Autores (p. o. de firma): Eugenia Gimeno-García^{a,b*}, Juan Antonio Pascual^a, Joan Llovet^c

^a Centro de Investigaciones sobre Desertificación-CIDE (CSIC, Universitat de València, Generalitat Valenciana), Camí de la Marjal, s/n, 46470-Albal, Valencia, Spain.

^b Fundació General Universitat de València.

^c Fundación Centro de Estudios Ambientales del Mediterráneo (CEAM). Universitat d'Alacant. Departament d'Ecologia. Campus de Sant Vicent del Raspeig - Ap.99. 03080, Alacant, Spain.

* Corresponding author: +34 961220540. Fax: +34 961270967. E-mail address:

eugenia.gimeno@uv.es

Título: Water repellency and moisture content spatial variations under *Rosmarinus officinalis* and *Quercus coccifera* in a Mediterranean burned soil

Revista: Catena

doi: 10.1016/j.catena.2010.12.001

Año: 2011

Water repellency and moisture content spatial variations under *Rosmarinus officinalis* and *Quercus coccifera* in a Mediterranean burned soil

Eugenia Gimeno-García^{a,b*}, Juan Antonio Pascual^a, Joan Llovet^c

^a Centro de Investigaciones sobre Desertificación-CIDE (CSIC, Universitat de València, Generalitat Valenciana), Camí de la Marjal, s/n, 46470-Albal, Valencia, Spain.

^b Fundació General Universitat de València.

^c Fundación Centro de Estudios Ambientales del Mediterráneo (CEAM). Universitat d'Alacant. Departament d'Ecologia. Campus de Sant Vicent del Raspeig - Ap.99. 03080, Alacant, Spain.

* Corresponding author: +34 961220540. Fax: +34 961270967. E-mail address:

eugenia.gimeno@uv.es

Abstract

Variations in the distribution pattern of soil water repellency (SWR) and soil moisture are of major importance for the hydrological and geomorphological processes in Mediterranean burned areas, and also for their ecological implications concerning to re-establishment of the vegetation cover. This paper studies the influence of *Rosmarinus officinalis* L. and *Quercus coccifera* L. vegetated patches on SWR and their relationships with soil moisture content (SMC) and soil organic matter (SOM) in burned and unburned calcareous soils of a Mediterranean shrubland ecosystem, considering the first rainfall event occurred after the wildfire in Les Useres (Castellón, eastern Spain).

In a burnt SSE facing hillslope (739605 West, 4449022 North), 8 microsites were selected under *Q. coccifera* and 20 under *R. officinalis*. Three concentric zones were distinguished around the plants: Zone I (stump), Zone II (intermediate) and Zone III (bare soil), showing differences on its soil surface appearance, which were considered for soil sampling and for field moisture measurements. In the nearest unburned zone, at the same hillslope, 8 microsites for each of the same species were also selected, on the basis that they were representative of the pre-fire conditions.

The obtained results imply that fire caused a significant increase in SWR at *R. officinalis* stumps (measured by means of the Water Drop Penetration Time test, WDPT). However, at burned *Q. coccifera* microsites, SWR was destroyed by fire, at least in the 2 mm soil fraction (WDPT<5s). Results also showed the presence of a gradient from the highest WDPT and SOM at Zone I to the lowest at Zone III for the two studied species, in that way that bare soil was wettable at burned and unburned microsites and this fact is also reflected on the spatial distribution of SMC. Field SMC showed an increasing gradient from the stumps towards the outer zone, and the differences between SMC in the stumps and bare soil were greater from burned than unburned microsites. Field SMC showed significant and negative correlation coefficients with the WDPT and SOM content for the two studied species. Moreover, a positive relationship between WDPT and SOM was found. Partial correlation analysis at burned microsites revealed that SMC and WDPT are influenced by the SOM. The hydrological and ecological implications of these results are discussed.

Keywords: Soil hydrophobicity, soil moisture content, wildfire, Mediterranean shrubland

1. Introduction

Due to the persistence, extensive dispersion, and long term environmental and socioeconomic impacts, Mediterranean wildfires have been widely studied. The Region could be considered as one where fires are among of the most permanent threats to the environment in the northern hemisphere (Pascual et al., 2008). Within the specific scope of environmental impacts, forest fires act as a triggering factor to initiate changes in Mediterranean ecosystems. Post-fire interactions between different components of the vegetation/soil interface have been widely studied. Most works have focused in the soil and vegetation changes, assuming that fire impacts affect soil properties and hydrological processes at different degrees, which are determined largely by fire severity and the immediate post-fire rain regime (Gimeno-García et al., 2004; Campo et al., 2006; Doerr et al., 2006; Gimeno-García et al., 2007; Llovet et al., 2009). Thus, existing research has been concentrated mainly on infiltration, soil moisture storage and runoff, which can be significantly affected by fire and are directly related with the soil water cycle (Imeson et al., 1992; Rubio et al., 1997; Robichaud et al., 2000; González-Pelayo et al., 2006; Cerdá and Doerr, 2005).

The pattern of vegetation structure and other soil surface components (superficial stoniness, rock outcrops, soil crust, bare soil), although less studied in the literature, are an increasing recognised factor of importance regarding runoff generation and water redistribution during the infiltration process, being specially emphasised where banded or spotted vegetation patterns occur like in Mediterranean landscapes (Bergkamp et al., 1996; Valentin and Poesen, 1999; Calvo-Cases et al., 2003; Boix-Fayos et al., 2006; Arnau-Rosalén, 2008). The role of bare soil patches, outcrops and the crusted bare areas between vegetation clumps as runoff generating areas (source areas), and the vegetation-covered areas as water-adsorbing patches (sink areas) is one of the most important features in patchy or banded

vegetation types under Mediterranean conditions (Cammeraat, 2004). This distribution of vegetation cover also plays an important role in controlling the soil organic matter inputs and the soil moisture contents.

Within this soil-vegetation interface transition, the topsoil moisture pattern has implications for understanding environmental processes such as infiltration regime, runoff generation and its superficial continuity across slope, and erosion and sedimentation driven by overland flow (Katra et al., 2007). At small scales, soil moisture responds to variations in soil properties, topographically driven changes in lateral flow, radiation, and vegetation (Western et al., 2002). Soil variables that affect infiltration and water storage include texture, structure, porosity, bulk density, organic matter, and so forth. Another soil property that influences on these processes is soil wettability. Soils in some vegetative types and regions can develop characteristic water repellency, caused by hydrophobic, long-chained organic molecules, released from naturally decomposing plant litter, from the root zone and the leaf surfaces of living plants, from fungal hyphae and soil microorganisms, or by volatilisation and condensation of such compounds during fire (Doerr et al., 2000). Soil water repellency has important effects in burned ecosystems, by modifying infiltration capacity, water movement in soil, and on the post-fire erosion processes, mainly rain drop splash and rill formation (DeBano, 2000; Doerr et al., 2000; Shakesby and Doerr, 2006).

Soil moisture influences water repellency of the soil surface in vertical and lateral reallocation of water at the finest scales (Imeson et al., 1992). It seems that cover density and plant species have a relationship with the persistence and distribution of SWR (DeBano, 1981; Doerr et al., 2000), and fire could act as a triggering factor enhancing or decreasing it related to their severity. Although recent studies on calcareous Mediterranean environments have demonstrated that water repellency can be found in both burnt (Mataix-Solera and Doer, 2004; Arcenegui et al., 2008; Llovet et al., 2009) and non-burnt environments (Verheijen and

Cammeraat, 2007), the post-fire hydrological implications of the fire-induced water repellent soils, when the vegetation is spotted or there is a patchy shrub mosaic, is still poorly studied. Moreover, there are few studies that consider the implications of the first rainfall event on natural wildfire areas.

