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REGULAR ARTICLE

# Water repellency of air-dried and sieved samples from limestone soils in central Portugal collected before and after prescribed fire

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**Abstract**
*Aims* Soil water repellency (SWR) in Mediterranean sub-humid environments is poorly studied in soils derived from basic bedrock. This study addressed this gap by comparing SWR in soil samples collected before/after a prescribed burning in a Mediterranean shrubland overlaying limestone.
*Methods* Sampling was performed on two adjacent slopes (NE/SW) underneath *Quercus coccifera, Pistacia lentiscus, Arbutus unedo* shrubs, and on bare inter-patches, at two depths (0–2 and 2–5 cm). Samples were sieved at <0.25, 0.25–1, 1–2 and <2 mm and SWR was assessed through the Water Drop Penetration Time (WDPT) in each fraction. Samples were analysed for pH, AS, $CaCO_3$ and SOM.
*Results* SWR was present before fire, mainly in the <0.25 and 0.25–1 mm fractions at 0–2 cm, which could be explained by SOM (amount and chemical composition). Persistence varied between the two slopes (NE > SW) and the four patches (*Arbutus unedo* > *Pistacia lentiscus* ≈ *Quercus coccifera* > Bare). The low-severity fire slightly increased SWR but did not affect the above-mentioned pre-fire differences.
*Conclusions* The wax and resins from different shrub species have implications for SWR persistence on the finer soil fractions. Prescribed fire increased the severity of SWR at surface but also its frequency at the subsurface layer.

**Keywords** Soil water repellency · Soil fractions · Texture · Plant-/inter-patches · Mediterranean · Shrubland · Prescribed fire

**Abbreviations**

| | |
|---|---|
| SWR | Soil water repellency |
| SMC | Soil moisture content |
| WDPT | Water drop penetration time |
| SOM | Soil organic matter |
| NE | North-east |
| SW | South-west |
| TC's | Thermocouples |
| TP's | Thermo-sensitive paints |

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| | |
|---|---|
| AS | Aggregate stability |
| $CaCO_3$ | Carbonate content |

## Introduction

The worldwide occurrence of soil water repellency (SWR) is well-established, having been reported for different types of soil and vegetation across the globe (Bisdom et al. 1993; Doerr et al. 2000; Jordán et al. 2008). In the Mediterranean climate zone, SWR has been reported for pine forest (Santos et al. 2013), eucalyptus forest (Doerr et al. 2005; Prats et al. 2012), deciduous forest (Jordán et al. 2008), Californian chaparral (Hubbert et al. 2006), and, more recently, also Mediterranean shrublands (Arcenegui et al. 2008; Gimeno-García et al. 2011). SWR of Mediterranean shrublands, however, has been studied more extensively for soils derived from acidic parent material in sub-humid conditions (Martínez-Zavala and Jordán-López 2009; Stoof et al. 2011) than for soils overlying carbonated bedrock (sedimentary rocks composed primarily of carbonate materials). Studies performed in Mediterranean carbonated bedrock soils from the east Iberian Peninsula have been showing a slight to strong SWR (Mataix-Solera and Doerr 2004; Mataix-Solera et al. 2007, 2013; Verheijen and Cammeraat 2007; Arcenegui et al. 2008; Gimeno-García et al. 2011). Under these semi-arid conditions, SWR have been attributed to: (i) microenvironment (fertility islands vs. bare interpatches); (ii) plant species; (iii) topsoil properties such as soil organic matter, aggregate stability, pH and mineralogy of clay fraction; (iv) soil particle size. Nonetheless, there are important knowledge gaps on the occurrence and severity of SWR in soils derived from carbonated bedrock in sub-humid areas, in particular with respect to the role of fire.

Plants are known to release different types of resins, waxes, aromatic oils and lipids that can induce SWR (Doerr et al. 2000). Especially plant litter and derived humus are considered to be important sources of hydrophobic substances (Mataix-Solera et al. 2007). Nevertheless, the relationship between SWR and plant species may not always be a direct one, because fungi and other microorganisms can also release substances that induce SWR, especially in soils with low pH (Doerr et al. 2000). In Mediterranean environments, a patchy vegetation cover is common, and can induce spatial differences on microenvironments and topsoil properties such as soil organic matter content (SOM), soil crusting, and aggregate stability (Cerdà 1998; Verheijen and Cammeraat 2007; Campo et al. 2008; Gimeno-García et al. 2011). These soil properties play an important role in water infiltration (González-Pelayo et al. 2010a) and runoff processes (Jordán et al. 2008). Since topsoil properties are markedly different depending on the presence/absence of vegetation and on the plant species, the occurrence and severity of SWR must, at least in part, be linked to the quantity and chemical composition of the litter layer (Mataix-Solera et al. 2007).

SWR is greatly influenced by soil water content, air humidity, and corresponding soil-water potential (Dekker and Ritsema 1994; Roy and McGill 2000; Doerr and Thomas 2000; Doerr et al. 2002). Moreover, 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 is well known that under field conditions, repellent soils alternate seasonally or over shorter intervals between repellent and wettable states in response to rainfall and temperature patterns (Santos et al. 2013). These changes have important implications for infiltration, rainsplash detachment, overland flow generation and soil loss (Prats et al. 2012).

The frequency and severity of SWR is also affected by fire, particularly peak temperature and residence time, as well as the heating regime of the soil (Gimeno-García et al. 2004; Doerr et al. 2005). As wildfire frequency in Mediterranean areas is predicted to increase in the future, prescribed (controlled) fire could be used routinely as a fuel management option to reduce wildfire hazard and its environmental impacts (Fernandes and Botelho 2003). The low fire severity associated with prescribed fire has reduced impacts on soil losses compared to less frequent but more severe wildfires (Shakesby et al. 2015). However, repeated prescribed fires have been shown to cause progressive soil degradation (González-Pelayo et al. 2010b). Several studies have investigated prescribed fire effects on soil quality (Úbeda et al. 2005), erosion (González-Pelayo et al. 2010b), soil organic matter losses (Johansen et al. 2003), $CO_2$ emissions (Vilén and Fernandes 2011), and soil water repellency (Vadilonga et al. 2008).

The present study aims to extend the knowledge of SWR in Mediterranean soils derived from basic parent material and the role of prescribed fire on this environment. For soils derived from limestone bedrock evolved under sub-humid climate conditions, the specific objectives of the present study are to: (1) quantify the frequency and severity of SWR beneath typical shrub species and on bare inter-patches of air-dried soil samples (<2 mm); (2) investigate the spatial SWR variation in different soil depths (0–2 cm and 2–5 cm); (3) assess the role of soil particle size (<0.25, 0.25–1, 1–2 mm) and selected soil properties (SOM, pH, AS, $CaCO_3$) on SWR; (4) evaluate the impact of prescribed fire on changes in SWR .

## Materials and methods

### Site description and experimental design

A shrubland area (3.8 ha.) in north-central Portugal (30 km south of Coimbra) (Fig. 1) was selected based on its bedrock (Jurassic limestones), vegetation composition and fire recurrence.

The study site has a sub-humid Mediterranean climate with an average annual precipitation of 1000–1200 mm and a dry period from July to September. The landscape is dominated by fractured dolomite Jurassic hills (less than 300 m a.s.l.) with few permanent watercourses. According to the World Reference Base (IUSS 2014), the soils are an association of Humic leptosol (covered by dense vegetation) and Haplic cambisol (covered by a patchy vegetation) developed on two facing slopes with NE and SW exposition, respectively. Soils on the NE slope averaged 15 % angle and are shallow, developed in pockets, and comprise horizons O, Ah (average SOM of 14.3 %) and R. Soils on the SW slope averaged 8 % angle, are deeper and have horizons O (comparatively thin), Ah (average SOM of 10.6 %), Bw, and C (Fig. 1, Table 3). The slope angle varies between very gently (2 %) to strongly sloping (20 %) according to FAO classification (IUSS 2014). Before the prescribed fire, on 22nd of April 2009, the shurbland area was dominated by resprouter species of the *Arisaro-Quercetum broteroi* phytosociological series, particularly by *Quercus coccifera, Pistacia lentiscus,* and *Arbutus unedo.* In 1991, the study site was burnt by a wildfire. The general characteristics of the study area are given in Table 1.

