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Soil water repellency in rangelands of Extremadura (Spain) and its relationship with land management

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ABSTRACT

Soil water repellency reduces infiltration capacity, enhancing overland flow and even runoff production, and may produce patchiness in water infiltration at the hillslope scale. Knowledge about hydrophobicity in rangelands of Mediterranean type climate and its relation with vegetation cover and land management is sparse. The objectives of the present work are to determine the degree and spatial occurrence of soil water repellency and to define its relationship with site characteristics, such as soil, vegetation and land management in rangelands of SW Spain. Field work was conducted in September 2009 in 22 environmental units belonging to 10 farms, distributed throughout the region of Extremadura. The Molarity of an Ethanol Droplet (MED) method was used for measuring water repellency of the soil surface. A total of 725 points were sampled and the study was combined with a detailed vegetation survey, the determination of soil properties and of land use and management characteristics. More than 70% of the measurement points were hydrophilic, however differences between farm units were found. The highest values of hydrophobicity were observed on soil surfaces below the canopy of holm oaks, as compared to the low values found below shrub canopies (*Retama sphaerocarpa*) and in open areas. With respect to ground cover, water repellency was highest at sites covered by holm oak litter. At soil surfaces covered by cork oak litter, dry grass and mosses the degree of repellency was lower. Almost all sites with a bare soil surface were hydrophilic, independent of whether these were located below a tree canopy or in open areas. A significant positive relationship between livestock density and the degree of bare soil existed, and consequently, areas with high animal numbers were dominantly hydrophilic. No significant relationships were encountered between the degree of soil water repellency and soil properties.

1. Introduction

Soil water repellency (SWR) is a natural phenomenon that occurs in many ecosystems ranging from tropical to subarctic regions influenced by biotic and abiotic factors (DeBano, 2000b; Doerr et al., 2000) and has been reported by many authors to reduce infiltration capacity, enhancing overland flow and even runoff production at the catchment scale (Burch et al., 1989; Imeson et al., 1992; Cerdà et al., 1998; Shakesby et al., 2000, among others). Increased amounts of surface flow may enhance soil erosion. On the other hand, the spatial variation of hydrophobicity may produce patchiness in water infiltration at the hillslope scale, especially in semi arid areas and under natural conditions (Imeson et al., 1992). Vegetation changes (species and/or density) may modify the hydrophobic characteristics of the soils and hence provoke changes in water infiltration and overland flow generation (Sevink et al., 1989).

This phenomenon has been traditionally linked to wildfire affected environments (Cerdà and Doerr, 2008; Doerr et al., 1998; Jordán et al., 2010; Llovet et al., 2009; Shakesby and Doerr, 2006) due to waxy substances derived from plant material burning that penetrate into the soil as a gas and condense in cooler soil layers and coat soil aggregates (DeBano, 2000a). However, not only this type of substances is responsible for producing water repellent soils; others derived from several groups of fungi and the activity of microorganisms have also been associated with the occurrence of hydrophobicity (Doerr et al., 2000). Hydrophobicity therefore also affects soils under unburned vegetation. Doerr et al. (2000) cite examples from Australia, USA and Europe. In Mediterranean forest systems high values of SWR were found in areas dominated by eucalyptus (Coelho et al., 2005; Doerr et al., 1998), pines (Arcenegui et al., 2008; Doerr et al., 1998; Mataix-Solera et al., 2007; Zavala et al., 2009) and cork oaks (Zavala et al., 2009), among others.

Few studies exist on the effects of animal activity on soil hydrophobicity. Cammeraat et al. (2002) highlighted the importance of ants and Contreras et al. (2008) demonstrated the role played by latrines of rabbits in SE Spain. Works focused on the effects of livestock on SWR are very sparse as compared to those that analyze other land management practices such as tillage (Hallett et al., 2001) and no-till

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farming (Blanco-Canqui, 2011). Related with livestock grazing, Krümmelbein et al. (2009) compared SWR measured from 4 plots with different sheep grazing intensities in grasslands from Inner Mongolia (China) and reported a tendency of decreasing water repellency at the soil surface with increasing grazing intensity.

Rangelands in the south-western part of the Iberian Peninsula are the result of continuous clearing of the traditional Mediterranean oak forest, composed mainly of the evergreen Holm oak (*Quercus ilex subsp. rotundifolia*) and cork oak (*Q. suber*). They occupy several million hectares of land and are grazed by domestic animals, mainly sheep, cattle and pigs. Tree density varies from treeless pasturelands to savannah-like woodlands with up to 150 trees per hectare. The tree-covered areas are called *dehesas* in Spanish language and are characterized by multiple land use: livestock ranching, forestry (cork, wood) and cultivation. At present, livestock is the most important income, and cultivation of cereals has been abandoned in many areas, due to the low productivity of the soils and adverse climatic conditions for rainfed agriculture. A characteristic feature of many farms is extensive pig ranching, based mainly on the acorns of Holm oaks.

Dehesas has undergone a situation of economic crisis since the decade of 1970 that caused serious problems of degradation, mainly related to soil and to the regeneration of trees (Campos et al., 2010). The loss of soil protection from vegetation removal by shrub clearing, cultivation or overgrazing, has supposed an important factor of land degradation, particularly in the driest years (Schnabel, 1997). Soil water repellency can boost soil losses by water erosion (mostly sheet erosion) at the beginning of autumn with the arrival of the first rains of the hydrologic year.

A study carried out by Cerdà et al. (1998) found high values of water repellency in soils from these ecosystems, particularly beneath the canopies of Holm oak. This work, however, shows some limitations, because sampling was carried out in only one small area and under drought conditions.

The present work belongs to a broader study on land degradation in rangelands of SW Spain, where past researches indicate that soils and their quality greatly varies even on the same lithology. The objectives of this paper are: [1] to characterize the spatial occurrence of soil water repellency in rangelands of SW Spain, [2] to analyze the relationships of hydrophobicity with vegetation cover and soil properties, and [3] to evaluate whether land use and livestock management have an influence on SWR.

2. Material and methods

2.1. Study areas

Research was carried out in ten privately-owned farms distributed throughout the region of Extremadura (SW Spain) (Fig. 1), representing the most important types of rangelands in the region, i.e. including treeless pasturelands and dehesas. It was decided to work at the farm scale because some farm specific attributes, such as land use and management practices, lead to differences with respect to vegetation cover, livestock species composition and agricultural activities.

