observations we hypothesize that DP occur in slightly depressed spots whereas WPs appears related to once prominent landforms (i.e., structural escarpments of horizontal strata). The distribution of dark (depressed) and white (prominent) areas is consistent with the geomorphic processes in the area, especially with the karstic weathering of the bedrock. An accurate DEM (Digital Elevation Model) would be needed for checking this hypothesis because the naturally undulated surface of Monegros is currently smoothed and homogenized by land systematization and earth movements.

The objective of this paper is to characterize the soil hydro-physical properties of the two contrasting colored adjacent agricultural soils in the semiarid zone of the central Ebro valley. This information will allow establishing if soil surface color is as a rapid diagnostic tool of soil

hydraulic properties, and to help farmers to manage their land in a way that saves on tillage and farm inputs.

2. Material and methods

2.1. Setting and sampling

The drylands of Monegros are an undulated agricultural plain located in the arid central Ebro Basin, NE Spain (41°26'N, 0°10'W), 65 km ESE of Zaragoza, 250 m above sea level (a.s.l.). The area is one of Europe's most arid zones (Herrero and Snyder, 1997). Rainfall is very irregular, with a minimum annual of 175 mm, a maximum of 535 mm, and an average of 355 mm for the last thirty years. The mean annual temperature is 14.4°C, and the absolute maximum and minimum registered in the area since 1985 are 45°C and -15°C, respectively.

Two contrasting colored areas, commonly named *blanqueros* (WP) and *fosqueros* (DP), were compared. Different agricultural plots that contain pairs of WP and DP sites were selected, with each WP-DP pair under the same soil condition (Fig. 1). The distance between WP and DP sites ranged between 30 m and 150 m. Three different soil agricultural treatments (ST) were studied: (i) recently tilled soil with moldboard plowing (MB); (ii) consolidated soil during crop development (C); and (iii) structured soil after six months of fallow (F). Twenty pairs of WP and DP soils were studied. A total of twenty five pairs of WP-DP sampling points corresponding to four different soil conditions were selected. Soil samplings were accomplished between March 2009 and September 2010.

2.2. Soil color and chemical properties

Wet color of the soil surface was determined at the lab using Munsell color charts. Relevant soil chemical properties were measured on the 0-10 cm depth. This soil depth was selected because of it is linked with the most critical phase of cereal establishment, germination and

early rooting. The gypsum was titrated by the loss of crystal water from the gypsum, in accordance with Artieda et al. (2006). The calcium carbonate was measured by gasometry and reported as calcium carbonate equivalent, CCE (Burt, 2004). The organic carbon was determined by an improved chromic-acid digestion and spectrophotometric procedure (Heanes, 1984), and the results transformed to organic matter by multiplying by the factor 1.724 (Burt, 2004). In all cases, one replication of soil chemical properties was performed per sampling site.

2.3. Soil physical properties

Soil particle-size distribution, soil bulk density (ρ_b), penetration resistance (SPR), saturated sorptivity (S_{1-10}) and hydraulic conductivity (K_{1-10}) and the water retention curves (WRC) of undisturbed soils were determined on the 1-10 cm depth soil layer of each sampling site. Unlike to ρ_b , S_{1-10} , K_{1-10} and SPR, which were measured in the twenty five pairs of WP-DP sampling sites, WRC measurements were only available in eighteen sampling sites (Table 2). A characterization of the saturated sorptivity (S_{crust}) and hydraulic conductivity (K_{crust}) of the soil surface crust (0-1 cm), only available in fallowed soil, was also performed.

The lab determination of particle size distribution in gypseous soils is problematic (Herrero, 1991) and an acceptable method has not been yet established. Notwithstanding laser diffraction has been found to be a promissory technique for gypseous soils (Arnett, 2009). The soil particle-size distribution was measured using the laser diffraction technique (COULTER LS230). One replication of soil particle-size distribution was performed per sampling site. Pre-treatment of soil samples included the organic matter removing with hydrogen peroxide, soil shaking with a water dispersant solution and ultrasonic treatment.

The soil dry bulk density (ρ_b) was determined using the core method (Grossman and Reinsch, 2002) with core dimensions of 50 mm diameter and 50 mm height. To determine the

dry weight of the soil, the samples were dried at 50 °C for 48 h. This temperature instead the routine 105 °C was used to avoid further faulty determinations due to the loss of crystallization water of gypsum, a process starting well under 80 °C (Artieda et al., 2006; Herrero et al., 2009). One replication was performed per sampling site. This sampling also made it possible to determine the volumetric water content at time of SPR measurements and initial water content needed to calculate the sorptivity and hydraulic conductivity.