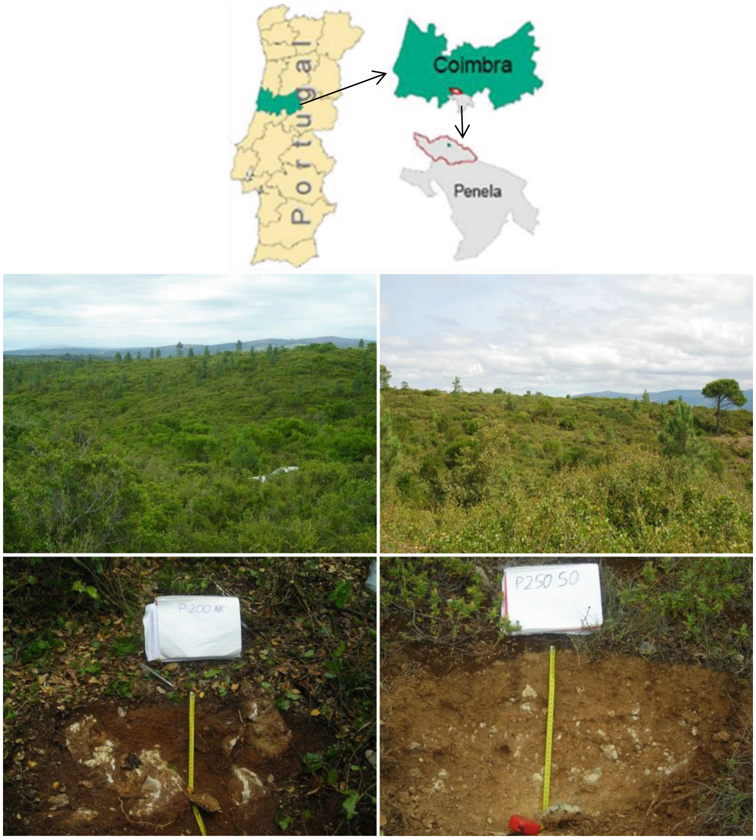
The experimental design was established to address the role of prescribed fire, soil cover (vegetated vs. bare), plant species (*Quercus coccifera* vs. *Pistacia lentiscus* vs. *Arbutus unedo*), soil depth (0–2 cm and 2–5 cm), and soil characteristics associated with two distinct landscape units differing in aspect (NE and SW) on SWR.

Pre-fire field data and sample collection was carried out during mid-April 2009. At the NE slope, nine sampling sites were selected for each of the three shrub species at regular distances along a transect running from the top to the bottom of the slope; at the SW slope, the same sampling scheme was implemented and nine additional sampling sites were selected at bare inter-patches. Previous to fire, at each sampling site the volumetric soil moisture content was measured using an EC5 soil moisture sensor connected to a hand-held reader (Decagon Devices), through three replicate readings performed at 0–5 cm depth. In each site, two soil samples of around 0.5 kg were collected at 0–2 and 2–5 cm depth, giving a total of 126 pre-fire samples. Immediately after the burning, soil sampling was repeated at the same 63 sampling sites, whose locations was marked with metal sticks during the pre-fire sampling.

Fuel load and fuel moisture content were also determined before the prescribed fire, following Gimeno-García et al. (2004). Within an area of homogeneous shrub cover, the aboveground standing biomass as well as the litter layer were clipped/collected in one plot of 1 $m^2$ on the NE slope and in one plot of 2 $m^2$ on the SW slope.

Specialized fire fighters conducted the prescribed fire in order to reduce the available fuel load. The prescribed fire was request by the local FLOPEN forestry association, responsible for the area's management. The date (22nd April 2009) was selected according with optimal weather conditions to conduct a prescribed fire, including low air temperature (<20 °C), low wind velocity (<5 m $s^{-1}$), and high air humidity (40–70 %). Fire severity was assessed at each of the 63 sampling sites using (1) the twig severity index (Maia et al. 2012), (2) thermo-sensitive paints (TP's) placed at the soil surface (OMEGALAQ® Liquid Temperature Lacquers, $n=94$), and (3) K-type thermocouples (ø1.5 mm, TC-direct, Netherlands) connected to data loggers (EL-USB-TC; 0.5 °C resolution, 1 °C logger accuracy, Lascar Electronics, UK). At each sampling site, two thermocouples (TC's) were installed at the soil mineral surface (i.e., underneath the litter layer) and at 2 cm depth.

**Fig. 1** Localization of study site, landscape view and soil profile. *Left*: North-East slope, *right*: South-West slope



Humic leptosol

Haplic cambisol

### Laboratory analysis

The pre- and post-fire soil samples were air dried (20–22 °C) and sieved to remove the stone fraction (>2 mm diameter). Each sample was then divided into two equal portions, one for measurement of SWR and the other for soil properties analysis.

The soil organic matter (SOM) content was determined by the Walkley-Black method (Jackson 1958), while soil pH was measured in water (1:5). Total carbonates were analysed using the Bernard calcimeter method (MAPA 1986), and aggregate stability (AS) using the Hennin and Feodorof method as modified by Primo-Yufera and Carrasco (1973).

Part of the sample portion for the SWR measurements was sieved in order to separate three distinct particle size fractions: <0.25, 0.25–1 and 1–2 mm. Manual sieving was used in order to avoid the destruction of aggregates. Sub-samples of approximately 30 g were placed on plastic dishes of 60 mm in diameter and 16 mm height, and levelled by gentle shaking and tapping the dish on the bench top. Prior to the assessment of SWR measurements, the sub-samples were kept under controlled conditions of temperature (20–22 °C) and relative humidity (~50 % relative humidity) for 2 days, in order to eliminate potential effects of any variations in preceding atmospheric humidity on soil (Doerr et al. 2002). In general SWR varies nonlinearly with soil moisture content (Regalado and Ritter 2005; Kawamoto et al. 2007). Despite its water dependency, soil repellency is usually characterized by repellency indexes measured at fixed soil moisture content. In the present study, because of the range of field conditions under which soil samples were collected (different shrub specie, two contrast facing slopes, ambient humidity and wind variation along the course of the day when sampling was carried out, etc.), SWR was only measured on air-dried samples. Similar soil moisture content between soil

**Table 1** General characteristics of the Podentes study site

| General characteristics | NE slope | SW slope |
|---|---|---|
| Location | 40°03′59.80″N/8°25′05.73″W | |
| Bedrock | Jurassic limestones | |
| Elevation (meters a.s.l.) | 270 | |
| Mean annual precipitation (mm) | 1000–1200 | |
| Mean annual temperature (°C) | 15 | |
| Fire frequency (last 30 years) | 2 | |
| Shrubland | *Arisaro-Quercetum broteroi* phytosociological serie | |
| Biomass (kg m$^{-2}$) | 5.6 | 4.6 (±0.3) |
| Fuel moisture (%) | 51 | 49 (±3.5) |
| Average slope angle (%) | 15 | 8 |
| Post-fire severity indicators | Twig severity index/black ashes on mineral surface/grey spots on top | |
| Soil type | Humic leptosol | Haplic cambisol |
| SOM (Ah layer, %) | 14.3 | 10.6 |
| Soil texture (Ah layer) | Loam | Loam |
| Samples | 108 | 144 |

samples will provide a standard physical condition to assess repellency, allowing a direct comparison since more similar constant matric potential is reached under air-drying.

The water drop penetration time (WDPT) test (Wessel 1988 in Mataix-Solera et al. 2007) was used to determine the severity of SWR, both for the entire samples (<2 mm: $n$=252) and for the three separated fractions (<0.25 mm: $n$=252, 0.25–1 mm: $n$=252; 1–2 mm; $n$=252). Each WDPT measurement consisted of placing ten drops of distilled water (~0.05 ml) on the sample surface, using a hypodermic syringe, and on recording the time required for their complete penetration. The penetration time of the ten drops were used to calculate the median value, which was used as a sample's WDPT value. The WDPT values were further classified in five severity ratings, following Bisdom et al. (1993): WDPT<5 s=class 0, wettable or non-water repellent; 5–60 s=class 1, slightly water repellent; 60–600 s=class 2, strongly water repellent; 600–3600 s=class 3, severely water repellent; WDPT>3600 s=class 4, extremely water repellent.

The collected litter layer was weighed upon arrival to the laboratory, as well as after drying at 85 °C for 48 h, whereas the aboveground biomass was only weighed after drying.

### Statistical analysis

Normality and homogeneity of variance of the different soil data were assessed using the Kolmogorov-Smirnov test and Levene's test. If normality and homogeneity of variance was not rejected, Analysis of Variance (ANOVA) was carried out, followed by Tukey's test in case of significant differences. Since rejection was the case for the SWR data, the non-parametric Kruskal–Wallis test was applied after logarithmic transformation of the WDPT values. The non-parametric Mann–Whitney *U*-test was then used to test between-group differences, using the Bonferroni correction for multiple comparisons to adjust the level of significance. The Spearman rank correlation coefficient was computed to determine and test the association of SWR with the other soil properties. In cases where a significant correlation was determined, a linear regression analysis was subsequently performed.

All statistical analyses were carried out with the software package SPSS 15 ®.and considered alpha= 0.05.