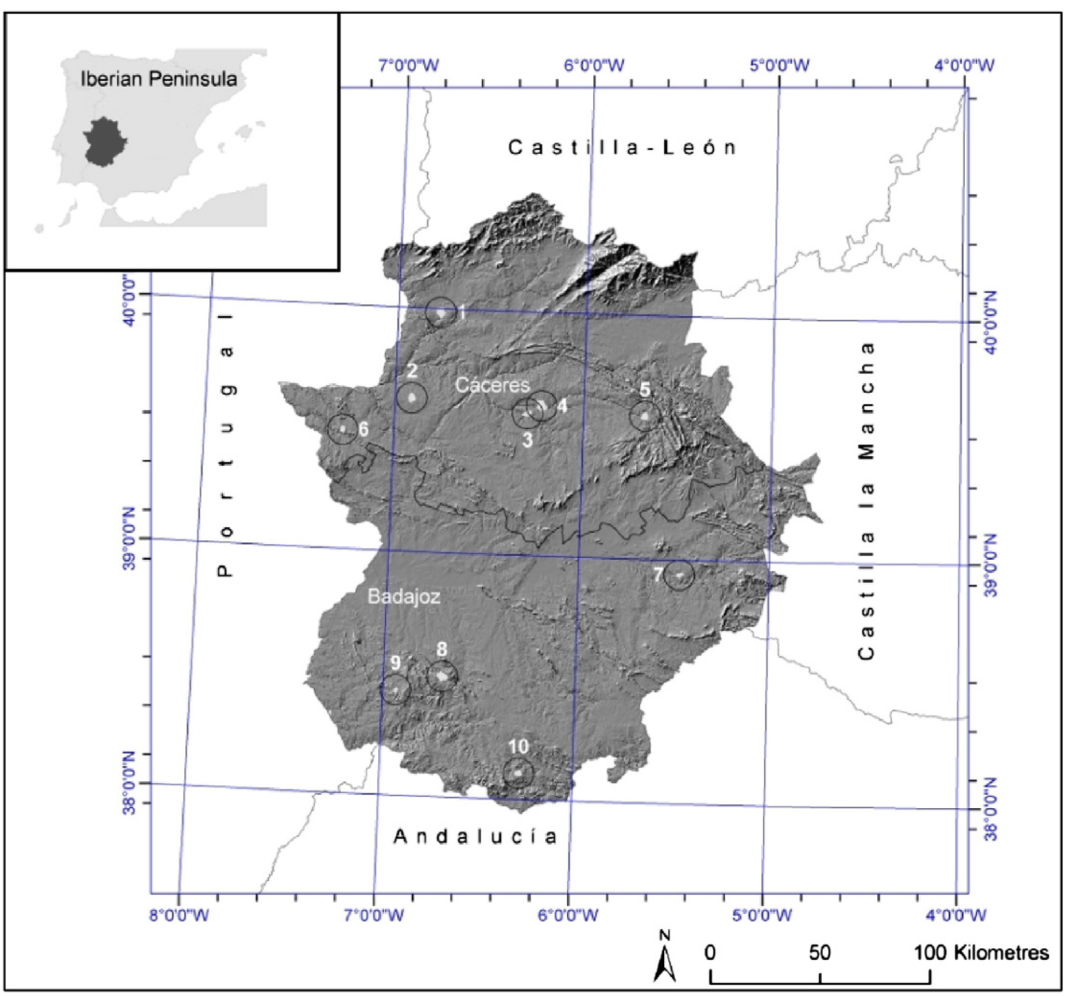

Fig. 1. Location of the study farms in the region of Extremadura (Spain).

Privately-owned farms occupy by far the largest extension of rangelands in SW Spain as compared to public lands. The ten farms comprise a subset of regional farms studied in previous research activities; established relationships with the owners and their willingness to collaborate represent a further selection criterion. The farms are located at variable altitude ranging from 300 to 695 m above sea level with sizes varying from 137 to 1024 ha. All the study areas are similar with respect to main lithology and relief, i.e. old erosion surfaces formed in Precambrian schist and greywacke, the dominant landform in the region (Gómez Amelia, 1985). The landscape is characterized by gently undulating surfaces, intersected by valleys with increasingly steep slopes as one approaches the main rivers.

Climate is Mediterranean with mean annual rainfall ranging from 505 to 732 mm, a wet season from October to May and a pronounced hot and dry period during summer, particularly in July and August. Interannual rainfall variability is high, and droughts are frequent with a duration of more than two years on average and an estimated return period of eight years (Schnabel, 1997). Mean annual air temperatures range from 15 to 17 °C, with average maximum values reaching 22.4 °C in July and mean minimum temperatures in January of 8.8 °C. The vegetation landscape is heterogeneous in space with areas covered by grasslands, scrublands and woodlands of varying shrub and tree densities.

Farms are large enough as to present meaningful variations in their physical characteristics as well as in vegetation cover and land management practices. To accommodate this environmental diversity, a total of 22 land units were selected as study areas, representing the most important combinations of livestock species, vegetation cover and slope gradients. A further criterion is management practices, especially animal density, for which it was necessary to select distinctive areas, delimited by fences. Usually two units were considered per farm, except for one where four units were selected. The selection of land units, as well as their characterization, was supported by interviews with farmers, field work and aerial photograph interpretation.

Personal interviews with the owners included information on animal species and numbers, grazing management (e.g. seasonal movement), pasture management (e.g. fertilization, seeding), forest activities (e.g. tree pruning), cultivation (e.g. types of crops, rotation system) and shrub clearing. Table 1 shows some of the main characteristics of the 22 units. Five units are treeless and a further two have very low tree density. The highest tree densities correspond to farms (F) 8, 9 and 10, located in the southern part of Extremadura with approximately 50 to 150 Holm oaks per hectare and their six corresponding units being grazed by pigs in combination with either sheep or cattle. Cork oak is only present in F1, being grazed by cattle and pigs. Two of the treeless farms are only grazed by sheep. One of these (F2) includes a unit which has never being cultivated and the other is being cropped with cereals in a four-year rotation system for animal consumption. In some units, beside trees and herbaceous plants, shrubs are also present, with *Retama sphaerocarpa* being by far the most dominant species.

Values of livestock density, expressed as cattle equivalent livestock unit per hectare (LU ha^{-1}), ranged from 0.19 to 15.79 (Table 1), corresponding the lowest value to the cultivated unit of F2. The second highest livestock density amounts to 3.0 LU ha^{-1}, being all the remaining values below 1.9 LU ha^{-1}.