The soil penetration resistance (SPR) was measured in situ with a Rimik CP40II Penetrometer, which automatically records the profile of penetration resistance. Five replications randomly selected and approximately separated 0.5 m one each other were performed per sampling site.

The soil hydraulic conductivity and sorptivity were characterized in the field using a tension disc infiltrometer (Perroux and White, 1988) with a base radius of 50 mm. Two different infiltration measurements, before and after removing the surface crust, were performed at each sampling site. The infiltration measurements on the soil crust were taken on areas cleared of large clods and crop residue. In order to ensure good hydraulic contact between the disc and the soil, a thin layer of commercial sand (80–160 μm grain size) was also poured onto the soil surface. The base of the disc was covered with a nylon cloth of 20- μm mesh. Only infiltration measurements at saturation were conducted. On average, the infiltration time was about 15 min. Flow readings were automatically recorded every 5 s from the drop in water level of the water supply reservoir, using a ± 0.5 psi pressure transducer that, connected to a datalogger (CR1000, Campbell Sci.), was installed at the bottom of the water supply reservoir (Casey and Derby, 2002). Two replications with and without surface crust separated around 20-30 cm one each other were performed per sampling site. The soil hydraulic conductivity and sorptivity at saturation were calculated from the transient cumulative infiltration using the Vandervaere et al. (2000) method. The final soil water content was sampled at the end of the infiltration

experiment from the upper centimeters of the soil, after removing the disc infiltrometer from the soil surface.

The subsurface water retention curve (WRC) for undisturbed soil samples was measured in the laboratory using a pressure head Time Domain Reflectometry (TDR)-Cell (Moret-Fernández et al., 2012), which uses the TDR technique to estimate the soil volumetric water content (θ). Water content was approached with the Topp and Reynolds (1998) equation, and the soil salinity effects on the water content estimations were corrected using the Evett et al. (2005) calibration. The undisturbed soil samples were taken from the soil surface after removing the surface crust using core dimensions of 50 mm diameter and 50 mm height (Grossman and Reinsch, 2002). Two soil core replications were taken per sampling site. A first measurement of θ was performed in air-dry soil conditions, corresponding to a soil suction head of about 166,000 kPa (Munkholm and Kay, 2002). Additional measurements of θ were made at soil water saturation and at suction heads of 1.7, 3, 5, 10, 50, 100, 500, and 1500 kPa. Assuming residual volumetric water content equal to zero, the WRCs and the corresponding effective saturation curves, $S_e(\psi)$ were fitted, using the SWRC Fit V.1.2 software (Seki, 2007) (<http://seki.webmasters.gr.jp/swrc/>), to the bimodal function (Durner, 1994):

$$\theta = (\theta_{sat}) \left[w \left[\frac{1}{1 + (\alpha_1 \psi)^{n_1}} \right]^{m_1} + (1 - w) \left[\frac{1}{1 + (\alpha_2 \psi)^{n_2}} \right]^{m_2} \right] \quad (1)$$

$$0 < w < 1$$

$$\sum w_i = 1$$

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

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (2)$$

where n_i is the pore-size distribution parameter, $m_i = 1-(1/n_i)$, α_i is the scale factor, θ_{sat} is the saturated volumetric water content, and w is a weighting factor for the subcurves. The same soil cores used to calculate the WRC were finally dried at 50 °C for 48 h and employed to calculate an additional value of ρ_b .

2.4. Statistical analysis

To compare the calcium carbonate, gypsum and OM contents between WP and DP soil types an independent-sample T-test was used with the SPSS 19.0 program (SPSS, Inc., Chicago, USA). To compare the effects of the soil type and management system on the soil hydro-physical properties, two-way ANOVA and correlation analyses for a completely randomized design were carried out. The distributions of the K_{1-10} , α_1 , n_1 and α_2 values were normalized using the decimal logarithmic function and K_{Crust} using the root square function.

3. Results

Soils in the studied agricultural fields of Ebro Basin are Typic Haplogypsis, Typic Calcigypsis, and Typic Haplocalcids (Soil Survey Staff, 2010). The electrical conductivity of the saturation extract (ECe) at the upper horizons ranges between 1 dS m⁻¹ and 18 dS m⁻¹, with an irregular distribution in the landscape. These soils do not show visual symptoms of sodicity in agreement with the facts that (i) the soil solution is saturated in calcium, and then the sodium adsorption ratio is well under the threshold for sodic soils, and (ii) clay is a minor component in many of the studied soils. The agricultural soils in the high topographic positions are predominantly white and shallower (white patches, WP) than those formed in relatively lower positions, which are largely dark and with higher organic matter contents (dark patches, DP) (Castañeda et al., 2010). Table 1 displays the description and analytical

data for two representative pedons of WP and DP. Dry farming, helped by subsidies, is practiced even though the low returns imposed by the hydric deficit and the shallow soils result in no yield in some years.

