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Intensity and persistence of water repellency at different soil moisture contents and depths after a forest wildfire

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Abstract: The Mediterranean mixed coniferous and broad-leaved forest of Moarda (Palermo) was affected by a large wildfire in summer 2020. In spring 2021, burned and unburned loam soil sites were sampled and the water drop penetration time (WDPT) and ethanol percentage (EP) tests applied to assess the influence of wetting-drying processes and soil water content on post-fire soil water repellency (SWR) as well as its vertical distribution. According to the WDPT test, the surface layer of the natural unburned soils was severely hydrophobic at intermediate soil water contents roughly corresponding to wilting point and SWR reduced either for very dry conditions (air- or oven-dried conditions) or wetter conditions close to field capacity. For these soils, EP test yielded results in agreement with WDPT. An influence of the wetting/drying cycle was detected as, for a given soil water content, WDPT was generally higher for the drying than the wetting process. The surface of burned soils was always wettable independently of the soil water content. The vertical distribution of SWR was modified by wildfire and the maximum hydrophobicity layer, that was located at the surface of the unburned soils, moved to a depth of 2–4 cm in the soils of burned sites. The results confirmed that wildfire can induce destruction of soil water repellency (SWR) naturally occurring at the surface of forest soils and create a shallow hydrophobic layer that may increase overland flow and erosion risk.

Keywords: Wildfire; Soil water repellency; Water drop penetration time test; Ethanol percentage test.

INTRODUCTION

Wildfire induced soil water repellency (SWR) can increase landscape’s vulnerability to extreme flooding and erosion events (DeBano, 2000). Combustion of the surface organic material (litter and duff) can create volatile material with hydrophobic properties that moves downward into the soil profile and condenses on cooler soil particles beneath the surface (Doerr et al., 2000). Intense water repellency is formed when soil is heated to temperatures between 176 and 204 °C but temperatures of at least 250 °C are necessary to fix the translocated substances (DeBano, 1981). Higher temperatures (above 270–300 °C) destroy substances responsible for water repellency (Doerr et al., 2000). Water repellency occurred at shallow depths (10–20 mm) for low heat treatment (< 150 °C) whereas higher temperatures eliminated SWR or, occasionally, moved hydrophobic substances to deeper depths (Robichaud and Hungerford, 2000). Burning thus can also induce destruction of naturally high background SWR (Doerr et al., 2006) and create a non-continuous hydrophobic layer that is generally parallel to, and within the first centimetres of, the mineral soil surface (Chen et al., 2020; DeBano, 2000; Doerr et al., 1998; Tessler et al., 2008). During a rain event, the thin wettable soil layer on the surface quickly becomes saturated. The water, which is hindered by the subsurface water repellent soil layer, cannot infiltrate deeper into the soil profile and becomes excess overland flow that easily entrains and carries the saturated soil downward (Doerr et al., 2006).

Soil water repellency, whether naturally occurring or fire induced, is not a stable phenomenon. Studying SWR is a complex task because this phenomenon depends on many factors, including fire severity, soil temperature gradient, vegetation type, fuel amount, soil texture, quantity and chemical composition of soil organic matter (e.g., DeBano, 1981; Fer et al., 2016; Jiménez-Morillo et al., 2017; Mao et al., 2015; Tessler et al., 2008). Consequently, SWR can show a noticeable spatial variability, even over short distances (e.g., Dekker et al., 2009; Oostindie et al., 2016; Wallach et al., 2005). Moreover, SWR can change substantially with time, also as a consequence of variations in soil water content (de Jonge et al., 1999; Dekker et al., 2001; Madsen et al., 2011; Plaza-Álvarez et al., 2018). Different investigations have reported a decrease in SWR a few weeks or even days following burning (Hubbert and Oriol, 2005; Johnson et al., 2005; Keizer et al., 2008; Malvar et al., 2016) even in the dry season (Tessler et al., 2008). From various investigations also conducted in Mediterranean forests in Italy and Spain, Doerr et al. (2009), concluded that wildfire induced SWR should generally be expected to break down within a few months to a couple of years. Tinebra et al. (2019) suggested that temporal changes in SWR could depend on the severity of the wildfire. SWR appeared to vanish one year after the passage of the fire when its severity was low or moderate but persisted, or even enhanced, in severely burned zones.