The present paper studies the influence of burned and unburned *Rosmarinus officinalis* and *Quercus coccifera* vegetated patches on soil water repellency (SWR), and their relationships with soil moisture content (SMC) and soil organic matter (SOM), considering the first rainfall event occurred after the wildfire. Since surface SMC, SOM, and SWR are influenced by vegetation and fire, and soil water and vegetation dynamics are functionally related, it could be expected to find some changes on these variables after fire occurrence.

2. Materials and Methods

2.1. Study area

The study area is located at Serra de la Creu, in the municipality of Les Useres, 40 km of Castellón city (Eastern Spain). This area suffered a wildfire from the 28th August 2007 to 7th September 2007. The total affected area covered 7482 hectares, of which 476 hectares corresponded to forest trees (with dominance of *Pinus halepensis* and in lower extension *Quercus rotundifolia*); 5299 hectares were dominated by shrublands and the remainder surface corresponded mainly to agricultural rainfed areas on terraces with almond, olive and carob trees (1707 hectares). The area has a dry sub-humid Mediterranean-type climate with a marked dry period from June to September. Mean annual temperature is 15.2°C and the mean annual precipitation is 567 mm (data from Vilafamés meteorological station).

In this area, a burned zone (739605 West, 4449022 North) of 7 m wide by 16 m long, located at 570 m a.s.l. on a South-South East facing hillslope with 12° slope angle was selected. The soil is a Rendzic Leptosol developed on Cretaceous limestone, with sandy-loam texture, alkaline pH (7.9) and an organic matter content of the Ah horizon of 7.6%. Despite fire, it was possible to identify the presence of two unique shrub species inside the plot: *Quercus coccifera* and *Rosmarinus officinalis*, which are distributed in a patchy mosaic. The upper and central part of the plot is occupied by individuals of *R. officinalis*, separated one from each other at least by 0.5 m. On both sides of the plot, from meter 6 to 16 (Figure 1), *Q. coccifera* is distributed in two longitudinal stripes, approximately of 2-3 m wide.

Field observations and measurements revealed that fire spread across the shrubland, burning branches of 4-5 mm diameter, and consumed all green leaves of these species. Under *Q. coccifera*, the litter layer was almost completely consumed, the dominant ash colour was grey and white, and the remainder twigs had, generally, a mean of 10 cm height and 2 cm diameter. In *R. officinalis* places, the longest standing twigs had 80 cm height and 2.5 cm diameter on average, the dominant ash colour was grey with some punctual areas with white ashes (mainly close to the stump) (Figure 2), and the litter layer was partially consumed, remaining some charred leaves, which helped to identify this species.

Out of the burned plot, at its right and left sides, unburned vegetation still stands, dominated by a shrubland of 0.6-1.2 m height, with *Q. coccifera*, *R. officinalis*, *Anthyllis citysoides* and *Brachypodium retusum* as dominant species, and also with some groves of *Quercus rotundifolia*. In that unburned zone, some vegetated patches of the same species as above were selected as control microsites (see next epigraph). Unburned *R. officinalis* individuals had a mean height of 90 cm and 60 cm canopy diameter, whereas *Q. coccifera* vegetation patches were 110 cm height and 200 cm wide.

2.2. Soil sampling and analysis

The patchy mosaic distribution of vegetation and the differences on soil surface appearance has been considered when soil sampling and field moisture measurements were made. A total of 44 microsites were selected: 16 at the unburned area (8 with *R. officinalis* and other 8 with *Q. coccifera*) and 28 microsites at the burned zone (20 with *R. officinalis* and 8 dominated by *Q. coccifera*). The distribution of burned microsites is represented in Figure 1. The selection of unburned microsites was made based on the proximity and similarity to the burned zone.

At burned microsites three weeks after the fire impact, it was possible to distinguish three concentric zones around the charred stumps showing differences on its soil surface appearance (Figure 2). Zone I corresponds to the soil closest to the burned stump, with a variable diameter between 40 and 60 cm, with grey and white ashes, and where the litter layer was almost completely consumed. Zone II is located between zones I and III, with variable size from 10 to 30 cm; showing dark grey ashes and litter combustion lower than Zone I. The zones I and II would correspond to the soil area covered by shrub canopy when unburned. Finally, the Zone III, located all around the previous ones, is the most distant from the stump and corresponds to the bare soil; it is characterised by the absence of ashes and more stones on the soil surface than the other zones. The soil appearance on those different zones indicate a gradient of fire severity, from the highest close to the stumps (Zone I) to the lowest on bare soil (Zone III), according to the classification criteria used by USDA Forest Service (Robichaud et al., 2000).

At each of the selected burned and control microsites, soil sampling and field soil moisture measurements were made. Additional information is given in Figure 2. A total of 132 soil samples were collected from the first 2 cm of the mineral A horizon on 26th

September 2007. Ash and litter layer were carefully removed with a soft brush (a spatula was used when necessary) prior the soil sampling. Soil samples were transported to the laboratory and air-dried at room temperature (20-22°C). Each soil sample was divided in two subsamples. One of them was sieved to remove the >2 mm diameter fraction and stored in airtight plastic boxes until analysis (SOM, texture and lab-soil water content). The other set of subsamples were carefully dry hand sieved, avoiding the destruction of aggregates, and two soil fractions <2 mm and <0.250 mm were separated and stored in airtight plastic boxes. This set was used for soil water repellency analysis. The average soil moisture of the air-dried samples was 3.8%.

Field soil moisture content measurements were made one day after the first rainfall event after fire (5 October 2007, five weeks after the wildfire), when 11.05 L m⁻² was registered by the rain gauge installed close to the plot. Volumetric soil moisture content was determined in the field by means of the moisture meter HH2 with ThetaProbe sensor type ML2x, which responds to changes in the apparent dielectric constant of soil. Five readings were taken at each of the three zones of the microsites (a total of 660 measures), separated one from another by 10 cm approximately (Figure 2).

Soil water repellency (SWR) was assessed using the Water Drop Penetration Time (WDPT) test (Letey, 1969). Only the air-dry samples were analysed in order to eliminate the additional influence of differing soil moisture contents on repellency variations. Approximately 30 g of each soil sample was placed into a 60 mm diameter and 16 mm height plastic dish, levelled by gently shaking and tapping the dish on the bench top. Those dishes were exposed to the laboratory atmosphere (20-22°C and ~50% relative humidity) for 24 hours to eliminate potential effects of any variation in preceding atmospheric humidity on soil (Doerr et al., 2002; Mataix-Solera et al., 2007). The WDPT test consisted in placing 5 drops (~0.05 ml) of distilled water onto the soil sample surface using a hypodermic syringe and

recording the time taken for their complete penetration. The average penetration time has been considered as representative of the WDPT of each sample. WDPT were classified by intervals and classes using the categories given in Table 1 according to Bisdom et al. (1993). Samples with a WDPT ≤ 5 s were classed as wettable and those WDPT > 5 s as hydrophobic or water repellent.