The soils of the study areas are generally shallow and have a sandy to silty loam texture. Organic carbon content of the surface horizon varies considerably and soils are moderately to strongly acid. Cation exchange capacities are low. A more detailed description of soil properties is presented below in the Results chapter.

2.2. Vegetation cover assessment

The farm units represent the most common combinations of animal species, livestock density and vegetation type in rangelands of Extremadura. For each unit, above-ground vegetation cover and soil surface cover were determined in September 2009, the time of the year when vegetation development is lowest due to the preceding dry summer period. Three 30 m long transects were placed at random locations, representative of the unit characteristics and were used as spatial reference lines for determining soil cover, using the following classes: bare ground, grasses, mosses, litter, stones (>2 mm) and rock outcrops (Fig. 2). Above ground cover of trees and shrubs was measured separately by determining the vertical projection of the plant cover along the measuring tape including the classes: open areas, tree canopy and shrub canopy. All the data were recorded along the transects at a centimeter scale and expressed as percentage of class cover per total transect length. For example if a total of 8.5 m was determined for the class Grasses along one transect, the resulting cover is 8.5 m/30 m or 28.3%.

Table 1
Characteristics of the study areas. Rain: Average annual rainfall (Data from Ninyerola et al., 2005); LD: Livestock density; TD: Tree density; Shrub (X — presence of *Retama sphaerocarpa*).

Farm	Unit	Surface (ha)	Rain (mm)	Cropping	Livestock	LD (LU ha^{-1})	Tree species	Shrubs	TD (tree ha^{-1})
1	1	46.2	731.8	–	Cattle, pigs	0.54	Cork and Holm oaks		39.6
1	2	103.5	731.8	–	Cattle, pigs	0.54	Cork oaks		39.2
2	3	37.6	504.8	–	Sheep	0.64	–		0.0
2	4	136.5	504.8	4 year rotation	Sheep	0.19	–		0.0
3	5	33.2	591.8	–	Cattle, pigs, sheep	1.83	Holm oaks	X	12.8
3	6	2.8	591.8	–	Cattle, pigs, sheep	15.79	–		0.0
4	7	146.2	596.2	–	Sheep, pigs	1.08	Holm oaks	X	24.1
4	8	30.3	596.2	–	Sheep, pigs	1.21	Holm oaks	X	6.3
4	9	74.1	596.2	–	Sheep, pigs	1.06	Holm oaks	X	33.4
4	10	19.1	596.2	–	Sheep, pigs	3.00	Holm oaks	X	23.9
5	11	21.8	646.3	–	Sheep, goats	1.17	Holm oaks		24.4
5	12	52.0	646.3	–	Sheep, goats	1.17	Holm oaks		14.5
6	13	10.7	661.1	Cropped 1997	Sheep	0.59	Holm oaks	X	0.0
6	14	12.8	661.1	–	Cattle	0.78	Holm oaks	X	0.3
7	15	120.3	526.9	–	Sheep	0.25	–		0.0
7	16	120.3	526.9	–	Sheep	0.25	–		0.0
8	17	34.2	565.2	Every 9 years	Sheep, pigs	0.54	Holm oaks		84.1
8	18	24.1	565.2	–	Sheep, pigs	0.54	Holm oaks		66.4
9	19	24.5	689.3	–	Cattle, pigs	0.59	Holm oaks		62.0
9	20	6.2	689.3	–	Cattle, pigs	0.59	Holm oaks		77.3
10	21	7.1	681.3	–	Sheep, pigs	0.43	Holm oaks		54.2
10	22	19.7	681.3	After pruning	Sheep, pigs	0.43	Holm oaks		65.1

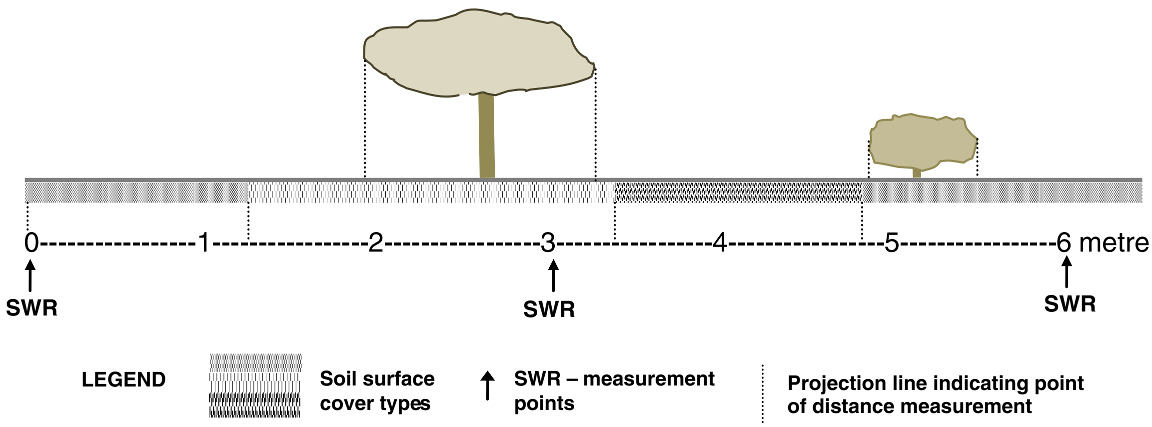

Fig. 2. Illustration of vegetation assessment and SWR measurement along a transect.

Furthermore, every 3 m and coinciding with the SWR measurement points, ground cover and above-ground cover were annotated. The latter determination was done in order to be able to assign the cover characteristics to each of the SWR measurements. The more detailed vegetation survey is necessary to get a better estimate of plant cover for the farm unit and the point data is necessary for relating the individual SWR values with site characteristics.

2.3. Hydrophobicity measurements

The hydrophobicity measurements were carried out along the vegetation transects in September 2009, preceded by a very dry hydrological year. One of the farms registered an annual rainfall amount of 296 mm in 2008–09, as compared with the average of 510 mm. However this drought was of short duration (one year) and therefore cannot be considered exceptional as compared to others observed in the region (Schnabel, 1997).