The Munsell wet colour values of the white and dark patches were on average 6 and 4, respectively (Table 2). The WP soils presented, in comparison to DP, significantly higher gypsum content ($p < 0.05$) (62.5% and 8.5% for WP and DP, respectively), but significant lower levels of calcium carbonate ($p < 0.05$) (20.0% and 39.2% for WP and DP, respectively) and organic matter ($p < 0.05$) (1.4% and 1.9% for WP and DP, respectively) (Table 2). The sum of gypsum plus calcium carbonate content measured on WP was significantly higher ($p < 0.001$) than the corresponding values measured in DP (Fig. 2). Overall, the WP soils presented coarser texture, with a higher percentage of sand (32.6% and 15.0% for WP and DP, respectively) and lower clay content (13.9% and 25.1 % for WP and DP, respectively) (Table 3).

The soil bulk density (ρ_b) ranged from 0.83 g cm⁻³ for the freshly tilled soils to 1.38 g cm⁻³ for soils after six months of fallow. Although no significant effect of soil type on ρ_b and the corresponding interaction was observed, the average ρ_b measured in WP was slightly lower than that measured in DP (Table 4). The ρ_b under MB was significantly lower than the corresponding values measured in C and F treatments (Table 4). The volumetric water content values at time of soil penetration resistance (SPR) measurements are summarized in Table 2. Due to SPR is directly affected by soil water content, pair of values of SPR with $\theta > 0.20$ m³ m⁻³ has been omitted from the analysis. Although the average SPR within the 0-10-cm soil layer in WP was higher than that measured in DP, no significant differences in SPR between soil types were observed (Table 4). On the other hand, significant differences in SPR were observed among the soil with different treatment. In this case, the lowest and highest SPR values corresponded to the MB and F systems, respectively. No significant soil type vs ST

interaction was observed. A consistent and significant power correlation was found between the SPR measured in WP and DP soils (Fig. 3).

Statistical analyses of the saturated sorptivity (S_{crust}) and hydraulic conductivity (K_{crust}) of the soil surface crust did not show significant differences between WP and DP (Table 4). Despite this non-significant difference, the K_{crust} in DP was on average 36% higher than that measured in WP. The S_{crust} and K_{crust} standard deviation measured in WP (0.22 and 0.011 for S_{crust} and K_{crust} , respectively) was lower than that measured in DP (0.26 and 0.021 for S_{crust} and K_{crust} , respectively).

The values of saturated soil sorptivity (S_{1-10}) and hydraulic conductivity (K_{1-10}) measured in the WP 0-10 cm depth soil layers were significantly lower than those measured in DP (Table 4). The S_{1-10} and K_{1-10} standard deviations measured in the WP ($0.22 \text{ mm s}^{-0.5}$ and 0.013 mm s^{-1} , respectively) were lower than the corresponding values measured in the DP soils ($0.44 \text{ mm s}^{-0.5}$ and 0.035 mm s^{-1} , respectively). A significant influence of ST on S_{1-10} and K_{1-10} was also observed. In this case, S_{1-10} and K_{1-10} measured on C was significantly higher than those measured in MB and F treatments. The interaction between the soil type and ST was only significant for the K_{1-10} soil parameter. The highest and lowest K_{1-10} values corresponded to the DP-C in the WP-MB system, respectively. The relative differences between K_{crust} and K_{1-10} , measured in F soils expressed as the quotient between the average K_{crust} and average K_{1-10} , were 28% and 50% for the WP and DP, respectively. The correlation analysis between the K_{1-10} in WP and DP showed that K_{1-10} under DP was, on average, 1.4 times higher than that measured in WP (Fig. 4).

Assuming residual volumetric water content equal to zero, a bimodal form of water retention curve was observed in all treatments (Fig. 5a). Average values of the WRC coefficients and the corresponding analysis of variance are summarized in Table 5. The w , α_1

and n_1 coefficients corresponding to the first “step” of the bimodal WRC were significantly affected by the soil type and/or management system (Fig. 5b). Compared to DP, WP showed significant higher values of w and α_1 , but lower n_1 values. Overall, θ_{sat} , α_1 and w calculated for the different ST followed the gradient $MB > C \approx F$ (Table 5). No significant soil type vs ST interaction was found. The non-significant effect of soil type and ST on α_2 and n_2 should be attributed to the limited θ values between 500 and 166,000 kPa, which prevented the SWRC-fit software to find accurate values of α_2 and n_2 .