Organic carbon content was determined in all samples by oxidation with potassium dichromate (Jackson, 1958). Organic matter percentage was obtained multiplying the organic carbon value by 1.724 (Walkley, 1947). Saturated soil water content (pF 0) was determined for each sample at laboratory by Richards' method (1947), and the results were expressed in percentage of water volume. Using this procedure, the bulk density for each soil sample was also calculated. Soil texture was assessed after destruction of the organic matter by the hydrometer method (Bouyoucos, 1936) and in this case, for burned *R. officinalis* sites a random selection of 24 samples were made (8 in each sampling zone).

2.3. Statistical analysis

Normality and homogeneity of variances for soil data were tested. The non-parametric Kruskal-Wallis test ($P \leq 0.05$) was used when normality and variance homogeneity were not assumed, like for WDPT data set, to test the differences between sampling zones; and the U-Mann-Whitney test ($P \leq 0.05$) was applied to analyse the differences between the two studied species. ANOVA was used to test the differences between burned and control treatments and sampling zones for field soil water content, organic matter, saturated soil moisture content and bulk density, assuming a normal distribution. Spearman's correlation coefficients (ρ)

and partial correlation analysis were calculated to analyse the relationships between soil variables.

3. RESULTS

3.1. Soil Water Repellency (SWR)

Results of SWR showed different frequency of water repellent samples amongst the two plant species tested, and also depending on fire effect at each sampling zone in the microsites (Figure 3). Considering the differences on soil surface appearance based on the three concentric zones identified around the burned stumps, the largest repellency persistence was found close to the charred *R. officinalis* stumps (Zone I), where 100% of samples rendered SWR in the fraction <2mm (Figure 3A), with mean WDPT of 67.75 s (Figure 4). The 85% of these samples showed slight SWR (6s <WDPT <60 s) and the persistence of SWR was between 61 and 300 s for the 10% of the samples, and thus classified as strong water repellent (Table 1). Only the 5% of burned *R. officinalis* samples at Zone I exhibited WDPT higher than 600 s, and were classified as severe repellent soils (Table 1). At the burned *R. officinalis* intermediate zone, only the 15% of samples were slightly water repellent, and all the burned bare soil samples (Zone III) were entirely wettable (Figure 3A). Similar trends were obtained from the soil fraction <0.250 mm (Figure 3C), where SWR appears in the 100% and 10% of *R. officinalis* samples from Zone I and II, respectively. However, at unburned microsites, slight SWR was present only in one of the 24 samples of the *R. officinalis* shrubs.

None of the samples taken at the burned *Q. coccifera* (fraction <2 mm) exhibited SWR (Figure 3B). In this case, SWR was only detected in the fraction <0.250 mm, where the 37.5% of samples from burned *Q. coccifera* stumps had WDPT >5s (Figure 3D). However, at the

unburned *Q. coccifera* microsites, SWR values were always highest around the stumps (mean WDPT ~ 56 s), and decreased from the Zone I to the Zone III (bare soil) (Figure 4). The 75% of samples from unburned *Q. coccifera* at Zone I and the 37.5% of samples from Zone II were classified as slightly water repellent (Figure 3B). Nevertheless, for this species the soil fraction <0.250 mm was entirely wettable at unburned microsites (Figure 3D).

The results also showed the presence of a gradient from the highest WDPT at Zone I (around the stump) to the lowest WDPT at Zone III (bare soil) for the two studied species (Figure 4). It is important to highlight that neither at burned nor unburned bare soil microsites of the two studied species there was any soil water repellency. Bare soil was wettable and this fact could have influenced on the spatial distribution of soil moisture content. This spatial pattern is also showed when SWR is absent (WDPT < 5 s), like at the burned *Q. coccifera* and control *R. officinalis* microsites.

3.2. Field soil moisture content (SMC) and their relationship with soil water repellency (SWR) and soil organic matter content (SOM)

Field SMC measured one day after the first rainfall event occurred in the study area (11mm volume of rainfall), showed statistical significant differences between the two species microsites and between the three sampling zones from each of them (Figure 5A). Both control and burned microsites showed the same trend, with an increasing gradient from the stumps towards the outer bare soil zone. However, burned microsites showed the lowest volumetric SMC in the Zone I (stumps), with mean values of 18.3% in *R. officinalis* microsites and 21.5% in the *Q. coccifera* ones, and the highest SMC in the bare soil, with 27.0% in *R. officinalis* and 29.5% in *Q. coccifera* microsites. Thus, the burned microsites showed larger differences between Zone I and Zone III for the SMC (8 units) than the unburned ones (3

units) (Figure 5A). In all cases, Zone II showed SMC values between those from Zone I and III.

The spatial pattern of SOM was similar between species, independently they were burned or not, although varying in magnitude (Figure 5C). The SOM values were always highest around the stumps and decreased towards the bare soil zones. Moreover, the SOM contents were higher in unburned than in burned microsites, especially in the soil close to the stumps, where differences were statistically significant (Figure 5C). Comparing the SOM content between wettable and water repellent soil samples for each of the species, results showed that burned *R. officinalis* soils that were water repellent (all samples from Zone I), showed an average SOM content of 8.8%. However, the burned *Q. coccifera* soil samples from stumps, with 10.3% of SOM content, were entirely wettable. On the other hand, the unburned soil samples from this species that were water repellent, had SOM contents of 14.9 and 14.2% for stumps and intermediate zones, respectively, whereas the wettable soil samples showed SOM contents ranging between 9.8 and 7.9%.

Spearman's test showed significant and negative correlation coefficients between SMC and WDPT for burned *Q. coccifera* ($r = -0.65$; $P < 0.01$) and *R. officinalis* microsites ($r = -0.6$; $P < 0.01$) (Table 2). Similar results between field SMC and WDPT were found in soil samples from control microsites (Table 2). Spearman's correlation between SMC and SOM at burned and control microsites, also showed significant and negative correlation coefficients (Table 2). Moreover, correlation coefficients between WDPT and SOM were always significant and positive.

The partial correlation analysis with SOM as control variable at burned microsites (Table 2) revealed that SMC and log WDPT are influenced by this parameter, because the above mentioned significant correlations disappeared. On the other hand, the analysis of the linear relationship between log WDPT and SOM displayed the best fit with unburned *Q.*

coccifera soil samples, showing that when the actual amount of organic matter present in this soil is higher than 13%, SWR appears (Figure 6). For the burned *R. officinalis* soil samples this relationship was less clear, and the SOM threshold value for SWR could be established around 8% of SOM (Figure 6).

3.3. Saturated soil water content (Sat-SWC)

Results revealed that there was a spatial pattern around the central stumps that decrease from them towards the bare soil, following an inverse trend than the described above for SMC under field conditions. For instance, burned *R. officinalis* microsites showed Sat-SWC of 62.8%, 60.3% and 55.8% for stump, intermediate and bare soil zones, respectively (Figure 5B). Similar trend was found when analysing burned *Q. coccifera* microsites. In this case, there was 60.8% volumetric water content in the stump zones and lowest water content in bare soil (52.5%), with statistical significant differences between them ($P < 0.05$). In control (unburned) microsites these pattern was also reflected, although with lower differences between zones than that observed for the burned ones (Figure 5B).