The MED method (Molarity of an Ethanol Droplet) (Letey, 1969) was used for measuring water repellency of the soil surface in the field. After surface litter was removed 3 drops of distilled water (0% ethanol) were placed on the soil surface during 5 s, if the soil absorbed at least 2 of them in this time period the annotated percentage of ethanol was 0%, and if the soil did not absorb the drops the Molarity of Ethanol was increased gradually (1, 3, 5, 8.5, 13, 18, 24, 36, and >36%) until the soil absorbed at least 2 of them in less than 5 s. The results in percentage of ethanol, ranging from 0 to >36%, were scaled in ordinal hydrophobicity classes ranging from 1 to 10 (Table 2). SWR tests were applied by this way along the vegetation transects at regular intervals of 3 m, resulting in a total of 725 sample points.

Hydrophobicity measurements were only carried out at the soil surface for various reasons: [1] most soils are very shallow; [2] SWR generally decreases strongly with depth, even in typically high hydrophobic soils as those of Eucalyptus forest (Keizer et al., 2005) and [3] organic matter is concentrated in a very shallow surface layer commonly thinner than 5 cm for the study areas (see description of soil properties below).

2.4. Soil analysis

A total of 45 soil profiles were described in the field (FAO, 2006) and 141 soil samples of the upper 5 cm were taken. Only the data of the uppermost layer are presented here because soil properties were related with the surface hydrophobicity. Soil samples were analyzed using standard laboratory methods (Table 3), including grain size distribution, pH, capacity of exchangeable cations and the content of calcium, magnesium, potassium, sodium, nitrogen, phosphorous, aluminum and soil organic carbon. Bulk density of the surface layer (0–5 cm) was determined taking 225 undisturbed soil samples extracted with cylindrical cores of 5x5cm size.

2.5. Data analysis

The influence of vegetation and ground cover on soil hydrophobicity was studied on the point scale, i.e. the data obtained along the transects at 3 m intervals. The total number of measurement points amounts to 725, each represented by a value of SWR, ground cover and canopy cover. Soil water repellency data was correlated, with ground cover on one hand and with canopy cover on the other hand, using Spearman rank order correlations and Kruskal–Wallis ANOVA. The analysis of the influence between SWR and soil properties and livestock density was carried out on the farm unit scale ($n=22$) using regression analysis. Ground cover and canopy cover data at the unit scale are based on the values obtained along the complete transects (30 m each). Statistical analysis were carried out using Statistica® 6.0 software package (Statsoft, 2001).

Table 2
Equivalence between % ethanol using the Letey (1969) method and hydrophobicity classes considered.

% Ethanol	Severity	Hydrophobicity class
0	Hydrophilic	1
1	Slightly hydrophobic	2
3	Slightly hydrophobic	3
5	Slightly hydrophobic	4
8.5	Strongly hydrophobic	5
13	Strongly hydrophobic	6
18	Severely hydrophobic	7
24	Severely hydrophobic	8
36	Extremely hydrophobic	9
> 36	Extremely hydrophobic	10

Table 3
Methods and measurement units used for determining soil properties.

Soil property	Unit	Method
Grain size distribution	%	Soil Survey Laboratory Methods Manual (2004)
Cations, cation exchange capacity	meq/100 g	MAPA (1986)
Available N	%	Dumas (1831)
Available P	ppm	Olsen et al. (1954)
Soil organic matter	%	Walkley and Black (1934)
Soil organic carbon	%	Van Bemmelen (1890)
pH	–	1:2.5, soil:water
Bulk density	g cm^{-3}	Soil cores (Coile, 1936)
Base saturation	%	$V=(Ca+Mg+K+Na/CEC)*100$
C/N ratio	–	SOC/available N

3. Results

3.1. Soil properties

Table 4 shows a summary of the basic descriptive statistics for the soil parameters of the surface samples (0–5 cm). The dominant texture classes are sandy-loam, silty-loam and loam, with a mean sand content of 53.9% and an average clay content of only 6.0%. Mean bulk density is 1.44 g·cm^{-3}. Most soils in the study area are moderately to highly acid, with pH values ranging from 5.04 to 6.01 for the 0.1–0.8 percentile. Mean soil organic carbon (SOC) content amounts to 2.43%, but varies considerably, given a standard deviation of 1.30. Considering the contents of exchangeable calcium, magnesium, potassium and sodium, the soils can be classified as poor in nutrients. Cation exchange capacities are low with an average of approximately 11 meq 100 g^{-1} and 90% of the samples showing values lower than 16.4 meq 100 g^{-1}. Phosphorous content is highly variable, with values ranging from 0.3 to 137.1 ppm and a coefficient of variation of 109%. This high variation is not observed in samples taken at greater in depth. Even at a depth of 5–10 cm P content is substantially lower (data not presented here). Therefore, the high P values registered in the upper 5 cm of the soil profile can probably be attributed to livestock excrements.

The dominant soil types are *dystri-epileptic Cambisols*, shallower than 50 cm and with an incipient subsurface soil formation, and *dystric Leptosols*, with almost all soils less than 50 cm thick and many shallower than 20 cm. A characteristic feature of these rangeland soils is the presence of a very shallow Ah-horizon, varying between zero and 7 cm (mean 3.4 cm), where most of the fine roots of herbaceous vegetation are found and SOC is clearly higher as compared to the underlying horizon.

Surface soil characteristics of areas below tree canopies are significantly different from those in open areas covered by grasses and forbs. Soil organic carbon, nitrogen, phosphorous content and cation exchange capacity are higher below the tree canopy. Bulk density was shown to be lower beneath the canopies.

3.2. Vegetation cover

Mean values of above-ground vegetation and soil surface cover of the 725 points where SWR was measured are presented in Table 5. On average 19.7% of the points were located below a tree canopy, 77.4% in open areas and only 2.9% were situated below shrub canopies, the latter mainly belonging to the species *R. sphaerocarpa*. With respect to soil surface cover, the largest percentage corresponds to bare soil (47.3%), followed by mosses and Holm oak litter, with 18.2% and 13.5%, respectively (Table 5). Dead grass amounts to 13.2% and litter, of either Cork oak or *Retama* shrub, is not frequent.

Table 6 presents the results of soil surface cover on the basis of transect measurements and shows that large differences exist between the farm units. A total of eleven units presented a cover of dry grasses and forbs of less than 5%. Although September is the time of the year with lowest grass cover, these values can be considered as very low and are attributed to the low rainfall amounts of the preceding hydrological year and/or excessive plant consumption by domestic animals (Schnabel, 1997). Noticeable is also the high cover of mosses in some units, with more than 80% in two cases that belong to the treeless farm 7. Holm oak and cork oak litter in tree-covered areas ranged from 9.4 to 60.4%. The percentage of litter cover is positively related with tree density, but also negatively with the percentage of grasses, forbs or mosses because their presence masks the litter. This is clearly seen in farms 8 to 10 with higher tree densities as compared to farm 1. The latter presented the highest value of litter cover, but very low grass cover (Table 6). Litter of the shrub *Retama*, registered values in the order of 30% only in two units of farm 4 and 6–9% in three further units.