Dry soils are generally thought to exhibit the highest level of SWR whereas, above a critical moisture content, soils appear to be wettable (Dekker and Ritsema, 1994). The concept of critical moisture threshold was revised by Dekker et al. (2001), who suggested that instead of a distinct threshold, a soil moisture transition zone exists in which soils may or may not be repellent. In contrast with the notion that water repellency is most strongly expressed in dry soils, there are several experimental evidences that when approaching very dry conditions, SWR may undergo reduction rather than continued enhancement (de Jonge et al., 1999; Doerr and Thomas, 2000; Hurraß and Schaumann, 2006; Regalado and Ritter, 2005). As a matter of fact, the relationship between water repellency and moisture content is still not completely understood (Hunter et al., 2011).

Sampling a forest soil a certain time after the wildfire implies accounting for natural wetting-drying cycles that may influence the SWR assessment as, for similar soil moisture conditions, different results could be obtained. It is well assessed that the processes determining reestablishment of SWR after burning, including plant litter decaying (Buczko et al., 2002), root activity (Doerr et al., 1998), or activity of fungi and other soil microorganisms (Doerr et al., 2000; Rillig, 2005), are all influenced by soil moisture regime. For example, Novák et al. (2009) found that the persistence of SWR after heating a sandy soil to 250 °C was influenced by the time of sampling with extreme SWR when the soil was sampled in a hot and dry spell and slightly or no SWR when the soil was sampled after a wet spell. However, to the best of our knowledge, the influence of the wetting-drying process on the assessment of the relationship between SWR and soil water content has been poorly investigated for fire affected soils in Mediterranean environment.

The water drop penetration time (WDPT) test has been diffusely applied, either in the field or in the laboratory, to quantify SWR since the experiment is easy and reasonably rapid (Doerr, 1998; Letey et al., 2000; Watson and Letey, 1970). The WDPT is a measure of the time required for the contact angle to change from its original value, which is greater than 90° in a hydrophobic soil, to a value approaching 90° (Cerdà and Doerr, 2007; Letey et al., 2000). Therefore, the WDPT test yields a measure of persistence of SWR whereas severity of SWR can be assessed by using different mixtures of water and ethanol. With the ethanol percentage (EP) test, the severity of SWR is associated to the concentration (or liquid–air surface tension) of the aqueous ethanol solution that enters the soil in approximately 5 s (Letey et al., 2000). Overall, the WDPT technique is considered mostly able to discriminate between hydrophobic and wettable soil conditions but less suitable for intermediate conditions in which infiltration is slowed but not impeded at all as in the case of sub-critical water repellency (Alagna et al., 2019; Ebel and Moody, 2013; Tillman et al., 1989). Despite this limitation, the WDPT test is more rapid and straightforward than techniques based on the use of ethanol as infiltrating liquid. Thus, it still remains the preferred option, especially for intensive field investigations in remote areas (Dekker et al., 2009). An unequivocal link between WDPT data and the spatial distribution of the wildfire severity was found among others by Gordillo-Rivero et al. (2014), Tessler et al. (2008) and Tinebra et al. (2019).

The current study was conducted with the aim to explore the characteristics of soil water repellency one year after a wildfire in a Mediterranean forest. Specifically, some open issues in the existing literature were investigated: 1) how SWR persistence and intensity in natural and severely burned soils is affected by soil water content; 2) whether SWR assessment is influenced by the sample type and its possible reuse; 3) how wetting-drying process influence SWR, and 4) how wildfire modifies the vertical distribution of SWR in forest soils.

MATERIALS AND METHODS

Site description and soil sampling

Investigation was carried out in the Moarda forest (11 km south of Palermo, Sicily) that was affected by a large wildfire on August 30th, 2020. The wildfire affected over 825 ha of the forested areas that included both native broad-leaved species (e.g., *Quercus ilex*) and exotic coniferous species (e.g., *Pinus halepensis*, *Cupressus sempervirens*) associated with shrubs such as *Juniperus oxycedrus* and *Cistus sp*. Four sites were selected in a south facing hillslope that was planted 35–40 years ago to re-naturalize a degraded site (Figure 1). Two sites (P1 and P2) were established within the area that was delimitated by the Sicilian Civil Protection Agency as affected by the 2020 wildfire; two sites were established in the nearby of those sites but outside the fire affected area (Table 1).