4. DISCUSSION

4.1. Soil water repellency (SWR) at unburned microsites

It is commonly accepted that SWR is caused by organic compounds derived from living or decomposing plants, soil microorganisms and fungi, which are subsequently incorporated into the soil. In absence of fire, certain evergreen tree types and shrubland species are known

to exhibit leaf water repellency, which is caused by different microstructures and epicuticular waxes, lipids, resins and/or aromatic oils (Nienhuis and Barthlott, 1997; Doerr et al., 2000; Verheijen and Cammeraat, 2007). Other studies found that water repellency is closely associated with the plant root activity (Dekker and Ristema, 1996; Doerr et al., 1998) or directly from the decomposition of organic matter. Water repellency has also been associated with fungal growth and soil microorganisms (Savage et al., 1972; Jex et al., 1985), which in turn can be associated with specific vegetation types (Doerr et al., 2000). Fungi are known to produce potentially hydrophobic exudates (Lin et al., 2006) to protect against desiccation stresses. Recent studies had drawn the attention in a kind of fungal proteins, namely hydrophobins that are potent surfactants and have the ability to self-assemble at hydrophobic-hydrophilic interfaces into an amphipatic protein film (Rilling, 2005). This suggests that they may also coat surfaces in soils, such aggregates, organic matter and fungal mycelium itself. Hydrophobin coatings on soil surfaces may have caused changes in polarity from hydrophilic to more hydrophobic and vice versa (Rilling, 2005).

In our case, the presence of SWR in 87.5% of the unburned *Q. coccifera* samples seems to be related mainly to the presence of mycelia into the litter layer (≈ 5 cm depth) observed in the field at the time of soil sampling, as also reported by other authors (Scott and Van Wyck, 1990; Crockford et al., 1991; Arcenegui et al., 2008), who found a more severe SWR under the litter layer of different plant species. Mataix-Solera et al. (2007) measured that the 30% of soil samples under *Q. coccifera* were water repellent and speculated that this SWR could be due mainly to fungi development. The spatial variability of SWR found under unburned *Q. coccifera* microsites, with a decreasing gradient in WDPT from the central stump towards the bare soil (Figure 4), has also been reported for other plant species in several studies carried out in natural ecosystems. With absence of fire Keizer et al. (2005) observed this pattern under *Eucalyptus* trees in Portugal, and Verheijen and Cammeraat (2007) found it under some

unburned Mediterranean shrubland species (*Stipa tenacissima*, *Rosmarinus officinalis* and *Anthyllis cytisoides*) in Spain.

Moreover, in the case of unburned *Q. coccifera* there was a linear relationship between log WDPT and SOM, and a threshold value of 13% SOM could be established to differentiate between wettable and SWR samples (Figure 6). Other authors, in unburned ecosystems, found a positive linear correlation between SWR and SOM content (Verheijen and Cammeraat, 2007), which may be caused by increased SOM equilibrium levels proportional to increased SWR. Those authors argue that an exponential function would be expected if the only cause of SWR was the input of hydrophobic compounds from the plants and its ectorganic profile.

On the other hand, the low percentage of SWR under unburned *R. officinalis* (4% of the samples) agrees with the results obtained by Mataix-Solera et al. (2007) and Verheijen and Cammeraat (2007) in semiarid Mediterranean environments. *R. officinalis* is an evergreen aromatic Mediterranean shrub that contains essential oils secreted by glandular trichomes mainly located in their leaves. This species has a high relative wax input rate, which is based on leaf wax contents and characteristics of the ectorganic profile, as it has been estimated by Verheijen and Cammeraat (2007). Those authors found the highest degree of SWR in the *R. officinalis* mulch layer underneath the ectorganic profile, meanwhile in the soil ‘crust’ under the mulch layer, only two samples displayed weak SWR, concluding that the source of water repellency might be the ectorganic profile. Other studies related the high wettability of soil under unburned *R. officinalis* with alkaline pH (Mataix-Solera et al., 2007) and fine soil texture, factors that have been found to influence SWR. In our case, soil pHs under unburned *R. officinalis* microsites ranged between 7.07 and 7.98, and the soil texture was clay loam, with 27.9% of sand and 43.9% of clay around the stumps. It seems that those soil factors enhance the wettable conditions, which agrees with the widely accepted theory that finest textured soils and with alkaline pH are less likely to develop SWR (DeBano, 1981), in spite

that, recently, several researchers in Mediterranean environments have identified SWR on unburned calcareous and finest textured soils (Mataix-Solera and Doerr, 2004; Mataix –Solera et al., 2007).

4.2. Soil water repellency (SWR) at burned microsites

The persistence of SWR is dependent on the studied species. From the results obtained in burned microsites, it is possible to infer that the wildfire created a mosaic of low and moderate severity burnt areas, because of the non-uniformity of fire temperature and duration. At our study scale, this soil severity mosaic seemed to be related mainly to the differences in fuel densities, litter depth, and probably, moisture content of litter, biomass and soil at the time of fire, between the two studied species. Most studies report that fire could induce, enhance or destroy SWR depending on fire severity. The destruction of SWR has been shown in laboratory studies to occur above a soil temperature threshold of 250-350 °C for a wide variety of soils (Savage, 1974; Scholl, 1975; DeBano et al., 1976; Robichaud and Hungerford, 2000; García-Corona et al., 2004). Our different results concerning SWR in unburned and burned *Q. coccifera* microsites -burned *Q. coccifera* microsites were entirely wettable (soil fraction 2 mm), whereas the 87.5% unburned ones showed water repellency ($6 < \text{WDPT} < 181$ s)- suggest that soil temperature surpassed the threshold of repellency destruction. The greatest biomass of *Q. coccifera* consumed during fire, supported by the remaining height and diameter of branches, the discontinuity and/or scarce depth of the charred litter layer measured in the field (<1 cm when remain after fire), the dominance of whitish ashes and a reduction in the SOM content when compared with control microsites (Figure 5C), give also evidences of a more severe fire in those microsites. However, SWR was found in the soil fraction <0.250 mm from burned *Q. coccifera* stumps, which seems to be related with the

presence of fine hydrophobic interstitial organic matter that can be concentrated when sieving the soil sample, as Mataix-Solera and Doerr (2004) had suggested.

The fire effect on the studied *R. officinalis* microsites enhances SWR. In this case, fire seems to be the triggering factor responsible of the WDPT increment. Highest SWR persistence was found, especially, around the central stumps (Zone I) in both soil diameter fractions analysed. We can propose several possible explanations to that increase in SWR.

Firstly, rosemary leaf shows glandular trichomes which contain aromatic oils. Dominant components are α -Pinene, a monoterpene hydrocarbon, and camphor as the main oxygenated monoterpene (Bousbia et al., 2009). Fire could affect those leaf oil-containing glands, causing their rupture when were subjected to the thermal stress, releasing those compounds. It was likely to involve losses of more volatile compounds during fire, although others could be incorporated into the soil surface coating soil particles which are rendered hydrophobic.

Secondly, a positive linear correlation between SOM and WDPT at *R. officinalis* microsites (rho Spearman=0.76, $P \leq 0.01$, Table 2) was found. In some cases, the existence of water repellency is not always proportional to the amount of organic matter present in soil (Figure 6). In other words, the type or quality of the organic material could have more influence on developing SWR rather than the total amount of organic mater or carbon (Wallis and Horne, 1992) present in the soil.

Finally, the soil fraction <0.250 mm at burned *R. officinalis* stumps (Zone I) was also water repellent for all soil samples. Some studies have found that the finest fraction of soil can exhibit some degree of repellency (Doerr et al., 1996; de Jonge et al., 1999; Mataix-Solera and Doerr, 2004; Arcenegui et al. 2008). It may be that particulate hydrophobic SOM is itself relatively fine, enhancing the degree of repellency in the fine sieved fraction (de Jonge et al., 1999). Moreover, the amount of hydrophobic material supplied by fire impact,

might be sufficiently high not only to cover the coarser, but also much of the finer-sized particles with an organic coating (Doerr et al., 1996; Doerr et al., 2000).