4. Discussion

The significant different color observed between WP and DP (Table 2), which should be related to the higher gypsum plus calcium carbonate content in WP (Fig. 2), may result in an easy method to soil discrimination in ground, airborne, and satellite images (Fig. 1). The differences in gypsum, calcium carbonate and OM contents and particle size distribution between WP and DP soils (Table 2 and 3) should be attributed to the landscape genesis, with karstic depressions associated to gyprock dissolution, accumulation of organic matter in the lower topographical areas, and detachment of soil material from the upper areas. This natural evolution of the landscape is masked by agriculture, especially by the yearly tillage required to earn agricultural subsidies, which enhanced the elimination of natural vegetation and then erosion and landscape homogenization..

The slightly lower average ρ_b measured in WP (Table 4) soils may be attributed to the low particle density of gypsum (2.30 g cm^{-3}) when compared to the average particle density of 2.62 g cm^{-3} typically assigned to silicate soils (Hillel, 1998). Although no significant differences in soil penetration resistance (SPR) were observed between soil type, the higher average SPR value measured in WP (Fig. 3) agrees with Poch and Verplancke (1997), who reported that

gypsum content was positively correlated with penetration resistance. According to these authors, the increase in penetration resistance caused by gypsum is due to the growth of gypsum crystals in pre-existing pores, which reduces the volume of regular and continuous voids necessary for root growth. As cited by many authors (Sauer et al., 1990; Logsdon et al., 1999; Green et al., 2003; Moret and Arrúe, 2007; Jabro et al., 2011), disruption and destabilization of soil structure by tillage increases the soil porosity, which promotes a significant reduction of ρ_b and SPR in the upper soil layers. Compared to MB, the higher ρ_b and SPR values in C and F should be 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).

Taking into account that all pairs of WP-DP measurements were sampled in a same field with identical soil managements and soil rejoining processes, the significantly lower K_{1-10} (Fig. 4) and S_{1-10} values in WP (Table 4), which presented a coarser texture and lower ρ_b (Table 2 and 4), should be attributed to the effects of the easy dissolution/precipitation of gypsum on the water conductive soil porosity. During the soil wetting, the gypsum that coats the macropore walls dissolves, and it subsequently grows in new gypsum crystals that obstruct pre-existing conductive pores (Poch and Verplancke, 1997). According to Poch et al. (1998), the lower saturated hydraulic conductivity in gypsiferous soils, i.e., most of our WP, is not due to the presence of gypsum ‘per se’, but to the size and distribution of the gypsum crystals. Similar results were observed by Moret-Fernández et al. (2011) when comparing ungrazed gypseous and non-gypseous soils in a semiarid region of Central Ebro Valley. The highest K_{1-10} and S_{1-10} in C would indicate that the soil infiltration rate, whose values change during the soil rejoining, has a maximum value between the post-tillage and the end of fallow. The fragile pore structure after tillage or the more compacted soil at the end of fallow (Table 4) may promote that infiltration rates reached maximal values during the crop development. The

significant soil type vs ST interaction in K_{1-10} (Table 4) indicates that K_{1-10} had a different behaviour depending on the soil type and the ST. This interaction was especially evident in the MB treatment, where the lowest K_{1-10} value observed in WP did not correspond with that measured in DP. As reported by Poch and Verplancke (1997), the different behaviour in gypseous soils should be attributed to the intrinsic characteristics of gypsum. As above mentioned, during soil wetting gypsum crystals 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 in the first millimetres with a very abrupt contact with the underlying dry soil.. This sticky paste of the gypseous soils that restricts the infiltration is well known by farmers, who designated it with local a name like “chabisque”. On the other hand, the increase of the soil porosity in DP after tillage, with a more consistent structural porosity than WP, made that K_{1-10} in DP-MB was higher than that measured in WP-MD and in DP-F systems, respectively (Table 4). The lower standard deviation observed in the WP K_{1-10} and S_{1-10} would be indicative of the hydraulic properties in these soils were less dependent on the soil treatment than in DP. These results would indicate that the water infiltration in gypsiferous soils is mainly regulated by the gypsum’s ability to obstruct the existing pores rather than by the initial soil structure.

Despite the non-significant differences in S_{crust} and K_{crust} between WP and DP, soil surface infiltration rates in DP were in general higher than that observed in WP. Similar results were observed by Pueyo et al. (2012) in similar gypseous and non-gypseous ungrazed soils in the Central Ebro Valley. As above mentioned, these differences should be attributed to the intrinsic characteristics of gypsum crystals, which tend to close the pre-existent pores (Poch and Verplancke, 1997). The lower relative differences between K_{crust} and K_{1-10} observed in WP suggest that, in contrast to DP, the water conductive porosity of the WP surface crust is quite

similar to that observed in the 0-10 cm depth soil horizons. This can be attributed, as described above, to the gypsum characteristics.