The values of bare surface (Table 6) represent the total of bare soil, rock fragments, rocky outcrops and lichen crusts measurements. This generalization is justified, on one hand, by the negligible occurrence of lichen crusts, stones and rock outcrops as compared to bare soil and, on the other hand, because all of them are surface covers void of plants or litter. The percentages of bare surface ranged approximately between 5 and 95%. Five units were bare in more than 50% of their surface.

Table 4
Descriptive statistics of soil parameters for 141 soil surface samples. SD: Standard deviation; CV: Pearson's coefficient of variation (%); P: Percentile; CEC: Capacity of Exchangeable Cation.

Variable	Mean	Min	Max	0.1 P	0.9 P	SD	CV
Clay (%)	5.96	1.40	19.43	3.07	9.13	3.03	50.9
Silt (%)	40.18	18.39	58.70	28.92	50.46	8.31	20.7
Sand (%)	53.87	33.20	79.88	41.46	67.12	9.58	17.8
BD (g cm^{-3})	1.44	1.08	1.71	1.25	1.56	0.13	8.9
pH	5.55	4.63	7.07	5.04	6.01	0.43	7.7
CEC (meq 100 g^{-1})	11.04	3.56	26.89	6.92	16.44	4.04	36.6
Ca (meq 100 g^{-1})	5.56	1.40	18.03	2.23	9.69	3.30	59.4
Mg (meq 100 g^{-1})	1.17	0.05	6.36	0.21	2.46	1.08	92.0
K (meq 100 g^{-1})	0.58	0.05	3.02	0.18	1.17	0.44	76.0
Na (meq 100 g^{-1})	0.29	0.09	2.08	0.10	0.54	0.35	117.6
Base saturation (%)	67.42	18.67	153.56	39.81	93.04	22.75	33.7
N (%)	0.26	0.01	0.77	0.09	0.46	0.16	62.1
P (ppm)	23.88	0.28	137.11	0.40	58.57	26.08	109.2
SOC (%)	2.43	0.34	6.26	1.08	4.43	1.30	53.7
C/N	10.74	3.49	32.87	6.92	15.73	4.30	40.0

Table 5
Average above-ground vegetation and average soil surface cover at the SWR sample points expressed as a percentage of the total sample points.

Vegetation cover	% sample points	Soil surface cover	% sample points
Open areas	77.4	Bare surface	47.3
Tree canopy	19.7	Moss	18.2
Shrub canopy	2.9	Holm oak litter	13.5
		Dead grass	13.2
		Cork oak litter	4.1
		Retama sphaerocarpa litter	3.6

Table 6
Mean soil surface cover measured along transects and mean SWR values (class: 1–10) for each farm unit (Grass: Dry grasses and forbs; L: litter).

Farm	Unit	Grass (%)	Moss (%)	Retama-L (%)	Cork oak-L (%)	Holm oak-L (%)	Bare soil (%)	SWR
1	1	0.2	20.3	0.0	47.3	7.0	25.2	1.4
1	2	0.2	3.7	0.0	60.4	0.0	35.6	1.8
2	3	4.6	59.6	0.0	0.0	0.0	37.8	1.3
2	4	71.3	0.4	0.0	0.0	0.0	28.3	1.4
3	5	8.2	1.1	6.1	0.0	0.0	84.6	1.0
3	6	4.3	0.6	0.0	0.0	0.0	95.3	1.0
4	7	0.0	23.8	29.9	0.0	0.0	46.4	1.1
4	8	0.0	21.9	27.7	0.0	0.0	50.4	1.1
4	9	0.0	45.1	0.0	0.0	38.9	16.1	1.8
4	10	0.1	36.7	7.6	0.0	10.8	44.8	1.3
5	11	26.7	0.4	0.6	0.0	13.1	59.5	1.4
5	12	19.3	0.4	0.0	0.0	9.4	73.7	1.0
6	13	48.1	12.8	0.0	0.0	0.0	39.8	1.2
6	14	50.3	29.6	8.8	0.0	0.0	15.4	2.4
7	15	4.1	87.0	0.0	0.0	0.0	9.3	1.5
7	16	2.8	84.0	0.0	0.0	0.0	14.0	1.2
8	17	44.0	9.9	0.0	0.0	40.6	5.5	3.3
8	18	41.4	0.9	0.0	0.0	45.0	12.7	4.4
9	19	54.2	3.8	0.0	0.0	22.1	20.0	2.9
9	20	34.3	2.7	0.0	0.0	36.4	26.5	3.1
10	21	0.1	52.4	0.0	0.0	32.7	14.9	3.7
10	22	42.3	4.7	0.0	0.0	33.7	20.6	1.8

Table 7
Frequency table of soil water repellency classes.

SWR-class	Count	Cumulative-Count	Percent	Cumulative-Percent
1	510	510	70.3	70.3
2	53	563	7.3	77.7
3	59	622	8.1	85.8
4	29	651	4.0	89.8
5	32	683	4.4	94.2
6	22	705	3.0	97.2
7	12	717	1.7	98.9
8	6	723	0.8	99.7
9	2	725	0.3	100.0

Table 8
Multiple comparisons z-values (2-tailed) of SWR for different vegetation canopies (*** significant at p-level 0.001).

	Tree canopy	Shrub canopy
Shrub canopy	4.154***	
Open area	9.611***	0.318

3.3. Soil water repellency

The frequency distribution of the SWR classes of the total of 725 measurements is shown in Table 7. More than 70% of the measurement points were hydrophilic (class 1, absorbing three drops of distilled water in less than 5 s). A further 19.5% corresponds to areas which were slightly hydrophobic, i.e. classes 2 to 4. The maximum hydrophobicity class observed was 9, but it was only registered twice. Points with strong and extreme hydrophobicity (classes$\geq$5) represent only 5.8% of the total (Table 7).