## Results

### Prescribed fire conditions and temperatures

The prescribed fire was carried out in the early morning of 22nd April 2009. Average surface soil (0–5 cm) moisture content (SMC) prior to fire ignition was 24 % ($n$=63). Prior to the fire, NE slope had greater biomass amount than SW slope (5.6 kg m$^{-2}$ and 4.6 kg m$^{-2}$, respectively), but similar fuel moisture (50 %) (Table 1).

During the prescribed fire surface soil layer reached higher temperatures, which were not able to penetrate deeper into the soil. Based on thermosensitive paints (TP's) method, average peak temperature at the soil surface was 144 °C (Table 2). However, according to the thermocouples (TC's) measurements, peak temperatures at the soil surface averaged 316 °C, lasting for 11 s (only 41 of the 68 TC's installed were operational). Nevertheless, the average soil surface temperatures which exceeded 100 °C was 189 °C, measured over 3.5 min (Table 2). At 2 cm soil depth average

**Table 2** Summary of statistics for temperature (°C) measured through thermosensitive paints (TP's, $n=94$) and thermocouples (TC's, $n=41$) at soil surface

| | TP's (°C) | | | TC's (°C) | | | |
|---|---|---|---|---|---|---|---|
| | Q | L | A | $T>100$ (°C) | Time with $T>100$ (sec.) | Peak T (°C) | Time of peak T (sec.) |
| NE | 138 (27) | 129 (40) | 133 (63) | 197 | 202 | 340 | 11 |
| SW | 138 (41) | 181 (78) | 147 (61) | 183 | 222 | 293 | 12 |
| Average | 138 | 155 | 140 | 189 | 213 | 316 | 11 |

Q, L, and A means *Quercus coccifera, Pistacia lent*iscus and *Arbutus unedo*, respectively. NE, north-east and SW, South-west. T, means temperature. Values between brackets are standard deviation. No statistically significant differences at $p<0.05$ have been detected (between shrub species and aspect)

temperature was 26 °C (68 TC's were operational). Considering the fuel moisture (Table 2) and the weather conditions, together with TP's and TC's results, as well as the twig severity index (Maia et al. 2012), the prescribed fire was classified as a low severity one, according to the classification established by Robichaud and Hungerford (2000).

## Water repellency in the entire soil fraction

Previous to the fire, SWR after sieving and in air-drying conditions was absent on bare soil but was identified under shrubland (Fig. 2). In the entire soil samples (<2 mm), SWR was stronger beneath *Pistacia lentiscus* and *Arbutus unedo* shrubs (11 % persistence of the strong class) than beneath *Quercus coccifera* in both soil layers (Fig. 2). Generally, SWR was higher below all the vegetation types on the NE than SW slope (Fig. 2), as observed for SOM content (Table 3). The direct relationship between SWR and SOM is in accordance with the findings that a higher SOM content can lead to major presence of the soil water repellency (Martínez-Murillo et al. 2013).

Clear differences were identified in natural conditions between surface (0–2 cm) and subsurface soil depths (2–5 cm), although differences with soil depth were attenuated by the fire impact (Fig. 2). At the surface soil samples (0–2 cm) a post-fire slight increase in the SWR persistence was observed beneath *Pistacia lentiscus* shrubs, while below *Quercus coccifera* and *Arbutus unedo* minor changes were detected. At the subsurface soil samples (2–5 cm), SWR was absent in pre-fire conditions, but after the fire, samples collected beneath *Pistacia lentiscus* and *Arbutus unedo* target plants displayed slight and strong SWR (Fig. 2). After the fire, the frequency of SWR was enhanced at the subsurface soil layer.

A minor impact of burning was observed on soil properties (Table 3). Nevertheless, the slight increase in the post-fire SOM content at 0–2 cm depth was in accordance with the increasing persistence of the SWR of the surface and mainly of the deeper soil samples.

## SWR behaviour in soil sieved fractions

SWR was mainly present in the smallest soil fractions (Figs. 3 and 4). Under pre-fire settings, no SWR was observed on surface soil beneath different shrubland species for the 1–2 mm soil fraction, while in the 0.25–1 mm fraction slight repellency was assessed for several sites, reaching 33, 44 and 66 % beneath *Quercus coccifera*, *Arbutus unedo* and *Pistacia lentiscus* on the NE slope (Fig. 3). On the SW slope, SWR was absent on bare soil and under *Pistacia lentiscus*, but reached 11 and 44 % of the sites beneath *Quercus coccifera* and *Arbutus unedo*, respectively.

The finest soil fraction (<0.25 mm) showed greater SWR frequency, particularly on the NE slope, where most of the monitored sites of *Quercus coccifera* and *Pistacia lentiscus* exhibited slight repellency (67 % and 78 % of the sites), while *Arbutus unedo* showed strong repellency in 55 % of the sites. On the SW slope, slight repellency covered 11, 44 and 88 % of the *Quercus coccifera*, *Pistacia lentiscus and Arbutus unedo* sites, respectively (Fig. 3). Bare soil was mainly wettable, but SWR in air-dried samples could have been favoured by sieving samples (<0.25 mm) with high $CaCO_3$ content (Table 4).

The WDPT performed at different fractions at the subsurface soil depth (2–5 cm) displayed a similar trend than at the surface layer (0–2 cm). Higher repellency

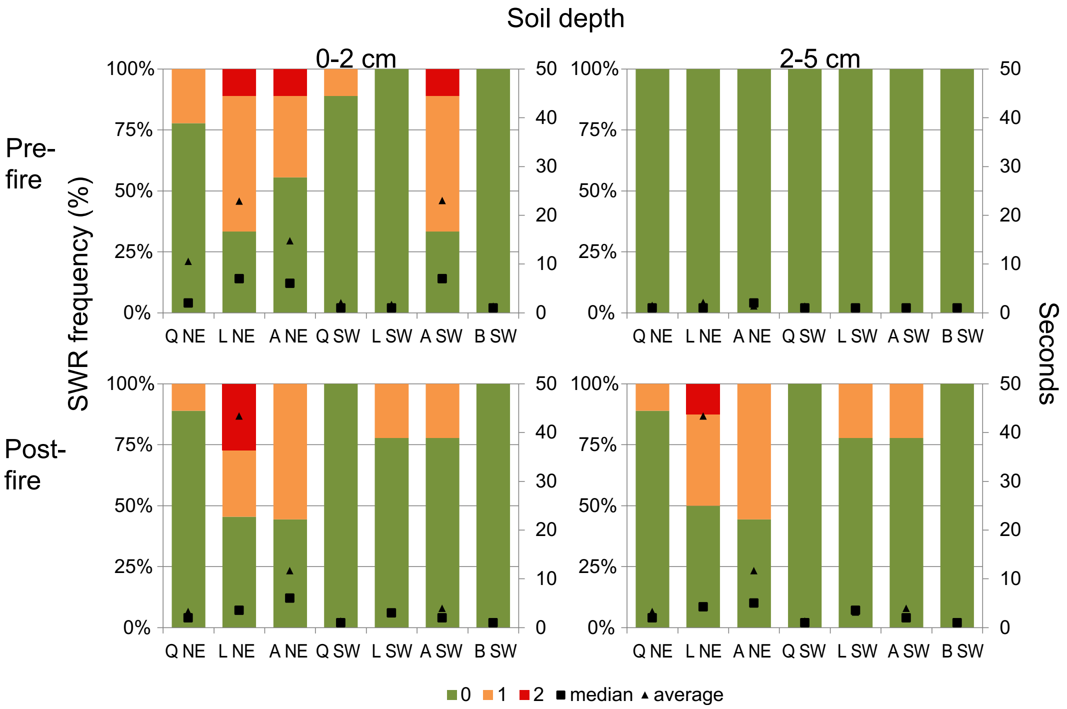


**Fig. 2** Pre- and post-fire frequency of water repellency classes for the composite fraction (<2 mm) under all the selected species (left axis) ($n$=9). Q, L, A, B means *Quercus coccifera*, *Pistacia lentiscus*, *Arbutus unedo*, and bare soil, respectively. NE and SW are the slope aspects (North-East and South-West, respectively). 0, 1, 2 are SWR persistence classes (wettable, slight and strong persistence, respectively). *Right axis* represents the water drop penetration time, with median (*squares*) and average (*triangles*) values on the total pool of drops ($n$=90) per selected specie (seconds)

was confined to the finest soil fractions and the frequency was affected by the aspect (NE>SW). Subsurface soil samples beneath SW *Arbutus unedo* shrubs also displayed severe repellency in 11 % of the sites (Fig. 4).