The bimodality (Fig. 5a and b) of all WRC indicates that the soils display a patent double porosity system (Durner, 1994). As suggested by Guérif et al. (2001) the soil porosity can be considered as (i) textural porosity: little affected by soil management and occurs between the primary mineral particles, and (ii) structural porosity: sensitive to soil management factors and comprised by microcracks, cracks, bio-pores, and macrostructures produced by tillage (Dexter, 2004). Assuming that the first “step” of the WRC bimodal function (Fig. 5a) is associated to the soil structural porosity, the higher weighing factor (w) under WP (Table 5) would indicate that this soil has, in comparison to DP, higher volume of structural porosity. Compared to DP, the higher α_I factor under WP indicates that this soil tends to retain less water at near saturation conditions. These results agree with Herrero and Boixadera (2002), who reported that gypsic soils, which tend to drain faster, present a lower water-holding capacity. Although non statistical differences in n_I were found between WP and DP ($p = 0.096$), the higher n_I under DP is indicative of the extent to which the soil porosity is concentrated into a narrow range of pore sizes, which may be associated to a better-defined microstructure (Dexter 2004). Similar results were obtained by Moret-Fernández et al. (2011) when comparing the WRC in ungrazing gypseous and non-gypseous soil in the Central Ebro Valley.

The higher values of θ_{sat} , α_I and w under MB (Table 5) indicates that freshly tilled soils has a higher total porosity and a larger volume of macropores. These results agree with Ahuja et al. (1998), who reported that tillage changes primarily the “effective pore space” within the 0 and 33 kPa water retention range. Soil breakdown by tillage forms large interaggregate pore space (Or et al., 2000; Green et al., 2003), which results in increasing θ_{sat} , α_I and w values. 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 θ_{sat} , α_l and w , which values gets lower by the time elapsed since the tillage operations increases.

4. Conclusions

The prominent surface color patches of the studied agricultural drylands are evidence of differences in soil composition, with the mean gypsum plus calcium carbonate content of white patches (83 %) twice the average of dark patches. This contrasting composition on the soil hydro-physical properties had a significant effect on the SPR, the soil hydraulic properties, and WRC parameters measured in the 1-10 cm depth soil layer. In general, WP soils present a higher SPR but lower S and K in both the surface crust and the 1-10 cm depth soil layer. Although WP showed higher volume of structural porosity, soil under DP, with higher OM and clay content, presented a better-defined microstructure with more water retention at near saturation conditions. Although gypsum content has a notable effect on the soil properties, further researches should be needed to find the interaction between gypsum and clay and OM contents on the soil hydro-physical properties. A significant effect of the ST on ρ_b , SPR, S_{1-10} , K_{1-10} and the w and α_l parameters was observed. Overall, ρ_b and SPR was lowest under MB, with maximal S_{1-10} and K_{1-10} values under the C treatment. Compared to C and F, MB treatment presented the highest volume of structural porosity and the lowest water retention at near saturation conditions. In the arid climate, these differences may explain the contrasting development of rainfed crops within the same plot. Gypseous soils in the area ought to be mapped and taken into account in rainfed agriculture subsidies and in the planned new on-farm irrigation developments.

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Figure captions

Figure 1. Location of soil sampling sites and studied agricultural plots, with white and dark sites (white and black circles, respectively) mentioned in the text. The Quickbird image (RGB 432 false color composite), July 19 1997, stresses the distribution of white and dark patches at farm-scale.

Figure 2. Relationship between the percentage of gypsum plus calcium carbonate equivalent (CCE) content measured in the white (WP) and dark (DP) patches. Each point represents a pair of WP-DP values.

Figure 3. Relationship between the resistance of soil to penetration at 0-10-cm depth measured in the white (WP) and dark (DP) patches. Points are the average value of the five replications performed per sampling site. r and p denote the correlation coefficient and the probability level, respectively

Figure 4. Comparison between the soil hydraulic conductivity at saturation for the 0-10 cm depth soil layer measured in the white (K_{1-10} WP) and dark (K_{1-10} DP) patches under three different soil conditions. r and p denote the correlation coefficient and the probability level, respectively

Figure 5. (a) Averaged measured (circles) and average modelled (line) water retention curves, and (b) effective saturation curves (Eq. 2) modelled from the water retention parameters showed in Table 5 for the white (WP) and dark (DP) patches under three different soil conditions: tilled, cropped and fallowed soils.