In order to analyze the spatial variations of hydrophobicity, the data were firstly grouped according to the type of above ground vegetation cover. The result of the Kruskall–Wallis ANOVA test performed showed that mean SWR of areas located below a tree canopy was significantly higher than in open areas or below shrub canopy, and that no significant difference exist between open areas and those covered by shrubs (Table 8). Fig. 3 clearly illustrates this, showing that below tree canopies only 30% of the points were hydrophilic, as compared to points in open areas and under shrub canopies, where approximately 80% and 85%, respectively, were hydrophilic. High hydrophobicity values (SWR-class$>$5) were nearly absent in open areas and below Retama shrubs.

With respect to the relation between SWR and ground surface cover, Table 9 shows some basic statistical parameters for soil water repellency values grouped by type of ground surface cover. Except for Holm oak litter sites, the most frequent SWR class of all the other surface types is 1 (hydrophilic). Fig. 4 presents the distribution of SWR classes for each cover type. Almost all the areas of bare soil were hydrophilic (96.2%). More than 50% of the samples in areas covered by dead grass, moss, *Retama* litter and cork oak litter were hydrophilic as well. The highest hydrophobicity values were observed on soil surfaces covered by holm oak litter, where approximately 37% of the sampling points where strongly hydrophobic (classes 5 and 6) and 17.3% were severely and extremely hydrophobic (classes$\geq$7). Water repellency was also found at soil surfaces covered by cork oak litter, dry grass and mosses; however the degree of water repellency was lower in these cases showing hydrophilic characteristics in more than 50% of the sites.

Table 9
Basic statistic parameters of SWR (class 1–10) for each soil surface cover type (Min — minimum, Max — maximum).

Soil surface cover	N	Mean	Median	Mode	Frequency of mode	Min	Max
Bare soil	343	1.05	1	1	330	1	5
Dry grasses and forbs	96	2.20	1	1	49	1	6
Moss	132	1.86	1	1	76	1	7
Retama litter	26	1.50	1	1	22	1	6
Cork oak litter	30	2.13	1	1	17	1	7
Holm oak litter	98	4.39	5	5	19	1	9

When looking for SWR variations among cover types, the Kruskall–Wallis ANOVA test showed some significant differences (Table 10). Highly significant was the difference between Holm oak litter and all the other surface cover types. Also Bare surfaces were significantly different to Dead grass, Moss and Cork oak litter. No significant differences could be found between Retama litter and the other surface classes, except for Holm oak litter. Nevertheless, the sample size of Retama litter and Cork oak litter, with 26 and 30 respectively, is fairly low as to consider the results as conclusive.

In order to analyze the possible relation between SWR and soil properties or livestock management, the data at the farm unit scale were used (n = 22). Table 1 presents the livestock densities, applied as an indicator for grazing intensity, and Table 6 shows the mean SWR data by unit. Spearman rank order correlations were used for analysis and the results are presented in Table 11. No relationship could be detected between SWR and any of the physical or chemical soil properties considered, except for the content of exchangeable calcium (Table 11). Although this relationship is statistically significant, no causal relation is supposed to exist because Ca^{++} content is positively related with tree density and negatively with the degree of bare soil. As shown above, areas with higher tree density display a higher degree of hydrophobicity and bare surfaces tend to be hydrophilic. The correlation analysis carried out at the unit scale (Table 11) also depicts the relationships between soil surface cover types and SWR.

Particularly remarkable is the lack of relation with soil organic carbon content. Considering that soil organic matter was not found to be

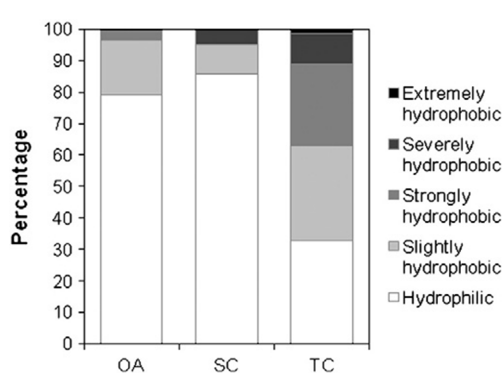

Fig. 3. Percentage of hydrophobicity severity classes assigned to points sampled under different canopies. OA — Open areas, SC — Shrub canopy and TC — Tree canopy.

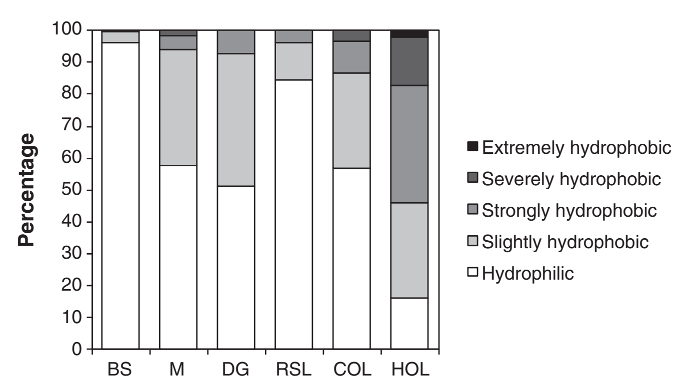

Fig. 4. Percentage of hydrophobicity severity classes under different soil surface cover types. BS: Bare soil; M: Mosses; DG: Dry grasses and forbs; RSL: *Retama sphaerocarpa litter*; COL: Cork oak litter; HOL: Holm oak litter.

Table 10
Multiple comparison z-values (2-tailed) of SWR for different soil surface cover groups (p-level: *0.05 **0.01 and ***0.001).

	Bare surface	Dead grass	Moss	Retama litter	Cork oak litter
Dead grass	6.676***				
Moss	5.992***	1.171			
Retama litter	1.123	2.454	1.796		
Cork oak litter	3.551**	0.454	0.308	1.670	
Holm oak litter	13.498***	5.398***	6.991***	5.973***	4.170***

related with the percentage of tree litter cover and that hydrophobicity is strongest in areas covered by Holm oak litter; the lack of a simple relationship is not surprising. In contrast to what would be expected, livestock density is positively correlated with SOC which could be due to the contribution of excrements. Furthermore, a significant negative statistical relationship was found between livestock density and SWR (Table 11). While a variety of indirect processes could be explored from this relation, we think, however, that it is related to the effect of livestock density on the degree of bare soil. This conclusion could be supported by Fig. 5, which presents the result of a regression analysis of the percentage of bare surface and SWR, showing a negative potential relationship between the two variables. The regression model suggests that the farm units with more than 50% of bare surfaces at the end of summer present a mean SWR of equal or less than 1.5, i.e. most of the soil surfaces are hydrophilic. Considering the positive relation between the degree of bare soil and livestock density it could therefore be argued that the statistical relationship of the latter variable with SWR is the result of its negative effect on plant cover.