Thus, it seems possible that the hydrophobicity under *R. officinalis* burned stumps was not only caused by a hydrophobic coating on coarser individual aggregates, but also by coating on finer soil particles, together with the existence of fine hydrophobic interstitial organic matter. The finding that the 15% of the strong repellent samples with WDPT>60s were found in the 2 mm fraction, whereas the other 85% of soil samples rendered slightly repellency, is in accordance with that suggested by Bisdom et al. (1993) of a hydrophobic coating on the coarser soil particles. On the other hand, the results obtained from the finest soil fraction (<0.250 mm), where the 90% of *R. officinalis* samples were slightly water repellent and the remainder 10% showed strong and severe water repellency, seems to support the existence of organic fine hydrophobic material together with a possible hydrophobic coating on the finest individual particles.

The nonexistence of SWR in bare soil samples (Zone III) both in *R. officinalis* and *Q. coccifera* microsites, showed their very low susceptibility to become water repellent, although those soils had enough SOM content to develop water repellency by burning. DeBano (1991) suggested that any soil containing more than 2% of organic matter is susceptible to becoming water repellent when heated. It has to be taken into account that rather than the total amount of organic matter, the type or fraction of the organic matter (litter and humus type, lipids, etc.) could be the responsible of SWR. In our case, the absence of litter layer at Zone III for both species microsites, could explain partially the hydrophilic behaviour of those soil samples, agreeing with the findings of Maitaix-Solera et al. (2008), who in a laboratory experience observed no soil sample became water repellent when burned without litter debris addition.

449 4.3. Field soil moisture content (SMC), saturated soil water content (Sat-SWC) and soil
450 organic matter (SOM) and their relationship with soil water repellency (SWR)

451
452 At *R. officinalis* microsites, burned soil samples from Zone I had the highest levels of
453 organic matter (8.8%) and clay content (43.5%) (Table 3), which led to a better aggregated
454 soil structure, and also the bulk density of 0.78 g cm^{-3} (Figure 5D) were indicative of high
455 porosity and therefore, it could be expected that those factors encouraged soil moisture
456 retention (Williams et al., 2003). On the other hand, samples from burned *R. officinalis* bare
457 soils (Zone III) had lowest levels of SOM (4.8%) and clay content (33.6%), and increased the
458 bulk density (1.00 g cm^{-3}) with a corresponding decrease in porosity, so it could be expected
459 lower SMC than the samples from Zone I. However, the obtained SMC results after field
460 measurements showed that the opposite occurs, indicating the influence of SWR in the
461 moisture content and on water redistribution around the burned stumps, because large
462 ($<2\text{mm}$) and fine ($<0.250\text{mm}$) soil fractions from samples at burned *R. officinalis* stumps
463 were entirely water repellent.

464 *Q. coccifera* burned microsites also showed the lowest SMC at burned stumps and the
465 highest moisture content at the bare soil zones, in spite that at stumps, the SOM was
466 significantly higher (10.3%) than in the intermediate (7.9%) and bare soil (5.7%) zones. Soil
467 from stumps had the largest clay content (40.6%) (Table 3) and the lowest bulk density (0.76 g cm^{-3}) compared with the surrounding bare soil zones (Figure 5D), so it could be expected
468 those soil variables contribute to increase moisture content. In this case, the influence of
469 hydrophobicity on SMC is less clear, because SWR was only detected in soil fraction <0.250
470 mm. A possible explanation for the spatial differences in SMC contents could be that the large
471 SOM content (10.3%) and the existence of fine hydrophobic material present in the burned *Q.*
472 *coccifera* stumps (Mataix-Solera and Doerr, 2004), seems to be sufficient to diminish the

wettability of those soil aggregates, lowering the SMC in those zones during the rainfall event studied.

However, the results obtained when soil samples were saturated in the laboratory showed that the largest SOM and clay contents, the highest Sat-SWC was found. It is often stated that repellency disappears after prolonged wet periods, and some studies have suggested a soil moisture threshold at which soils cease to be water repellent (DeBano, 1981; Doerr and Thomas, 2000; Huffman et al. 2001). The finding that under laboratory saturation conditions the soil from stump zones showed larger water content than the bare soil zones indicates that the threshold for the elimination of SWR is surpassed, and supports the influence of hydrophobicity on the SMC under field conditions.

The differences in SMC between stumps, intermediate and bare soil zones after the studied rainfall event, with a clear gradient of increasing soil moisture from the stump towards the bare soil may be explained by two mechanisms. On the one hand, the highest SOM content, including the fine hydrophobic material at Zone I (stumps), and the largest persistence of water repellency in some sites, may decrease the wettability of aggregates, slowing their wetting rates (Chenu et al., 2000), which may not completely occur during the studied rainstorm. This seems to be occurred mainly at control or unburned microsites, where the SMC gradient was smoother than in burned ones. In this case, additional spatial variability factors like the variations in the storage capacity of the canopy, litter and duff layers, will determine how much water will be delivered to the soil surface during a rainfall event (Doerr and Moody, 2004). Those factors, together with the hydrophobic nature of *R. officinalis* litter and the abundant fungi mycelia in *Q. coccifera* litter, seems to be the main factors influencing SMC gradient in both unburned microsites.

On the other hand, the infiltration capacity of burned soils could be reduced by their hydrophobic nature, especially under *R. officinalis*, and causes rainwater to pond at the stump

zone, and thus increases overland flow (McNabb et al., 1989; Imeson et al., 1992; Cerdá and Doerr, 2007), which it could be expected to infiltrate once the closest area of wettable soil is reached, that corresponds to the intermediate and bare soil, increasing the SMC in those zones. In this case, as several authors found (Katra et al., 2007), the surface soil moisture on the first day after rainfall may represent a distribution of source and sink areas of water around shrubs during rainfall. Considering this rainfall event, the water repellent soil closest to burned stumps could act as a source of runoff, which is transferred towards the bare soil areas. If these bare soil also acts as a source of runoff must be depend on rainfall characteristics, especially rain intensity (Calvo-Cases et al., 2003).

In addition, for the two studied species microsites, it is necessary to consider the existence of root channels, macropores, cracks and animal borrows with the development of preferential flow pathways that affect the water movement into the soil, and could enhance deeper water infiltration around the stump areas (Doerr and Moody, 2004; Doerr et al., 2006).

The spatial variability of SWR and SMC at finest scale found in this study could have important implications in the reestablishment of the vegetated cover after the fire impact. The absence of SWR at the burned *Q. coccifera* stumps allowed it to retain 14.6% more water than soil around *R. officinalis* stumps, which probably play an important role in the regeneration of this resprouter species, together with other post-fire environmental advantages like the sudden release of nutrients coming from ashes, more light and more open space available, between other factors. In semiarid Mediterranean areas where after summer wildfires there is a rainy season in autumn, the spatial variability for SWR, SMC and SOM found around the shrubs may play an important role in the infiltration and spatial distribution of water into the soil.