Figure 1.

Figure 2.

Fig. 3

Figure 4.

Figure 5

Table 1. Morphological and chemical properties of two pedons representative of WP and DP.

CCE: calcium carbonate equivalent, EC1:5: electrical conductivity of 1:5 soil:water extract, SP: saturation percentage, ECe: electrical conductivity of the saturated paste extract.

Horizon	Depth cm	Munsell color (moist)	CCE	Gypsum	Organic matter	Structure	Roots
% Pedon BU5 (white patch)							
Ap	0 - 33	10YR 7/4	13.5	82.3	0.6	1 vf & f sbk	1 vf
R	33 - 59/63						
Cavity	59/63 - 67/78						
By	78/82 - 100	10YR 6/4	25.3	71.1	0.3	1 f sbk	1 vf
2Cy	100 - 120	10YR 5/4	nd	nd	nd	0	0
3Cy	120 - 140	10YR 5/4	26.7	51.6	nd	0	0
Pedon BU6 (dark patch)							
Ap	0 - 25	10YR 4/6	40.61	< 1.6	1.1	3 f sbk	1 vf & f
Bw	25 - 49	10YR 5/4	46.72	3.0	0.9	2 f sbk	3 vf
By1	49 - 78	10YR 6/4	18.16	75.5	0.3	1 f sbk	0
By2	78 - 128	10YR 6/4	29.49	38.5	0.4	0	0

Structure: 0, structureless; 1, very weak; 2, weak; 3, moderate; vf, very fine; f, fine; m, medium; co, coarse; sbk, subangular blocky.

Roots: 0, without roots; 1, few; 2, common; 3, many; vf, very fine; f, fine; m, medium; co, coarse; nd, Not determined.

Horizon	EC1:5 dS m ⁻¹	SP	ECe dS m ⁻¹	Cl ⁻	NO ³⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	SAR
meq L ⁻¹ (mmol _C L ⁻¹) ^{0.5}											
Pedon BU5 (white patch)											
Ap	2.6	37	5.6	1.01	0.66	5.41	0.97	0.14	3.31	3.63	0.7
R											
Cavity											
By	3.1	33	12.3	1.56	0.03	9.46	2.37	0.25	1.75	9.50	2.4
2Cy	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	
3Cy	2.6	nd	nd	nd	nd	nd	nd	nd	nd	nd	
Pedon BU6 (dark patch)											
Ap	1.4	39	3.1	0.09	0.37	3.27	0.14	0.05	3.77	0.75	0.1
Bw	2.3	51	4.2	0.25	0.01	5.12	0.45	0.01	3.42	2.56	0.3
By1	2.4	33	3.9	0.26	0.02	5.80	0.37	0.01	3.04	2.49	0.3
By2	2.5	30	4.6	0.27	0.03	6.06	0.55	0.03	2.85	3.92	0.5

nd, Not determined.

Table 2. Soil management, Munsell color, gypsum, calcium carbonate equivalent (CCE), organic matter (OM) and volumetric water content at time of penetration resistance measurement (θ_i) of the 0-10 cm depth horizon at the studied soils. *: Samples with water retention curve determinations.