Furthermore, the data also indicate the overriding effect of Holm oak litter in increasing hydrophobicity. Fig. 6 presents the result of a regression analysis at the unit scale, which shows a positive linear correlation between SWR and Holm oak litter cover ($R = 0.79$).

The most intensively grazed farm units (10, 11 and 12) showed low SWR values, even beneath tree canopies (Tables 1 and 6), which is possibly the effect of high livestock densities in preventing tree litter accumulation.

4. Discussion

According to some authors SWR markedly increases when the soil has been subjected to high temperatures and/or prolonged dry periods (Contreras López and Solé-Benet, 2003; Doerr et al., 2000; Imeson et al., 1992). In our case, after a preceding hydrological year

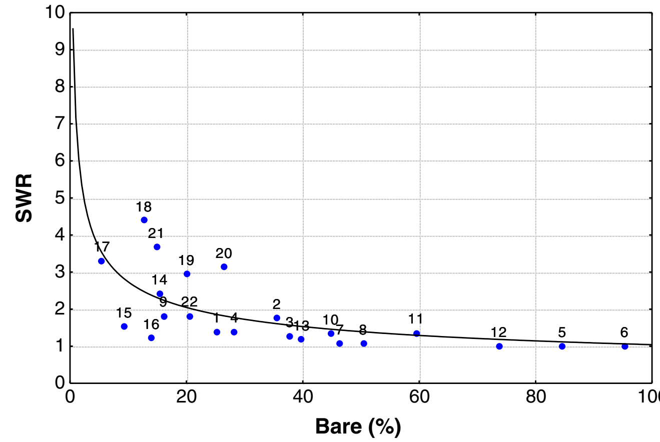

Fig. 5. Relationship between percentage of bare soil surface and SWR of mean values for each farm unit ($n = 22$). The regression is significant at the 99% confidence level, variance accounted for is 0.406, model: $SWR = 7.1811 \cdot Bare^{(-0.419)}$. The numbers refer to the farm units (see Table 1).

with very low rainfall amounts more than 70% of the measurements were hydrophilic. Cerdà et al. (1998) carried out work in a Holm oak dehesa in Extremadura with similar environmental and management conditions to several of our study farms. The authors found strong soil water repellency below Holm oak canopies (in more than 80% of the sites beneath trees). In general terms SWR reported by Cerdà et al. (1998) was higher than that in our study areas, which is probably the result of a more severe drought experienced in the area. However, their field measurements are not completely comparable with ours, because they used only distilled water in the test and they only investigated in a small watershed. The findings, however, agree in that water repellency in Holm oak dehesas is mainly produced by the tree litter.

Work carried out by Jordán et al. (2010) and Zavala et al. (2009) in open cork oak woodlands of southern Spain reported higher values than the ones described in the present paper. However, our study was limited to only one farm with cork oak trees and therefore future tests should be carried out in order to establish whether there exist differences between the two oak species (*Q. ilex*, *Q. suber*).

The influence of *R. sphaerocarpa* on SWR was studied by Contreras et al. (2008) in South-east Spain, reporting higher values of hydrophobicity than the ones presented here. The higher SWR found there could be related with the generally drier conditions, given the

Table 11
Coefficients of Spearman rank order correlations between SWR, soil properties, livestock density (LD), percentages of grasses and forbs (Gras), bare soil (Bare) and tree litter cover (Litter) at the unit scale ($n = 22$). Cation Exchange Capacity (CEC), Soil organic carbon (SOC). The soil data correspond to the 0–5 cm layer. Coefficients with significance $p < 0.05$ are highlighted.

	SWR	Clay	Silt	Sand	pH	CEC	Ca	Mg	K	Na	N	P	SOC	LD	Gras	Bare	Litter
Clay	−0.32																
Silt	−0.03	0.34															
Sand	0.13	**−0.58**	**−0.95**														
pH	−0.17	**0.52**	0.03	−0.16													
CEC	0.37	−0.18	−0.12	0.21	−0.08												
Ca	**0.50**	−0.14	−0.11	0.17	−0.17	**0.82**											
Mg	0.12	0.17	**−0.47**	0.38	0.18	**0.61**	**0.50**										
K	0.10	−0.29	−0.29	0.32	−0.31	**0.59**	0.36	0.42									
Na	0.16	0.24	−0.02	−0.01	0.30	0.11	0.09	0.21	−0.03								
N	0.01	−0.26	−0.24	0.33	−0.35	**0.74**	**0.67**	0.41	**0.54**	0.15							
P	−0.14	−0.33	−0.35	0.37	−0.37	0.14	0.02	0.14	**0.75**	0.04	0.32						
SOC	−0.09	−0.25	0.08	0.05	−0.20	**0.60**	**0.46**	0.15	0.38	0.14	**0.80**	0.26					
LD	**−0.56**	0.09	0.25	−0.24	−0.16	0.12	−0.09	0.10	0.33	−0.32	0.26	0.28	**0.44**				
Gras	0.29	−0.38	−0.39	0.41	−0.06	0.04	0.03	0.15	0.41	−0.06	−0.15	**0.44**	−0.20	−0.26			
Bare	**−0.80**	−0.00	0.12	−0.13	−0.03	−0.24	**−0.47**	−0.17	0.10	−0.41	0.07	0.20	0.23	**0.75**	−0.17		
Litter	**0.53**	−0.20	**0.48**	−0.37	−0.24	0.18	0.18	−0.25	−0.04	−0.08	−0.08	−0.22	0.14	−0.05	−0.27	−0.24	
Tree	**0.68**	−0.35	0.26	−0.14	−0.40	0.38	0.41	−0.07	0.15	−0.26	0.04	−0.14	0.14	−0.14	0.06	−0.34	**0.87**

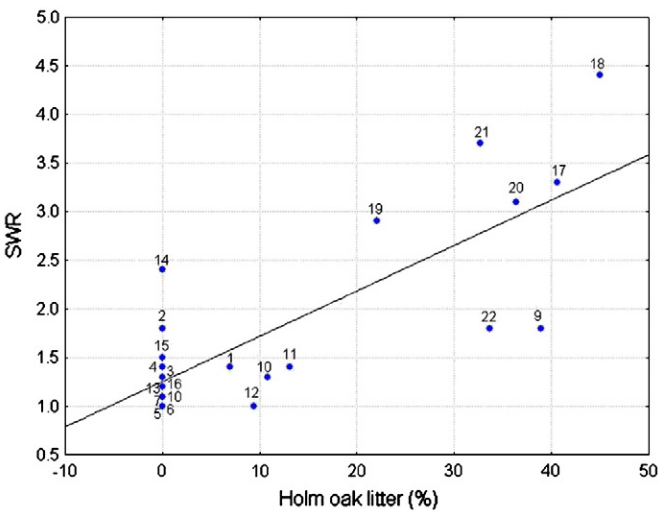

Fig. 6. Relationship between the percentage of Holm oak litter cover and SWR for mean values at the farm unit scale (n = 22). Regression is significant at the 99% confidence level, variance accounted for is 0.624, R = 0.79.

annual rainfall of approximately 300 mm. The same authors reported also very high values of water repellency on bare soil surfaces, which contrasts with our findings. Bare soil surfaces in our study areas were almost completely hydrophilic.