CONCLUSIONS

Fire promoted a different effect on surface soil water repellency at this particular site and it was related to the plant species. The persistence of soil water repellency was found to vary widely in short distances around the shrubs as influenced by a mosaic of fire severity in the different plant species microsites. The more severe fire at *Quercus coccifera* stumps lead to the combustion of organic matter and associated hydrophobic compounds, rendering the soil surface wettable (soil fraction <2 mm), which was the opposite to the observed in those unburned microsites, where the 75% of soil samples were water repellent. The lower fire severity at *Rosmarinus officinalis* microsites seemed to have produced the release of hydrophobic compounds from their leaves and litter, rendering the soil surface water repellent at the stump zone for all samples in the two soil fractions analysed (<2 and <0.250 mm). However, the unburned *Rosmarinus officinalis* microsites were wettable. Moreover, the entire bare soil sampling zones around the burned or unburned central stumps of both plant species were fully wettable, and this fact have influenced on the spatial distribution of soil moisture content.

The mosaic of field soil moisture distribution was inversely related to the soil water repellency and to the soil organic matter content, and it could reflect the potential runoff soil patches in the first rainfall event after the wildfire. The spatial variability of soil water repellency and soil moisture content at short distances should imply that runoff generation would be very patchy around the burned stumps and the overland flow generated in these areas could be transferred towards the bare soil areas, which increased their soil moisture content one day after the first rainfall event registered after the wildfire. The existence of this spatial pattern of areas with contrasting soil properties and hydrological response should play

an important role on the water redistribution and also on the re-establishment of the vegetation cover in this Mediterranean burned area.

ACKNOWLEDGEMENTS

This research was carried out as part of the project *Estudio de la variabilidad espacial de los patrones de humedad del suelo en zonas incendiadas de la Comunidad Valenciana: su relación con la respuesta hidrológica y erosiva del suelo y con la regeneración de la vegetación*, GV/2007/063, funded by the Generalitat Valenciana, and also was supported by Programa Ramón y Cajal from the Spanish Ministerio de Ciencia e Innovación. Fundación CEAM is supported by Generalitat Valenciana and Bancaja, as well as by the Program CONSOLIDER-INGENIO (GRACCIE Project). We also would like to acknowledge Maite Silvestre and Roger Grau for their field and laboratory assistance.

ABBREVIATIONS

SWR: soil water repellency; SMC: soil moisture content; SOM: soil organic matter; WDPT: water drop penetration time; Sat-SWC: soil water content under saturation conditions

REFERENCES

572 Arcenegui, V., Mataix-Solera, J., Guerrero, C., Zornoza, R. Mataix-Beneyto, J., Gracia-
 573 Orenes, F., 2008. Immediate effects of wildfires on water repellency and aggregate
 574 stability in Mediterranean calcareous soils. *Catena* 74 (3), 219-226.

575 Arnau-Rosalén, E., Calvo-Cases, A., Boix-Fayos, C., Lavee, H., Sarah, P., 2008. Analysis of
 576 soil surface component patterns affecting runoff generation. An example of methods
 577 applied to Mediterranean hillslopes in Alicante (Spain). *Geomorphology* 101, 595-606.

578 Bergkamp, G. Cammeraat, E.L.H., Martinez-Fernandez, J., 1996. Water movement and
 579 vegetation patterns on shrubland and an abandoned field in two desertification threatened
 580 areas in Spain. *Earth Surface Processes and Landforms* 21, 1073-1090.

581 Bisdom, E.B.A., Dekker, L.W., Schoute, J.F.Th., 1993. Water repellency of sieve fractions
 582 from sandy soils and relationships with organic material and soil structure. *Geoderma* 56,
 583 105-118.

584 Boix-Fayos, C., Martínez-Mena, M., Arnau-Rosalen, E., Calvo-Cases, A., Castillo, V.,
 585 Albaldejo, J., 2006. Measuring soil erosion by field plots: understanding the sources of
 586 variation. *Earth-Science reviews* 78, 267-285.

587 Bousbia, N., Vian, M.A., Feraht, M.A., Petitcolas, E., Meklati, B.Y., Chemet, F., 2009.
 588 Comparison of two isolation methods for essential oil from rosemary leaves:
 589 Hydrodistillation and microwave hydrodiffusion and gravity. *Food Chemistry* 114, 355-
 590 362.

591 Bouyoucos, G.J., 1936. Directions for making mechanical analysis of soils by the hydrometer
 592 method. *Soil Science* 42, 225-228.

593 Calvo-Cases, A., Boix-Fayos, C., Imeson, A.C., 2003. Runoff generation, sediment
 594 movement and soil water behaviour on calcareous (limestone) slopes of some
 595 Mediterranean environments in southeast Spain. *Geomorphology* 50, 269-291.

596 Cammeraat, E.L.H., 2004. Scale dependent thresholds in hydrological and erosion response of
 597 a semi-arid catchment in southeast Spain. *Agriculture, Ecosystems and Environment* 104,
 598 317-332.

599 Campo, J., Andreu, V., Gimeno-García, E., González, O., Rubio, J.L., 2006. The occurrence
 600 of soil erosion after repeated experimental fires in a Mediterranean environment.
 601 *Geomorphology* 82, 376-387.

602 Cerdá, A., Doerr, S.H., 2005. Long-term soil erosion changes under simulated rainfall for
 603 different vegetation types following a wildfire in eastern Spain. *Journal of Wildland Fire*
 604 14, 423-437.

605 Cerdá, A., Doerr, S.H., 2007. Soil wettability, runoff and erodibility of major dry-
 606 Mediterranean land use types on calcareous soils. *Hydrological Processes* 21, 2325-2336.

607 Chenu, C. Le Bissonnais, Y., Arrouays, D., 2000. Organic matter influence on clay wettability
 608 and soil aggregate stability. *Soil Science Society of America Journal* 64, 1479-1486.

609 Crockford, S., Topadilis, S., Richardson, D.P., 1991. Water repellency in a dry sclerophyll
 610 forest-measurements and processes. *Hydrological Processes* 5, 405-420.

611 de Jonge, L.W., Jacobsen, O.H., Moldrup, P., 1999. Soil water repellency: effects of water
 612 content, temperature and particle size. *Soil Science Society of America Journal* 63, 437-
 613 442.

614 DeBano, L.F., 1981. Water repellent soils: A state-of-the-art. General Technical Report PSW-
 615 46. USDA Forest Service, Pacific Southwest Forest and Range Experimental Station
 616 Berkeley, California.

617 DeBano, L.F., 1991. The effects of fire on soil properties. General Technical Report. INT-
 618 280. USDA Forest Service. Berkeley, California , pp. 151-156.

619 DeBano, L. F., 2000. The role of fire and soil heating on water repellency in wildland
 620 environments: a review. *Journal of Hydrology* 231-232, 195-206.

621 DeBano, L.F., Savage, S.M., Hamilton, A.D., 1976. The transfer of heat and hydrophobic
622 substances during burning. *Proceedings of the Soil Science Society of America* 40, 779-
623 782.

624 Dekker, L.W., Ristema, C.J. 1996. Variation in water content and wetting patterns in Dutch
625 water repellent peaty clay and clayey peat soil. *Catena* 28, 89-105.

626 Doerr, S.H., Thomas, A.D. 2000. The role of soil moisture in controlling water repellency:
627 new evidence from forest soils in Portugal. *Journal of Hydrology* 231-232, 134-147.

628 Doerr, S.H., Moody, J.A. 2004. Hydrological effects of soil water repellency: on spatial and
629 temporal uncertainties. *Hydrological Processes* 18, 829-832.

630 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D. 1996. Soil water repellency variations with depth
631 and particle size fraction in burned and unburned *Eucalyptus globulus* and *Pinus pinaster*
632 forest terrain in the Águeda basin, Portugal. *Catena* 27 (1), 25-47.