Soil treatment ¹	White patches						Dark patches					
	Pedon #	Gypsum (%)	CCE (%)	OM (%)	Color ²	θ_i (m ³ m ⁻³)	Pedon #	Gypsum (%)	CCE (%)	OM (%)	Color ²	θ_i (m ³ m ⁻³)
F	BL 07	83.2	12.2	1.2	10YR6/3	0.04		1.9	50.3	1.6	10YR4/3	0.05
F*	BL 09	60.1	25.4	2.2	10YR7/3	0.03	BL 10	3.1	50.0	2.2	10YR4/4	0.02
F*	BL 14	71.8	11.6	1.7	10YR7/3	0.02	BL 53	7.2	29.0	1.8	2.5YR4/2	0.05
F*	BL 16	62.9	26.7	2.0	10YR6/2	0.02	BL 17	11.0	53.3	2.0	7.5YR4/2	0.03
F*	BL 18	90.1	8.3	0.9	10YR8/3	0.05	BL 19	40.3	22.8	2.0	10YR6/3	0.06
F	BL 21	70.1	26.4	1.4	10YR6/3	0.11	BL 22	2.1	26.4	1.8	10YR4/4	0.14
F / F*	BL 23	73.9	14.6	1.2	10YR6/2	0.21 / 0.14	BU 04	3.8	33.7	1.1	7.5YR4/4	0.19 / 0.14
F	BL 28	25.3	47.1	1.9	7.5YR5/1	0.14	BL 29	4.2	26.8	2.3	10YR4/2	0.2
C*	BL 31	57.5	19.9	1.7	10YR5/3	0.08	BL 30	19.1	33.4	2.6	10YR4/3	0.1
MB*	BL 39	82.6	8.8	0.7	10YR6/2	0.05	BL 38	4.0	47.1	1.7	10YR4/3	0.05
MB*	BL 41	78.0	14.1	1.2	10YR7/2	0.18	BL 40	9.0	22.9	2.5	10YR4/2	0.24
F*	BL 42	36.5	23.9	2.0	10YR4/2	0.24	BL 43	4.2	30.4	2.2	10YR4/2	0.18
MB*	BL 45	72.7	17.6	0.9	10YR7/2	0.12	BL 44	5.8	43.3	1.7	10YR4/2	0.17
C*	BL 46	49.8	24.6	2.5	10YR5/3	0.05	BL 47	2.5	54.3	2.5	10YR4/3	0.05
C*	BL 48	85.7	8.7	1.0	10YR6.5/2	0.05	BL 49	3.7	57.1	1.7	10YR4/2	0.05
MB*	BL 50	91.8	6.2	0.9	10YR6.5/2	0.05	BL 51	5.2	47.8	1.9	10YR5.5/3	0.05
F / C*	BU 01	68.4	17.4	1.0	10YR6/3	0.18/0.08	BU 02	18.2	28.7	1.9	10YR4/3	0.19/0.08
F	BU 05	82.3	9.0	0.9	10YR7/4	0.13	BU 06	1.6	57.1	1.4	10YR4/6	0.18
F / C* / C*	BU 07	2.5	40.8	1.1	10YR6/3	0.09/0.04/0.12	BU 08	15.7	18.8	2.0	2.5Y5/2	0.12/0.15/0.19
C* / F*	BU 11	3.9	36.7	1.9	10YR6/3	0.06/0.17	BU 10	6.6	51.4	1.3	10YR4/2	0.10/0.17
Average ³		62.5 a	20 b	1.4 b				8.5 b	39.2 a	1.9 a		

¹ F = structured soil during fallow; MB = recently tilled soil with moldboard plowing; C = consolidated soil during crop development

² Munsell color of wet soil samples

³ Within the same soil determination, means of WP and DP followed by the same letter are not significantly different by T-test Student at $P < 0.05$.

Table 3. Particle-size distribution and textural classification (USDA) of the studied soils.

White patches	Sand	Silt	Clay	Textural classification	Dark patches	Sand	Silt	Clay	Textural classification
	%					%			
BL 07	27.9	60.1	12.1	Silt loam	BL 08	27.6	49.7	22.7	Loam
BL 09	53.5	35.9	10.7	Sandy loam	BL 10	13.7	56.8	29.6	Silty clay loam
BL 14	29.5	62.7	7.9	Silt loam	BL 53	7.3	62.4	30.3	Silty clay loam
BL 16	47.3	40.1	12.7	Loam	BL 17	29.9	48.3	21.9	Loam
BL 18	41.7	52.2	6.1	Silt loam	BL 19	38.3	46.7	15.1	Loam
BL 21	28.3	62.3	9.4	Silt loam	BL 22	6.6	63.1	30.3	Silty clay loam
BL 23	28.2	37.1	34.7	Clay loam	BU 04	28.2	55.5	16.4	Silt loam
BL 28	21.0	61.7	17.4	Silt loam	BL 29	4.9	67.4	27.7	Silty clay loam
BL 31	25.1	61.0	14.0	Silt loam	BL 30	25.3	59.8	15.0	Silt loam
BL 39	55.3	39.0	5.7	Sandy loam	BL 38	5.3	64.2	30.5	Silty clay loam
BL 41	32.2	58.4	9.4	Silt loam	BL 40	2.5	62.7	34.9	Silty clay loam
BL 42	12.4	72.0	15.7	Silt loam	BL 43	6.1	68.8	25.1	Silt loam
BL 45	32.2	58.1	9.7	Silt loam	BL 44	3.5	60.8	35.7	Silty clay loam
BL 46	23.3	64.0	12.8	Silt loam	BL 47	24.7	54.8	20.6	Silt loam
BL 48	33.2	57.8	9.1	Silt loam	BL 49	22.9	54.7	22.5	Silt loam
BL 50	68.4	28.0	3.7	Sandy loam	BL 51	20.3	55.6	24.2	Silt loam
BU 01	35.7	53.7	10.7	Silt loam	BU 02	7.1	71.6	21.3	Silt loam
BU 05	51.5	44.1	6.0	Sandy loam	BU 06	7.9	65.5	26.6	Silt loam
BU 07	6.6	63.3	30.1	Silty clay loam	BU 08	3.5	71.5	25.1	Silt loam
BU 11	5.2	64.1	30.7	Silty clay loam	BU 10	7.4	56.9	35.8	Silty clay loam
Average	32.9	53.8	13.4			14.6	9.8	25.6	
Standard deviation	16.3	12.1	8.7			11.2	7.3	6.3	