Studies of SWR over large areas are not common, this being the first work carried out at a regional scale in Extremadura. Most soil surfaces in our study farms are hydrophilic or present low degrees of hydrophobicity, a result that can probably be extrapolated to the rangelands found in SW Spain. Severe or extreme hydrophobicity was limited to surfaces covered with Holm oak litter.

On the basis of the available data and the statistics performed, no relationship could be established between SWR and soil properties in our study areas. Hydrophobicity is caused by organic compounds derived from living or decomposing plants or microorganisms (bacteria, fungi or algae) and conditioned by biotic factors as vegetation type and age, fungal growth, microorganisms activity, soil organic matter and humus and by abiotic factors as soil temperatures (fire affected areas), texture and clay content (Doerr et al., 2000). According to Doerr et al. (2000) the relationship between the total amount of soil organic carbon and the degree of soil water repellency was analyzed by many authors and produced inconsistent results. It is argued, to this respect, that only small amounts of hydrophobic compounds are necessary to cause shifts in water repellency, which is not proportional to the total amount of soil organic matter present in a soil horizon. Several authors including Sevink et al. (1989) and Imeson et al. (1992) related the occurrence of SWR with a mor-type humus, though no information about the humus type is available for our study area.

In our study, no relationship could be established between soil physical and chemical properties. Traditionally, water repellency occurrence was linked to coarse-textured soils (DeBano, 2000b), and water repellent soils have even been treated with clay in order to ameliorate them (Ward and Oades, 1993). However, water repellency has also been reported in loamy (McGhie and Posner, 1980) and clayey soils (Dekker and Ritsema, 1996; Giovanni et al., 1983) from Australia, Italy and The Netherlands, respectively.

Chemical properties such as soil pH and exchangeable cations and their relationship with water repellency have been little studied. Few studies have systematically investigated the relationship between pH and SWR (Diehl, 2010) in despite of acidic soils are considered a priori more prone to hydrophobicity than the basic ones. Cerdà and Doerr (2007) indicate that the calcareous nature of soils may restrict the development of water repellency. Nevertheless, SWR has also been found on calcareous soils (Mataix-Solera et al., 2007).

There are no relevant studies about the effect of domestic animals on soil hydrophobicity. Although livestock density has a significant negative correlation with SWR, it is thought to be an indirect effect through reducing grass cover and increasing the degree of bare soil, preventing litter accumulation and reducing SWR occurrence.

The consequences of overgrazing on ground cover were studied under different environmental conditions, particularly in semi arid areas. Many authors highlighted the occurrence of exposed soil surfaces, reaching their maximum at the end of the dry season (Gamougoun et al., 1984; Mulholland and Fullen, 1991; Schnabel, 2003; Shakesby et al., 2002). In our case, the percentages of bare soil at the end of summer were highly variable (CV = 67.48%), with values in excess of 70% in units with high livestock densities (1.2 to 15.8 LU ha^{-1}). Apart from grazing pressure, interannual rainfall variation also effects vegetation cover. During drought periods grasses and forbs are considerably reduced due to a lack of plant available water in combination with plant consumption by domestic animals, even under moderate grazing pressure, as demonstrated for a rangeland area in Extremadura similar to our study sites by Schnabel (1997).

Water repellency is known to display temporal variability, with highest values occurring in dry soils and decreasing gradually as they become wet (Doerr and Thomas, 2000). Therefore drought conditions should enhance SWR because of an accumulation of hydrophobic substances. In contrast, our results indicate that a strong reduction of the vegetation cover may lead to a loss of hydrophobic substances, therefore even during drought periods, high livestock densities may provoke a decrease of soil hydrophobicity. The reason for this response may be quite complex: (i) the effect of animal trampling dry tree litter may destroy and disperse it, (ii) the reduction of grasses and forbs due to excessive livestock consumption exposes litter and (iii) this may increase litter erosion due to surface wash. The increase of surface wash along hillslopes in dehesas as a consequence of droughts was described by Schnabel (1997) and Schnabel et al. (2009). This effect may be enhanced by high intensity rainstorms, producing large amounts of overland flow along hillslopes, easily eroding litter.

5. Conclusions

In rangelands of southwest Spain soil water repellency is low, even under a priori favorable conditions, i.e. after a dry year. Soils beneath *Q. ilex* canopies were the most water-repellent. Most areas covered by dead grass, moss, *R. sphaerocarpa* litter and *Q. suber* litter were hydrophilic or slightly hydrophobic. Bare soil areas were hydrophilic in almost all sites. On the basis of our data analysis, no significant relationship could be established between SWR and soil physical or chemical properties. Hydrophobicity seemed to be more strongly related with the soil surface cover than with the type of canopy cover (Holm oak, cork oak, *R. sphaerocarpa*, open area). A significant negative correlation was found between SWR and the percentage of bare soil, while it was positively correlated with the percentage of Holm oak litter. Almost all sites with a bare soil surface showed to be hydrophilic, independently of whether they were located below a tree canopy or in open areas. Therefore, farms with the higher densities of Holm oak and low amount of exposed soil were the ones with the highest average SWR. Instead, farms with large exposed soil surfaces, showed hydrophilic soils. Since the degree of bare soil is positively related with livestock density, farms with high stocking densities were the ones with lowest SWR.

The effect of antecedent rainfall conditions on soil hydrophobicity has been reported by several authors, which suggest increased SWR values after prolonged dry conditions. Our results indicate that grazing animals could counteract this effect, so that during drought conditions and with constant livestock density the herbaceous cover is reduced, increasing the degree of bare soil and producing a reduction of tree litter.

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