633 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D. 1998. Spatial variability of soil water repellency
634 in fire-prone eucalyptus and pine forest, Portugal. *Soil Science* 163, 313-324.

635 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D. 2000. Soil water repellency: its causes,
636 characteristics and hydro-geomorphological significance. *Earth Science Reviews* 51, 33-
637 65.

638 Doerr, S.H., Dekker, L.W., Shakesby, R.A., Ristema, C.A., Bryant, R. 2002. Water repellency
639 of soils: the influence of ambient relative humidity. *Soil Science Society of American*
640 *Journal* 66, 401-405.

641 Doerr, S.H., Shakesby, R.A., Blake, W.H., Chafer, C.J., Humphreys, G.S., Wallbrink, P.J.
642 2006. Effects of differing wildfire severities on soil wettability and implications for
643 hydrological response. *Journal of Hydrology* 319, 295-311.

644 García-Corona, R. Benito, E., de Blas, E., Varela, M.E. 2004. Effect of heating on some soil
645 physical properties related to its hydrological behaviour in two north-western Spanish
646 soils. *International Journal of Wildland Fire* 13, 195-199.

647 Gimeno-García, E. Andreu, V., Rubio, J.L. 2004. Spatial patterns of soil temperatures during
648 experimental fires. *Geoderma* 118, 17-38.

649 Gimeno-García, E. Andreu, V., Rubio, J.L. 2007. Influence of vegetation recovery on water
650 erosion at short and medium-term after experimental fires in a Mediterranean shrubland.
651 *Catena* 69 (2), 150-160.

652 González-Pelayo, O., Andreu, V., Campo, J., Gimeno-García, E., Rubio, J.L. 2006.
653 Hydrological properties of a Mediterranean soil burned with different intensities. *Catena*
654 68, 186-193.

655 Huffman, E.L., MacDonald, L.H., Stednick, J.D. 2001. Strength and persistence of fire-
656 induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range.
657 *Hydrological Process* 15, 2877-2892.

658 Imeson, A.C., Verstraten, J.M., Van Mullingen, E.J., Sevink, J. 1992. The effects of fire and
659 water repellency on infiltration and runoff under Mediterranean type forests. *Catena* 19,
660 345-361.

661 Jackson, M.L. 1958. *Soil Chemical Analysis*. Prentice Hall, Englewood Cliffs. New Jersey.

662 Jex, G.W., Bleakley, B.H., Hubbel, D.H., Munro, L.L. 1985. High humidity-induced increase
663 in water-repellency in some sandy soils. *Journal of the Soil Science Society of America* 49,
664 1177-1182.

665 Katra, I., Blumberg, D.G., Lavee, H. Sarah, P. 2007. Spatial distribution dynamics of topsoil
666 moisture in shrub microenvironment after rain events in arid and semi-arid areas by means
667 of high resolution maps. *Geomorphology* 86, 455-464.

668 Keizer, J.J., Ferreira, A.J.D., Coelho, C.O.A., Doerr, S.H., Malvar, M.C., Domingues, C.S.P.,
 669 Perez, I.M.B., Ruiz, C., Ferrari, K. 2005. The role of tree stem proximity in the spatial
 670 variability of soil water repellency in a eucalypt plantation in coastal Portugal. Australian
 671 Journal of Soil Research 43(3), 251-259.

672 Letey, J. 1969. Measurement of contact angle, water drop penetration time, and critical
 673 surface tension. In: DeBano, L.F., Letey, J. (Eds.), Water repellent soils. Proceedings of
 674 the Symposium on Water Repellent Soils, University of California Riverside, CA, pp. 43-
 675 47.

676 Lin, C-H., Chou, W-C., Tsai, J-S., Lin, W-T. 2006. Water repellency of Casuarina
 677 windbreaks (*Casuarina equisetifolia* Forst.) caused by fungi in central Taiwan. Ecological
 678 Engineering 26, 283-292.

679 Llovet, J., Ruiz-Valera, M., Josá, R., Vallejo, R. 2009. Soil responses to fire in Mediterranean
 680 forest landscapes in relation to the previous stage of land abandonment. International
 681 Journal of Wildland Fire 18, 222-232.

682 Mataix-Solera, J., Doerr, S.H. 2004. Hydrophobicity and aggregate stability in calcareous
 683 topsoils from fire-affected pine forests in southeastern Spain. Geoderma 118, 77-88.

684 Mataix-Solera, J., Arcenegui, V., Guerrero, C., Mayoral, A.M., Morales, J., González, J.,
 685 García-Orenes, F., Gómez, I. 2007. Water repellency under different plant species in a
 686 calcareous forest soil in a semiarid Mediterranean environment. Hydrological Processes
 687 21(17), 2300-2309.

688 Mataix-Solera, J., Arcenegui, V., Guerrero, C., Jordán, M.M., Dlapa, P., Tessler, N.,
 689 Wittenberg, L. 2008. Can *terra rossa* become water repellent by burning? A laboratory
 690 approach. Geoderma 147, 178-184.

691 McNabb, D.H., Gaweda, F., Froehlich, H.A. 1989. Infiltration, water repellency, and soil
692 moisture content after broadcast burning a forest site in southwest Oregon. *Journal of Soil*
693 *and Water Conservation* 44, 87-90.

694 Nienhuis, C., Barthlott, W. 1997. Characterization and distribution of water-repellent, self-
695 cleaning plant surfaces. *Annals of Botany* 79, 667-677.

696 Pascual Aguilar, J.A., Gimeno-García, E., Llovet, J., 2008. A recent history of Mediterranean
697 wildfires and its influence on soil erosion. *Proceedings ISCO 2008-15th International Soil*
698 *Conservation Organisation Conference*. Geographical Research Institute, Hungarian
699 Academy of Sciences, Budapest, 4 pp.

700 Richards, L.A. 1947. Pressure-membrane apparatus, construction and use. *Agricultural*
701 *Engineering* 28, 451-454.

702 Rilling, M.C. 2005. A connection between fungal hydrophobins and soil water repellency?
703 *Pedobiologia* 49, 395-399.

704 Robichaud, P.R., Hungerford, R.D. 2000. Water repellency by laboratory burning of four
705 northern Rocky Mountain forest soils. *Journal of Hydrology* 231-232, 207-219.

706 Robichaud, P.R., Beyres, J.L., Neary, D.G. 2000. Evaluating the effectiveness of postfire
707 rehabilitation treatments. *USDA Forest Service Gen. Tech. Rep. RMRS-GTR-63*. 85 pp.
708 United States Department of Agriculture, Forest Service Rocky Mountain Research
709 Station.

710 Rubio, J.L., Forteza, J., Andreu, V., Cerni, R. 1997. Soil profile characteristics influencing
711 runoff and soil erosion after forest fire: a case study (Valencia, Spain). *Soil Technology*
712 11, 67-78.

713 Savage, S.M. 1974. Mechanism of fire-induced water repellency in soils. *Proceedings of the*
714 *Soil Science Society of America* 38, 652-657.

715 Savage, S.M., Osborn, J., Letey, J., Heton, C. 1972. Substances contributing to fire induced
716 water repellency in soils. *Proceedings of the Soil Science Society of America* 36, 674-678.

717 Scholl, D.G. 1975. Soil wettability and fire in Arizona chaparral. *Proceedings of the Soil*
718 *Science Society of America* 39, 356-361.