Table 4. Average soil bulk density (ρ_b), resistance to penetration (SPR), soil surface crust sorptivity (S_{Crust}) and hydraulic conductivity (K_{Crust}) at saturation and saturated soil soptivity (S_{1-10}) and hydraulic conductivity (K_{1-10}) for the 1-10 cm soil depth, measured on white patches (WP) and dark patches (DP) soil under different soil structural conditions: freshly tilled soils (MB) and cropped (C) and fallowed (F) soil.

		ρ_b (g cm ⁻³)	SPR (kPa)	S_{Crust} (mm s ^{-0.5})	S_{0-10} (mm s ^{-0.5})	K_{Crust} (mm s ⁻¹)	K_{0-10} (mm s ⁻¹)
<i>Main factors</i>							
Soil Type	WP	1.12	1290	0.448	0.521 b	0.018	0.023 b
	DP	1.14	984	0.557	0.829 a	0.028	0.053 a
Management system	MB	1.04 b	221 c	-	0.560 b	-	0.032 b
	C	1.15 a	980 b	-	0.796 a	-	0.049 a
	F	1.17 a	1444 a	0.502	0.652 b	0.023	0.034 b
<i>Interaction</i>							
WP	MB	1.04	196	-	0.331	-	0.013 e
	C	1.11	1042	-	0.597	-	0.027 cd
	F	1.17	1674	0.448	0.554	0.018	0.025 d
DP	MB	1.03	247	-	0.790	-	0.051 b
	C	1.18	918	-	0.981	-	0.070 a
	F	1.17	1214	0.557	0.761	0.028	0.045 bc
<i>Significance</i>							
Soil type		NS	NS	NS	***	NS	***
Management system		*	***	-	*	-	**
Soil type × management system		NS	NS	-	NS	-	*

Two-way ANOVA analysis. Within each column, means followed by the same letter are not significantly different at * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS not significantly different, by Duncan's multiple range test.

Table 5. Average values of the water retention curve coefficients Eq. (1) estimated for the 0-10 cm depth soil layer on white patches (WP) and dark patches (DP) soils under different soil conditions: freshly tilled (MB), cropped (C) and fallowed (F) soil.

		θ_{ras} $m^3 m^{-3}$	w	α_1 kPa^{-1}	n_1	α_2 kPa^{-1}	n_2
<i>Main factors</i>							
Soil Type	WP	0.493	0.471 a	1.100 a	1.779 b	4.56 10^{-04}	1.430
	DP	0.490	0.383 b	0.386 b	2.257 a	4.92 10^{-04}	1.408
Management system	MB	0.510	0.547 a	1.442 a	2.072	5.24 10^{-04}	1.406
	C	0.496	0.390 b	0.641 b	1.851	4.21 10^{-04}	1.431
	F	0.476	0.399 b	0.473 b	2.157	4.99 10^{-04}	1.415
<i>Interaction</i>							
WP	MB	0.511	0.608	2.397	1.638	4.43 10^{-04}	1.379
	C	0.492	0.443	0.771	1.785	4.72 10^{-04}	1.438
	F	0.482	0.416	0.752	1.863	4.49 10^{-04}	1.454
DP	MB	0.509	0.476	0.487	2.578	6.19 10^{-04}	1.437
	C	0.499	0.337	0.511	1.917	3.75 10^{-04}	1.424
	F	0.469	0.382	0.194	2.451	5.50 10^{-04}	1.375
<i>Significance</i>							
Soil type		NS	***	***	**	NS	NS
Management system		NS	***	***	NS	NS	NS
Soil type $\times$ management system		NS	NS	NS	NS	NS	NS

Two-way ANOVA analysis. Within each column, means followed by the same letter are not significantly different at * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS not significantly different, by Duncan's multiple range test.

Two contrasting white (WP) and dark patches (DP) of agricultural soils were compared

Three soil managements (tilled, MB; cultivated, C; fallowed, F) were contrasted.

Hydro-physical soil properties for the 1-10 cm and surface crust layers were studied

Soil water infiltration was the highest in DP under C soil conditions

WP and MB presented the lowest water retention at near saturation conditions