Although the differences between pre- and post-fire conditions, the low fire severity did not significantly affect the studied soil properties ($p$>0.05). Nonetheless, the slight increase on SWR frequency in the finest soil fractions on both,

**Table 3** Pre- and post-fire average values for soil organic matter content (SOM, %), pH, carbonates ($CaCO_3$, %) and aggregate stability (AS, %) in surface soil samples (0–2 cm depth)

| | | Q NE | Q SW | L NE | L SW | A NE | A SW | Bare |
|---|---|---|---|---|---|---|---|---|
| Pre-fire | SOM (%) | 13.6 bc | 9.4 a | 15.1 c | 10.7 ab | 14.2 bc | 14.3 bc | 8 a |
| | pH | 6.8 a | 7.2 ab | 6.7 a | 7.6 b | 7.2 ab | 7.5 b | 8 c |
| | $CaCO_3$ (%) | 2.1 a | 3.4 a | 2.3 a | 3.8 a | 4.4 a | 5.0 a | 12.8 b |
| | AS (%) | 59.1 b | 63.9 b | 60.2 b | 63.1 b | 48.4 a | 63.4 b | 40.8 a |
| Post-fire | SOM (%) | 14.8 ab | 10.9 a | 16.8 b | 12.2 ab | 16.4 b | 13.6 ab | 9.2 a |
| | pH | 7.2 a | 7.5 a | 7.2 a | 7.6 a | 7.2 a | 7.7 a | 8 b |
| | $CaCO_3$ (%) | 1.4 a | 1.8 a | 1.6 a | 2.5 ab | 2.6 ab | 3.9 b | 5 b |
| | AS (%) | 53.6 a | 65.4 b | 54 a | 67.3 b | 62.4 b* | 63.6 b | 42.7 a |

Q, L, A means *Quercus coccifera*, *Pistacia lentiscus*, and *Arbutus unedo*, respectively. NE and SW are the slope aspects (North-East and South-West, respectively). $N$=63

Different letters in rows display statistical significant differences detected by ANOVA's test followed by Tukey's post-hoc test

*Means pre- and post-fire statistical significant differences ($p$-value<0.05)

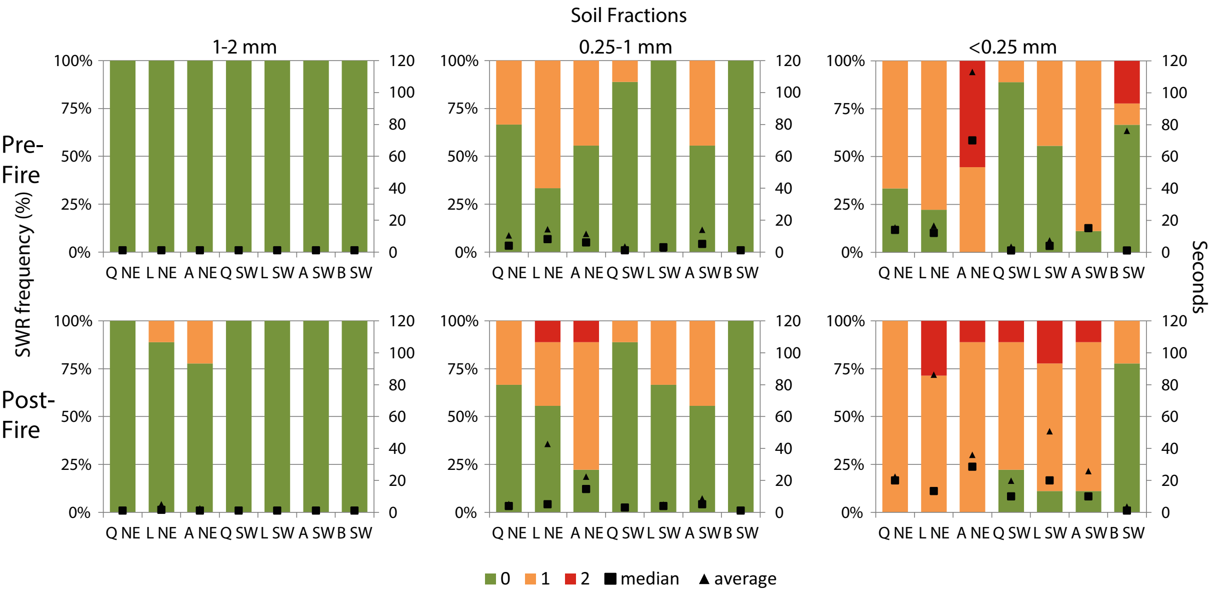


**Fig. 3** Pre- and post-fire frequency of the SWR persistence for the surface soil samples (0–2 cm) sieved at different fractions: <0.25, 0.25–1 and 1–2 mm (*left axis*) ($n$=9). Q, L, A, B means *Quercus coccifera*, *Pistacia lentiscus*, *Arbutus unedo*, and bare soil, respectively. NE and SW are the slope aspects (North-East and South-West, respectively). 0, 1 and 2 are SWR persistence classes (wettable, slight and strong persistence, respectively). *Right axis* represents the water drop penetration time, with median (*squares*) and average (*triangles*) values on the total pool of drops ($n$=90) per selected specie (seconds)

surface and subsurface soil samples, after the fire (Figs. 3 and 4), can be linked with greater SOM content (post-fire increases of 1.7 and 0.8 % on NE and SW, respectively) (Table 3) and the hypothesized post-fire changes in SOM composition (Campo et al. 2011). The fire impact did not affect

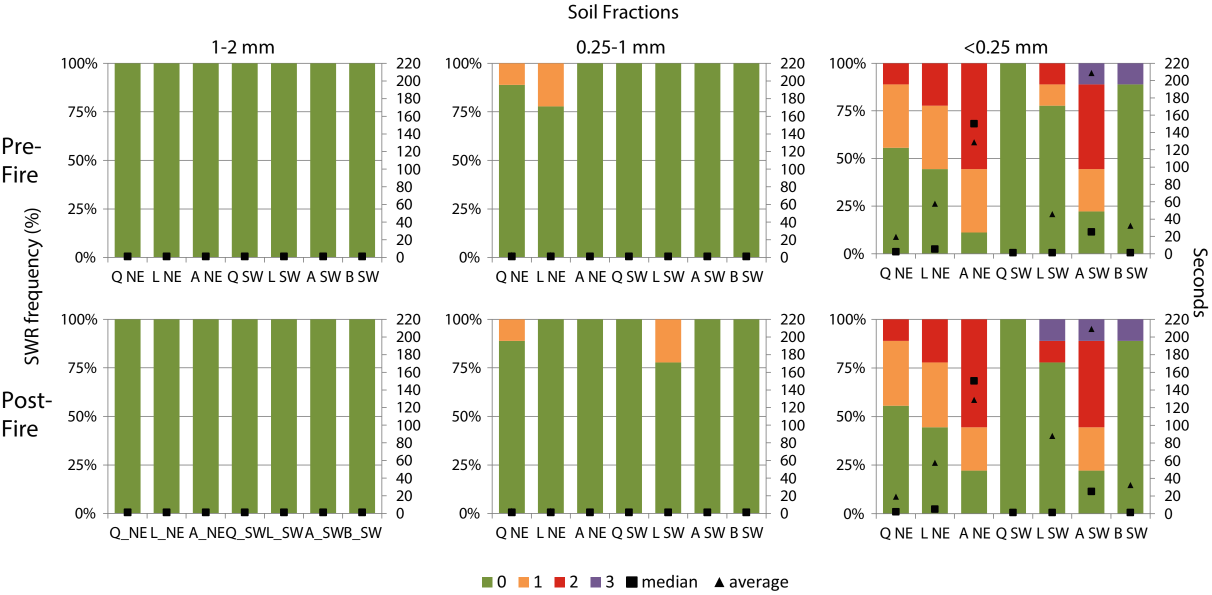


**Fig. 4** Pre- and post-fire frequency of the SWR persistence for the surface soil samples (2–5 cm) sieved at different fractions: <0.25, 0.25–1 and 1–2 mm (left axis) ($n$=9). Q, L, A, B means *Quercus coccifera*, *Pistacia lentiscus*, *Arbutus unedo*, and bare soil, respectively. NE and SW are the slope aspects (North-East and South-West, respectively). 0, 1, 2 and 3 are SWR persistence classes (wettable, slight, strong and severe persistence, respectively). *Right axis* represents the water drop penetration time, with median (*squares*) and average (*triangles*) values on the total pool of drops ($n$=90) per selected specie (seconds)