719 Scott, D.F., Van Wyk, D.B. 1990. The effects of wildfire on soil wettability and hydrological
720 behaviour of an afforested catchment. *Journal of Hydrology* 121, 239-256.

721 Shakesby, R.A., Doerr, S.H. 2006. Wildfire as a hydrological and geomorphological agent.
722 *Earth-Science Reviews* 74, 269-307.

723 Valentin, C., Poesen, J. (Eds.) 1999. The significance of soil, water and landscape processes
724 in banded vegetation patterning. *Catena* 37 (1-2), 1-274.

725 Verheijen, F.G.A., Cammeraat, E.L.H. 2007. The association between three dominant shrub
726 species and water repellent soils along a range of soil moisture contents in semi-arid
727 Spain. *Hydrological Processes* 21, 2310-2316.

728 Wallis, M.G., Horne, D.J. 1992. Soil water repellency. *Advances in Soil Science* vol. 20, 91-
729 146, Stewart BA (ed.), Springer, New York.

730 Walkley, A. 1947. A critical examination of a rapid method for determining organic carbon in
731 soils-effect of variations in digestion conditions and of inorganic soil constituents. *Soil*
732 *Science* 63, 251-264.

733 Western, A.W., Grayson, R.B., Blöschl, G. 2002. Scaling of soil moisture: A hydrologic
734 perspective. *Annu. Rev. Earth Plant Sci.* 30, 149-180.

735 Williams, A.G., Ternan, J.L., Fitzjohn, C., de Alba, S., Pérez-González, A. 2003. Soil
736 moisture variability and land use in a seasonally arid environment. *Hydrological Processes*
737 17, 225-235.

738 Table 1. Classes of water repellency and Water Drop Penetration Time (WDPT) intervals used in the present study (after Bisdom et al., 1993)

	Classes of water repellency									
	Wettable	Slight			Strong			Severe		Extreme
WDPT intervals (s)	≤ 5	6-10	11-30	31-60	61-180	181-300	301-600	601-900	901-3600	> 3600
Log WDPT interval	≤ 0.7	0.7-1.0	1.0-1.5	1.5-1.8	1.8-2.3	2.3-2.5	2.5-2.8	2.8-3.0	3.0-3.6	> 3.6

739

740

Table 2. Spearman's correlation coefficients between field soil moisture content (F-SMC), soil organic matter (SOM) and water drop penetration time (WDPT) for *Rosmarinus officinalis* and *Quercus coccifera* microsites

	Microsite	Treatment	F-SMC (%)	S.O.M. (%)	F-SMC correlation ^a partial
WDPT (s)	<i>Rosmarinus officinalis</i>	Burned (n=60)	-0.60 **	0.76 **	0.006 ns
		Control (n=24)	-0.435 *	0.611 **	0.322 ns
	<i>Quercus coccifera</i>	Burned (n=24)	-0.65 **	0.887 **	0.015 ns
		Control (n=24)	-0.617 **	0.797 **	-0.263 ns
F-SMC (%)	<i>Rosmarinus officinalis</i>	Burned (n=60)		-0.640 **	-
		Control (n=24)		-0.719 **	-
	<i>Quercus coccifera</i>	Burned (n=24)		-0.644 **	-
		Control (n=24)		-0.462 *	-

**, * significant level for $P < 0.01$ and $P < 0.05$ respectively; ns: not significant

^a Coefficient of partial correlation between log WDPT and F-SMC controlling the effect for SOM

751 Table 3. Soil texture (0-2 cm depth) in burned and control *Rosmarinus officinalis* and
752 *Quercus coccifera* microsites. Mean value ^a ± standard error

Microsite	Position	Sand (%)	Silt (%)	Clay (%)
Burned <i>R. officinalis</i>	Stump	30.1 ± 1.1 a	26.4 ± 1.7 a	43.5 ± 1.5 a
	Intermediate	35.0 ± 3.3 ab	26.1 ± 1.1 a	38.9 ± 2.7 ab
	Bares oil	39.9 ± 1.2 b	26.5 ± 1.3 a	33.6 ± 1.6 b
Control <i>R. officinalis</i>	Stump	27.9 ± 1.4 a	28.1 ± 1.7 a	43.9 ± 2.4 a
	Intermediate	29.1 ± 2.2 ab	28.2 ± 1.2 a	42.7 ± 2.2 a
	Bares oil	36.9 ± 2.9 b	25.6 ± 1.6 a	37.5 ± 2.5 a
Burned <i>Q. coccifera</i>	Stump	23.1 ± 2.8 a	25.7 ± 2.9 a	51.2 ± 2.7 a
	Intermediate	n.d. ^b	n.d.	n.d.
	Bares oil	40.6 ± 2.2 b	24.2 ± 1.8 a	35.1 ± 1.7 b
Control <i>Q. coccifera</i>	Stump	17.8 ± 3.8 a	27.2 ± 2.9 a	54.9 ± 3.7 a
	Intermediate	24.9 ± 3.5 ab	23.2 ± 1.1 a	51.8 ± 3.4 ab
	Bares oil	34.3 ± 4.7 b	25.4 ± 1.6 a	40.3 ± 4.3 b

753

754 ^a Means not sharing the same letter indicates the existence of statistical significant differences
755 with Tukey Test at P≤0.05 between sampling zones from each species microsite

756 ^b n.d.: not determined

757

Figure captions

Figure 1. Location of Les Useres study area and schematic representation of burned vegetation at the selected plot

Figure 2. Example of the three soil sampling zones and moisture measurement points at one *Rosmarinus officinalis* microsite in Les Useres burned plot, three weeks after the fire impact. Zone I: close to the stump; Zone II: intermediate area; Zone III: bare soil. (▲): soil sampling points; and (■) points for field soil moisture measurements

Figure 3. Frequency distribution of Water Drop Penetration Time (WDPT, s) intervals for soil samples taken at burned and control (unburned) microsites for *Rosmarinus officinalis* and *Quercus coccifera*. (A) and (B) soil fraction <2mm Ø; (C) and (D) soil fraction <0.250mm Ø

Figure 4. Mean values for Water Drop Penetration Time (WDPT) for soil samples considering the two studied species and the distance from the central stump. ‘Stump, Intermediate and Bare soil’ correspond with Zones I, II and III, respectively. Standard error in bars. * Significant differences with Kruskal-Wallis Test ($P \leq 0.05$)

Figure 5. Mean values for (A) volumetric field soil moisture content (vol. SMC); (B) saturated soil water content (SWC); (C) soil organic matter (SOM) and (D) bulk density considering the two studied species and the distance from the central stump. Standard errors in bars. Different lower case letters show the statistical significant differences with Tukey Test ($P \leq 0.05$) between the different sampling zones: ‘Stump, Intermediate and Bare soil’.

782 Different capital letters show the statistical significant differences between burned and control
783 microsites with Mann-Whitney U-Test ($P \leq 0.05$)

784

785 Figure 6. Relationship between soil organic matter content (SOM, %) and persistence of
786 water repellency (log WDPT, s) of soil samples taken in *Rosmarinus officinalis* and *Quercus*
787 *coccifera* burned and unburned microsites. Wettable ($\diamond$) and water repellent soil samples ($\blacklozenge$)

788

789
790
791

792
793

Figure 1

Figure 2.

807 Figure 3

808
809
810

811 Figure 4.

812
813
814 Figure 5.
815

Burned *R. officinalis*

Unburned *R. officinalis*

Burned *Q. coccifera*

Unburned *Q. coccifera*