**Table 4** Surface soil properties under pre- (left) and post- (right) fire conditions (mean value±standard deviation): soil organic matter content (SOM, %), pH, aggregate stability (AS, %) and carbonates ($CaCO_3$, %)

| | | Pre-fire | | | | | Post-fire | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SOM (%) | pH | AS | Ca $CO_3$ | *n* | SOM (%) | pH | AS | Ca $CO_3$ | *n* |
| Q NE | Repellent | **14.9±1.2** | 6.7±0.4 | 59.6±4.2 | 2±0.5 | 6 | 14.8±3.8 | 7.2±0.3 | 53.6±2.1 | 1.4±0.4 | 9 |
| | Wettable | 11±0.7 | 7.0±0.6 | 58.3±5.7 | 2.3±1 | 3 | – | – | – | – | 0 |
| Q SW | Repellent | **10.9±0.4** | 7.2±0.16 | 63.2±5 | 4.2±1.3 | 2 | 9.7±3.7 | 7.5±0.16 | 64.9±4.8 | 1.9±1 | 8 |
| | Wettable | 9.0±0.9 | 7.2±0.13 | 64.2±3.2 | 3.1±2.5 | 7 | 9.6 | 7.7 | 68.8 | 1.32 | 1 |
| L NE | Repellent | 15.5±2.6 | 6.6±0.6 | 60.5±1.5 | 2.1±1.6 | 8 | 16.8 | 7.2 | 54 | 1.6 | 9 |
| | Wettable | 12.3 | 7.5 | 58 | 3.7 | 1 | – | – | – | – | 0 |
| L SW | Repellent | 11.1±2 | 7.6±0.08 | 63.4±2.4 | 4.8±1 | 4 | **12.4±1.4** | 7.6±0.3 | 67.4±0.6 | 2.5±1.3 | 8 |
| | Wettable | 10.3±2.4 | 7.5±0.1 | 62.8±1.5 | 3±2 | 5 | 10.7 | 7.9 | 66.8 | 2.5 | 1 |
| A NE | Repellent | 14.2 | 7.2 | 48.4 | 4.4 | 9 | 16.4 | 7.2 | 62.3 | 2.6 | 9 |
| | Wettable | – | – | – | – | 0 | – | – | – | – | 0 |
| A SW | Repellent | **15.4±2.6** | 7.5±0.07 | 63.9±3 | 5.2±1 | 8 | **14.9±2.5** | 7.6±0.1 | 63.5±3 | 3.6±0.8 | 8 |
| | Wettable | 5 | 7.6 | 59.6 | 3.5 | 1 | 9.9 | 7.9 | 63.5 | 6.5 | 1 |
| BS | Repellent | **4.4±1.2** | **8.2±0** | **20.3±5.2** | 29.9±31.27 | 3 | No data | No data | No data | No data | |
| | Wettable | 8.6±1.3 | 7.8±0.1 | 51±12.5 | 4.2±1.6 | 6 | No data | No data | No data | No data | |

Q, L, A, BS means *Quercus coccifera*, *Pistacia lentiscus*, and *Arbutus unedo* and bare soil, respectively. NE and SW are the slope aspects (North-East and South-West, respectively). Values in black mean statistical significant differences between wettable (WDPT<5 s) and water repellent samples (WDPT≥5 s) for the soil fraction<0.25 mm, assessed through ANOVA ($p$-value<0.05). $N$=126

differences in SWR frequency in both slopes at different sampling depths. Despite SWR was always more frequent on the NE slope, in the <0.25 mm soil fraction of subsurface post-fire samples, severe SWR was measured under *Pistacia lentiscus* and *Arbutus unedo* on the SW slope (Fig. 4).

In summary, an increasing trend in SWR presence was observed in the <0.25 mm soil fraction beneath the different shrubland species (*Arbutus unedo* > *Pistacia lentiscus* ≈ *Quercus coccifera* > Bare soil), and depending on the aspect (NE > SW). Fire slightly increased SWR in both surface and subsurface soil samples. Pre-fire differences on SWR according with shrub species were also maintained after the fire. The microenvironment created by *Arbutus unedo* shrubs developed greatest soil hydrophobic conditions, before and after the prescribed fire.

### Soil water repellency and soil properties

SOM was higher in NE than SW slope, under pre- and post-fire conditions, but it was slightly increased by the fire (NE: 14.3 vs 16 % and SW 10.6 vs 11.4 % in pre-and post-fire, respectively) due to incomplete organic matter combustion (Table 3). SOM was significantly higher in the water repellent soil samples (Table 4).

Significant correlations were observed between SOM and SWR in surface soil samples, including the entire sample (<2 mm) and the different sieved fractions (<0.25, 0.25–1 and 1–2 mm), under pre-fire conditions. In post-fire samples, significant correlations were also found between SOM and SWR, except for the <0.25 mm soil fraction (Table 5). At the subsurface soil layer (2–5 cm depth), SOM did not correlate with the SWR except for the <0.25 mm soil fraction before the fire.

Considering the influence of vegetation and the aspect, SOM content did not correlate significantly with SWR in the finest soil fraction (<0.25 mm), except beneath *Quercus coccifera* placed on SW slope and *Arbutus unedo* on NE (Table 6). However, significant positive correlations were found in the fractions<2 mm and 0.25–1 mm from samples collected beneath all the three vegetation types in both slopes, except for *Quercus coccifera* and *Pistacia lentiscus* in SW (Table 6).

**Table 5** Pre- and post-fire Spearman (Rho) correlation coefficients between soil organic matter content (SOM, %) and repellency (log WDPT) at different soil fractions (<0.25, 0.25–1, 1–2 and <2 mm), for the surface (0–2 cm depth) and subsurface (2–5 cm depth) soil samples

| Soil depth | SOM | log WDPT<2 mm | log WDPT 1–2 mm | log WDPT 0.25–1 mm | log WDPT <0.25 mm |
|---|---|---|---|---|---|
| 0–2 cm | Total (*n*=108) | 0.759 | 0.577 | 0.761 | 0.332 |
| | Pre-fire (*n*=54) | 0.846 | 0.656 | 0.774 | 0.523 |
| | Post-fire (*n*=54) | 0.749 | 0.548 | 0.759 | – |
| 2–5 cm | Total (*n*=108) | – | – | – | 0.261 |
| | Pre-fire (*n*=54) | – | – | – | 0.274 |
| | Post-fire (*n*=54) | – | – | – | – |

Correlation is significant at 0.01 level

Opposite to surface soil results, on the subsurface layer (2–5 cm depth) no significant correlation was found between SWR and SOM, reason why correlations are not shown on Table 6.

Furthermore, before the prescribed fire, the SOM and SWR results from different surface soil showed a direct relationship ($R^2$=0.6) in the fractions<2 mm and 0.25–1 mm (Fig. 5). The higher repellency measured in the finest fraction (<0.25 mm) (Figs. 3 and 4) showed a poor relationship with SOM, traduced in a low $R^2$ under pre- but also post-fire samples (Fig. 5). In fact, in surface soil samples collected after the fire, as well as all the subsurface samples (2–5 cm depth), a consistently poor $R^2$

**Table 6** Pre- and post-fire Spearman (Rho) correlation coefficients between soil organic matter (SOM) and repellency (log WDPT) at different soil fractions (<0.25 mm, 0.25–1 mm, 1–2 mm and <2 mm), for the surface (0–2 cm depth) soil samples beneath shrubs

0–2 cm depth

| | SOM | log WDPT<2 mm | log WDPT 1–2 mm | log WDPT 0.25–1 mm | log WDPT<0.25 mm |
|---|---|---|---|---|---|
| Pre-fire | Q | 0.723 | 0.621 | 0.793 | 0.784 |
| | Q NE | 0.778 | 0.753 | 0.862 | – |
| | Q SW | 0.78 | – | 0.772 | 0.767 |
| | P | 0.867 | 0.639 | 0.76 | – |
| | L NE | 0.683 | 0.777 | 0.733 | – |
| | L SW | 0.705 | – | – | – |
| | A | 0.871 | 0.751 | 0.76 | – |
| | A NE | 0.95 | 0.707 | – | −0.683 |
| | A SW | 0.75 | 0.782 | 0.865 | – |
| Post-fire | Q | 0.733 | – | 0.731 | – |
| | Q NE | 0.731 | – | 0.778 | – |
| | Q SW | 0.707 | – | 0.78 | – |
| | P | 0.522 | 0.671 | 0.597 | – |
| | L NE | – | – | – | – |
| | L SW | 0.898 | 0.73 | 0.874 | – |
| | A | 0.758 | 0.629 | 0.795 | – |
| | A NE | – | 0.678 | 0.765 | – |
| | A SW | 0.831 | – | 0.778 | – |

Q, L, and A means *Quercus coccifera, Pistacia lentiscus* and *Arbutus unedo*, respectively. NE and SW are slope aspects (North-East and South-West, respectively). Correlation is significant at 0.01 level

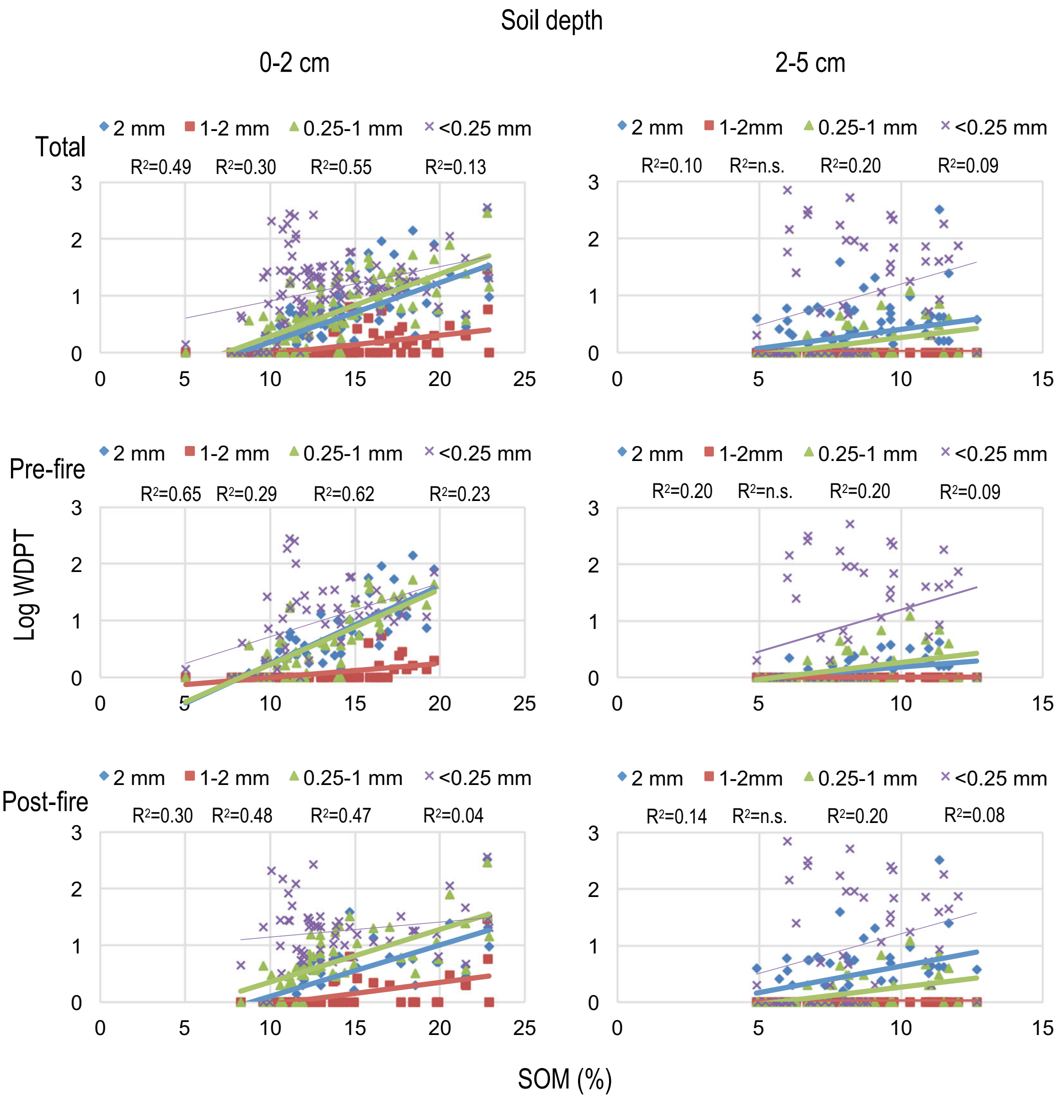


**Fig. 5** Multiple linear regression analyses ($R^2$) between SOM content (%) and Log WDPT for the different sieved soil fractions (<0.25, 0.25–1, 1–2 and <2 mm) of surface (0–2 cm) and subsurface (2–5 cm) soil samples. Analyses for the total pool of soil samples and for the pre and post-fire samples (*n*=252)

demonstrates that SOM amount is not the only factor inducing soil hydrophobicity.

The fire induced a slight increase on soil pH (Table 3), possibly due to ashes incorporation (Bodí et al. 2014). After the fire, AS also increased but only in half of the pooled samples. Nevertheless, the increase in AS was only significant beneath *Arbutus unedo* located on the SW slope (Table 3). Contrary to prior soil properties, $CaCO_3$ content showed a slight decrease after fire (Table 3). The results from logarithmic transformation of SWR (log WDPT) did not significantly correlate with pH, AS and $CaCO_3$ content.

## Discussion

### Natural soil water repellency

In the target shrubland SWR was present under natural conditions, ranging from wettable to strong severity according with the vegetation type. These findings are in accordance with results found on soils evolved from acidic bedrock (Jordán et al. 2008; Martínez-Zavala and Jordán-López 2009; Stoof et al. 2011), as well as on Luvisols and Leptosols developed in limestone bedrock (Mataix-Solera and Doerr 2004; Cerdà and Doerr 2007;

Arcenegui et al. 2008; Gimeno-García et al. 2011). Moreover, analyses from soil subsurface (2–5 cm), showed limited natural repellency only for the smallest soil fractions (<0.25 mm) (Figs. 3 and 4), which confirms that natural hydrophobicity tends to decrease with increasing soil depth as observed by other authors (Doerr et al. 2000; Mataix-Solera and Doerr 2004; Tessler et al. 2008), also in carbonated bedrock soils.

Slope aspect also seems to influence SWR persistence. On the SW slope in Podentes study site, the lack of a surface duff layer, the thin O horizon, and the smaller SOM content, which could be due to high SOM mineralization rate (Andreu et al. 2001; Tessler et al. 2008), may have led to the soil wettable properties. The absence of repellency, under these conditions agrees with the finding of Verheijen and Cammeraat (2007), Martínez-Murillo et al. (2013) and Bodí et al. (2013). These variables could explain differences in the surface SWR, at least in the entire (<2 mm) and in the 0.25–1 and <0.25 mm soil fractions beneath the *Quercus coccifera* and *Pistacia lentiscus* shrubs (Figs. 2, 3, and 4).

The similar bedrock and clay mineralogy within both slopes of Podentes study site highlight the importance of plant species output (above ground biomass, roots and litter) in SWR. Different shrub species release different substances and litter compounds, which affect SOM chemical composition and thus, SWR. Nevertheless, other authors have also reported the impact of clay mineralogy on spatio-temporal variation of SWR (Mataix-Solera et al. 2013). In Podentes, SWR did not correlate significantly with soil pH and $CaCO_3$ content, in contrast to other authors (Mataix-Solera et al. 2007; Jordán et al. 2008; Martínez-Zavala and Jordán-López 2009).

In the shrubland of Podentes, a natural SWR was more frequent in the finest soil fractions of the soil surface samples. Positive correlations between SOM and the finest aggregate soil fraction were also reported by other authors, as a result of (1) linking agents between soil micro-aggregates, such as hyphae and the root exudates (Boix-Fayos et al. 2001), and (2) differences in the inter-particle bonds of micro- and macro-aggregates, determined by the transient effects related to polysaccharides or fine humic polymeric substances in combination with clay particles and iron and aluminium complexes.

Since the high SWR frequency was observed in the finest soil fraction, despite its poor correlation coefficient with SOM amount, repellency seems to be more influenced by the SOM chemical composition resultant from different shrub vegetation than SOM content, reinforcing the results from Arcenegui et al. (2007) in alkaline soils, and De Blas et al. (2010) in acid soils. According to Verheijen and Cammeraat (2007), different wax and phenolic substances released by plant leaves, will be incorporated into soil aggregates (Boix-Fayos et al. 2001) and soil matrix (Mataix-Solera and Doerr 2004). This incorporation must influence the contribution of the finest soil aggregates fraction to the SWR. In Podentes study site, SWR was more frequent under *Arbutus unedo* species, which is due to the phenolic substances and wax composition in their leaves (Neinhuis and Barthlott 1997; Rotondi et al. 2003) that are transformed in litter and incorporated by the SOM into soil aggregates as binding agents (Boix-Fayos et al. 2001; Campo et al. 2014) and thus, influence the soil hydrophobic behaviour.

## Fire temperatures

Before the fire, fuel and soil moisture conditions (50 and 24 %, respectively) in the study area prevented high peak temperatures on the soil surface, which together with short residence time (Table 2), promoted a low fire impact on soil properties compared to other studies based on experimental fires (Gimeno-García et al. 2004). On the other hand, during Podentes prescribed fire the soil surface temperatures were similar to those obtained in an experimental fire in a shrubland in Central Portugal (45–188 °C), despite the higher fire front intensity (Stoof et al. 2013). Under this experimental fire, the quick fire spread led to short duration of elevated soil temperatures. In addition, the spatial variation of vegetation moisture also controlled the soil surface temperatures and its duration (Stoof et al. 2013).

In the Podentes fire, thermocouples buried at 2 cm depth did not reflect a fire front in subsurface soil, which may be due to (1) vegetation moisture conditions (Table 1), which provided a briskly burn of the shrub canopies, leading to a minimum heating of the underlying litter and soil layers, and (2) the presence of a duff layer, typical during low intensity prescribed fires, which prevents soils from reaching lethal temperatures for roots and biota (Valette et al. 1994).

## Fire effects on SWR

During the prescribed fire in Podentes, soil temperature was unable to destroy SWR. The averaged 189 °C at soil surface was below the temperature threshold of 220–300 °C to break down SWR, reported in studies elsewhere (Robichaud and Hungerford 2000; Zavala et al. 2010; Campo et al. 2014). In fact, the low intensity of the Podentes prescribed fire, intensified the natural SWR in surface and subsurface soil samples, particularly in the finest soil fractions (<0.25 and 0.25–1 mm), although pre-fire differences between shrub species were maintained (*Arbutus unedo* > *Pistacia lentiscus* ≈ *Quercus coccifera* > Bare soil).

Different litter composition supplied by shrub type and its partial combustion due to low fire severity, promotes an increase of the short-term repellency and its migration into deeper soil layers depth (5 cm depth). Hubbert et al. (2006) also reported an increasing post-fire SWR persistence with soil depth, which was partially attributed to the downward translocation of organic compounds released from litter and plant material. Letey (2001) showed the influence of temperature gradient over soil depth on the migration of hydrophobic compounds into deeper soil layers during a fire event. In contrast, Vadilonga et al. (2008), in Cambisols developed on calcareous bedrock, reported a modest decrease of SWR after a low-severity prescribed fire, due to the reduced pre-fire repellency and the short time of soil heating. However, Dlapa et al. (2013) also detected the highly aromatic and hydrophobic nature of ashes from fires with low combustion completeness, in turn influencing post-fire soil samples (Bodí et al. 2014).

It is plausible that water repellency is a result of the presence of fine, hydrophobic interstitial organic matter mainly in smallest soil aggregates, as suggested by Mataix-Solera and Doerr (2004) and other authors found in the <0.25 mm soil fraction (Arcenegui et al. 2008; Gimeno-García et al. 2011). In Podentes prescribed fire, the temperatures and its duration did not seem to affect significantly soil AS (Table 3), contrary to the finding from Arcenegui et al. (2008) (Table 3). The heating effects on the SOM of macro- and microaggregates were observed by Campo et al. (2011), in a Mediterranean carbonated soil. These authors found that when soil temperature reached 220 °C the composition of some lipids and lignin compounds increased in soil macro-aggregates, whereas in micro-aggregates the changes were observed on polysaccharides composition, possibly released from waxes and resins of burned shrub tissues. However, Malkinson and Wittenberg (2011) argued that the short-term hydrophobic properties generated during a fire are vegetation specific, and are probably due to the heating effects on the organic compound, highlighting the importance of testing the specific vegetation impact on spatial SWR variation.

## Next steps

In Mediterranean environments, more attention must be given to the mineralization/humidification processes, where slope aspect characteristics and vegetation composition could intensify changes on SOM composition and affect SWR and slope hydrology.

On the other hand, to confirm the hypothesis that the different hydrophobic soil behaviour must be related to the plant SOM and exudates, a detailed analysis of the SOM chemical composition on the different soil aggregates fractions is required to characterize the organic components involved in the formation of small soil aggregates beneath the different shrub species, as has been done for lipids by Lozano et al. 2013, humic substances and black carbon by González-Pérez et al. (2004) and, binding agents in soil aggregates by Campo et al. (2011).

Moreover, the fact that the post-fire regeneration mechanism of the shrub species investigated here is by a resprouter strategy (Paula and Pausas 2008) and also that natural SWR is present on soil, makes it feasible that the promoted SWR which is linked to litter supply could be a shrub strategy to avoid competitive seedling establishment under the canopies. The discussion established by Bochet et al. (2007) reinforced this idea. In accordance with this hypothesis, we ask if the natural and/or fire-enhanced SWR could be used as a new parameter in ecological models such as the ones developed by Mazzoleni et al. (2010). To test this idea, authors should stress the implementation of SWR as a new factor in ecological models and also, explore if a new methodological approach based on seeders and resprouters shrubs ecology should be implemented in SWR studies.

## Conclusions

1. Soils evolved on carbonated bedrock in sub-humid Mediterranean environments exhibited a strong to slight soil water repellency. SWR was influenced by vegetation type: *Arbutus unedo* > *Pistacia lentiscus* ≈ *Quercus coccifera* > Bare soil. The frequency of SWR tended to decrease with increasing soil depth.
2. The different wax and resins depending on the shrub species must have implications for the SWR persistence for the finer soil fractions. Thereby, the litter supplied by *Arbutus unedo* seems to be more hydrophobic than that supplied by the other shrub species. The results emphasize the importance of the chemical composition of the soil organic matter as a binding and SWR agent in the different soil aggregation fractions.
3. The high moisture content in the soil and vegetation prior to the prescribed fire, led to a low fire severity, which promoted negligible changes in soil properties. Nevertheless, the fire impact induced a slight increase in the persistence of the soil water repellency on the soil surface and the migration of hydrophobic substances into deeper soil layers (2–5 cm).
4. SWR was mainly observed in the finest soil fractions (<0.25 and 1–0.25 mm) in both pre- and post-fire conditions. This was more noticed in the NE slope than in the SW slope. Depending on its aspect; the finest soil fractions from the NE slope showed greater SWR than soils from the SW slope. Immediately after the prescribed fire, the persistence and frequency of SWR also increased in the finest fractions.

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## References

Andreu V, Imeson AC, Rubio JL (2001) Temporal changes in soil aggregates and water erosion after a wildfire in Mediterranean pine forest. Catena 44:69–84

Arcenegui V, Mataix-Solera J, Guerrero C, Zornoza R, Mayoral AM, Morales J (2007) Factors controlling the water repellency induced by fire in calcareous mediterranean forest soils. Eur J Soil Sci 58:1254–1259

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

Bisdom EBA, Dekker LW, Schoute JFT (1993) Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. Geoderma 56:105–118

Bochet E, García-Fayos P, Alborch B, Tormo J (2007) Soil water availability effects on seed germination account for species segregation in semiarid roadslopes. Plant Soil 295:179–191

Bodí MB, Muñoz-Santa I, Armero C, Doerr SH, Mataix-Solera J, Cerdà A (2013) Spatial and temporal variations of water repellency and probability of its occurrence in calcareous Mediterranean rangeland soils affected by fires. Catena 108:14–25

Bodí MB, Martin DA, Balfourd VN, Santín C, Doerr SH, Pereira P, Cerdà A, Mataix-Solera J (2014) Wildland fire ash: production, composition and eco-hydro-geomorphic effects. Earth Sci Rev 130:103–127

Boix-Fayos C, Calvo-Cases A, Imeson AC, Soriano-Soto MD (2001) Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. Catena 44:47–67

Campo J, Gimeno-García E, Andreu V, González-Pelayo O, Rubio JL (2008) Aggregation of under canopy and bare soils in a Mediterranean environment affected by different fire intensities. Catena 74(3):212–218

Campo J, Nierop KGJ, Cammeraat E, Andreu V, Rubio JL (2011) Application of pyrolysis-gas chromatography/mass spectrometry to study changes in the organic matter of macro- and microaggregates of a Mediterranean soil upon heating. J Chromatogr A 1218:4817–4827

Campo J, Gimeno-García E, Andreu V, González-Pelayo O, Rubio JL (2014) Cementing agents involved in the macro- and microaggregation of a Mediterranean shrubland soil under laboratory heating. Catena 113:165–176

Cerdà A (1998) Soil aggregate stability under different Mediterranean vegetation types. Catena 32(2):73–86

Cerdà A, Doerr SH (2007) Soil wettability, runoff and erodibility of major dry-mediterranean land use types on calcareous soils. Hydrol Process 21:2325–2336

De Blas E, Rodríguez-Alleres M, Almendros G (2010) Speciation of lipid and humic fractions in soils under pine and eucalyptus forest in northwest Spain and its effect on water repellency. Geoderma 155:242–248

Dekker LW, Ritsema CJ (1994) How water moves in a water repellent sandy soil. 1. Potential and actual water repellency. Water Resour Res 30:2507–2517

Dlapa P, Bodí MB, Mataix-Solera J, Cerdà A, Doerr SH (2013) FT-IR spectroscopy reveals that ash water repellency is highly dependent on ash chemical composition. Catena 108:35–43

Doerr SH, Thomas AD (2000) The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. J Hydrol 231–232:134–147

Doerr SH, Shakesby RA, Walsh RPC (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth Sci Rev 51:33–65

Doerr SH, Dekker LW, Shakesby RA, Ritsema CJ, Bryant R (2002) Water repellency of soils: the influence of ambient relative humidity. Soil Sci Soc Am J 66:401–405

Doerr SH, Douglas RC, Morley CP, Mullinger NJ, Bryant R, Shakesby RA (2005) Effects of heating and post-heating equilibration times on soil water repellency. Aust J Soil Res 43:261–267

Fernandes PM, Botelho HS (2003) A review of prescribed burning effectiveness in fire hazard reduction. Int J Wildland Fire 12: 117–128

Gimeno-García E, Andreu V, Rubio JL (2004) Spatial patterns of soil temperatures during experimental fires. Geoderma 118: 17–38

Gimeno-García E, Pascual JA, Llovet J (2011) Water repellency and moisture spatial variations under *Rosmarinus officinalis* and *Quercus coccifera* in a Mediterranean burned soil. Catena 85:48–77

González-Pelayo O, Andreu V, Gimeno-García E, Campo J, Rubio JL (2010a) Effects of fire and vegetation cover on hydrological characteristics of a Mediterranean shrubland soil. Hydrol Process 24:1504–1513

González-Pelayo O, Andreu V, Gimeno-García E, Campo J, Rubio JL (2010b) Rainfall influence on plot-scale runoff and soil loss from repeated burning in a Mediterranean-shrub ecosystem, Valencia, Spain. Geomorphology 118:444–452

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter—a review. Environ Int 30(6):855–870

Hubbert KR, Preisler HK, Wohlgemuth PM, Graham RC, Narog MG (2006) Prescribed burning effects on soil physical properties and soil water repellency in a steep chaparral watershed, southern California, USA. Geoderma 130:284–298

Imeson AC, Verstraten JM, van Mulligen EJ, Sevink J (1992) The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest. Catena 19:345–361

IUSS Working Group WRB (2014) World Reference Base for Soil Resources (2014) International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome

Jackson ML (1958) Soil chemical analysis. Prentice Hall Inc, London

Johansen MP, Hakonson TE, Whicker FW, Breshears DD (2003) Pulsed redistribution of a contaminant following forest fire. J Environ Qual 32:2150–2157

Jordán A, Martínez-Zavala L, Bellinfante N (2008) Heterogeneity in soil hydrological response from different land cover types in southern Spain. Catena 74:137–143

Kawamoto K, Moldrup P, Komatsu T, de Jonge LW, Oda M (2007) Water repellency of aggregate size fractions of a volcanic ash soil. Soil Sci Soc Am 71(6):1658–1666

Letey J (2001) Causes and consequences of fire-induced soil water repellency. Hydrol Process 15:2867–2875

Lozano E, Jiménez-Pinilla P, Mataix-Solera J, Arcenegui V, Bárcenas GM, González-Pérez JA, García-Orenes F, Torres MP, Mataix-Beneyto J (2013) Biological and chemical factors controlling the patchy distribution of soil water repellency among plant species in a Mediterranean semiarid forest. Geoderma 207–208:212–220

Maia P, Pausas JG, Arcenegui V, Guerrero C, Pérez-Bejarano A, Mataix-Solera J, Varela MET, Fernandes I, Pedrosa ET, Keizer JJ (2012) Wildfire effects on the soil seed bank of a maritime pine stand—the importance of fire severity. Geoderma 191:80–88

Malkinson D, Wittenberg L (2011) Post fire induced soil water repellency-modeling short and long-term processes. Geomorphology 125(1):186–192

MAPA (1986) Métodos oficiales de análisis (suelos). Ministerio de Agricultura, Pesca y Alimentación. Madrid, 531

Martínez-Murillo JF, Gabarrón-Galeote MA, Ruiz-Sinagoga JD (2013) Soil water repellency in Mediterranean rangelands under contrasted climatic, slope and patch conditions in southern Spain. Catena 110:196–206

Martínez-Zavala L, Jordán-López A (2009) Influence of different plant species on water repellency in mediterranean heatland soils. Catena 76:215–223

Mataix-Solera J, Doerr SH (2004) Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forest in southeastern Spain. Geoderma 118:77–88

Mataix-Solera J, Arcenegui V, Guerrero C, Mayoral AM, Morales J, González J, García-Orenes F, Gómez I (2007) Water repellency under different plant species in a calcareous forest soil in a semiarid mediterranean environment. Hydrol Process 21: 2300–2309

Mataix-Solera J, Arcenegui V, Tessler N, Zornoza R, Wittenberg L, Martínez C, Caselles P, Pérez-Bejarano A, Malkinson D, Jordán MM (2013) Soil properties as key factors controlling water repellency in fire-affected areas: evidences from burned sites in Spain and Israel. Catena 108:6–13

Mazzoleni S, Bonanomi G, Giannino F, Incerti G, Dekker SC, Rietkerk M (2010) Modelling the effects of litter decomposition on tree diversity patterns. Ecol Model 221:2784–2792

Neinhuis C, Barthlott W (1997) Characterization and distribution of water-repellent, self-cleaning plant surfaces. Ann Bot 79: 667–677

Paula S, Pausas JG (2008) Burning seeds: germinative response to heat treatments in relation to resprouting ability. J Ecol 96: 543–552

Prats SA, MacDonald LH, Monteiro M, Ferreira AJD, Coelho COA, Keizer JJ (2012) Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. Geoderma 191:115–124

Primo-Yufera E, Carrasco JM (1973) Química Agrícola I. Suelos y Fertilizantes. Alhambra, Madrid

Regalado CM, Ritter A (2005) Characterizing water dependent soil repellency with minimal parameter requirement. Soil Sci Soc Am 69(6):1955–1966

Robichaud PR, Hungerford RD (2000) Water repellency by laboratory burning of four northern Rocky mountain forest soils. J Hydrol 231–232:207–219

Rotondi A, Rossi F, Asunis C, Cesaraccio C (2003) Leaf xeromorphic adaptations of some plants of coastal Mediterranean macchia ecosystem. J Mediterr Ecol 4(3-4): 25–35

Roy JL, McGill WB (2000) Flexible conformation in organic matter coatings: an hypothesis about soil water repellence. Can J Soil Sci 80:143–152

Santos JM, Verheijen FGA, Wahren FT, Wahren A, Feger KH, Bernard-Jannin L, Rial-Rivas ME, Keizer JJ, Nunes JP (2013) Soil water repellency dynamics in pine and eucalypt plantations in Portugal—a high resolution time series. Land Degrad Dev. doi:10.1002/ldr.2251

Shakesby RA, Bento CPM, Ferreira CSS, Ferreira AJD, Stoof CR, Urbanek E, Walsh RPD (2015) Impacts of prescribed fire on soil loss and soil quality: an assessment based on an experimentally-burned catchment in central Portugal. Catena 128:278–293

Stoof CR, Moore D, Ritsema CJ, Dekker LW (2011) Natural and fire-induced soil water repellency in a Portuguese shrubland. Soil Sci Soc Am J 75(6):2283–2295

Stoof CR, Moore D, Fernandes PM, Stoorvogel JJ, Fernandes RES, Ferreira AJD, Ritsema CJ (2013) Hot fire, cool soil. Geophys Res Lett 40:1–6

Tessler N, Wittenberg L, Malkinson D, Greenbaum N (2008) Fire effects and short-term changes in soil water repellency—Mt. Carmel, Israel. Catena 74:185–191

Úbeda X, Lorca M, Outeiro LR, Bernia S, Castellnou M (2005) Effects of prescribed fire on soil quality in Mediterranean grassland (Prades Mountains, north-east Spain). Int J Wildland Fire 14:379–384

Vadilonga T, Úbeda X, Germann PF, Lorca M (2008) Effects of prescribed burnings on soil hydrological parameters. Hydrol Process 22:4249–4256

Valette J, Gomendi V, Marechal J, Houssard C, Guillon D (1994) Heat transfer in the soil during very low-intensity experimental fires: the role of duff and soil moisture content. Int J Wildland Fire 4(4):225–237

Verheijen FGA, Cammeraat LH (2007) The association between three dominant shrub species and water repellent soil, along a range of soil moisture contents in semi-arid Spain. Hydrol Process 21:2310–2316

Vilén T, Fernandes PM (2011) Forest fires in Mediterranean countries: $CO_2$ emissions and mitigation possibilities through prescribed burning. Environ Manag 48:558–567

Zavala LM, Granged AJP, Jordán A, Bárcenas-Moreno G (2010) Effect of burning temperature on water repellency and aggregate stability in forest soils under laboratory conditions. Geoderma 158:366–374