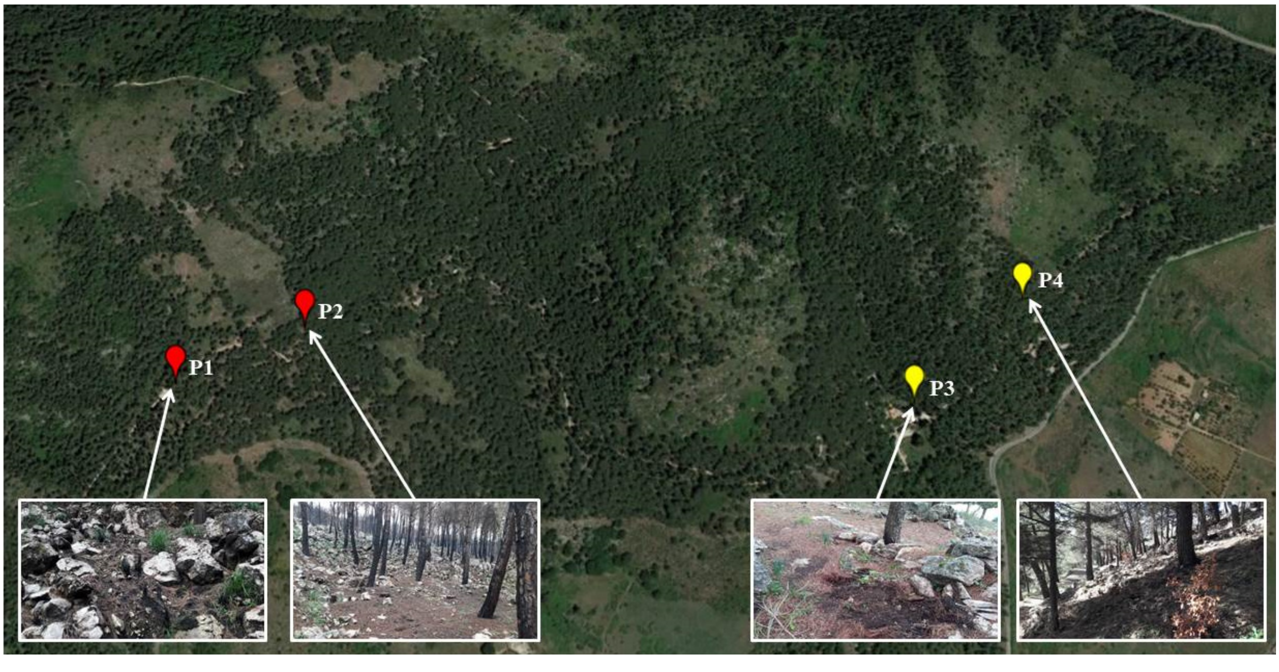

Fig. 1. Location of the studied sites at the Moarda Forest (P1 and P2 fire-affected sites, P3 and P4 natural sites) (from Google Earth, image acquired on June 2020 before the wildfire occurrence).

Table 1. Location, characteristics and fire severity classification of the sampled sites at the Moarda forest.

	Site P1	Site P2	Site P3	Site P4
Coordinates UTM	33S 0350947 4210367	33S 0351131 4210446	33S 0352030 4210310	33S 0352205 4210460
Elevation (m a.s.l.)	916	877	813	815
Exposure	S-E	S-E	S	S-E
Slope (m m^{-1})	0.465	0.250	0.364	0.652
Tree species	*Cedrus*, *Cupressus sempervirens*, *Pinus halepensis*	*Pinus halepensis*	*Cedrus*, *Cupressus sempervirens*, *Pinus halepensis*	*Pinus halepensis*
Fire severity	Moderate or severe surface burn	Moderate or severe surface burn	Unburned/Scorched	Unburned/Scorched

Trees at sites P1 and P2 showed canopy cover partly killed, but needles not totally consumed; some logs were charred. The undergrowth plants were charred but the charring of the soil organic layer was limited to a few mm depth. According to classification proposed by Keeley (2009), the wildfire can be considered moderate or severe at these sites. Sites P3 and P4 were classified as unburned even if the canopy suffered by heat radiation with some stems scorched. Soil organic layer was largely intact even if randomly patches of black ashes were detected probably determined by previous low severity wildfires.

In spring 2021, the surface layer was sampled after removing the new undecomposed litter. In the burned sites, the ash was maintained in situ. At each site, six undisturbed soil cores were collected into 8 cm diameter by 5 cm height cylindrical stainless steel samplers that were gently pushed from the surface down into the soil profile while removing the soil outside to limit sample disturbance. The soil cores were sealed into plastic sheets to avoid evaporation and weighted within 6 h to determine volumetric soil water content at the time of sampling. Then, they were stored for approximately three months at 4 °C to limit biological activity until execution of WDPT tests according to the procedure described below.

Scrubbed soil samples were collected in the surface layer (approximately 2 cm thick) for determination of WDPT and EP at different water contents. Soil was air dried for 15 days in laboratory under controlled temperature conditions (22 ± 2 °C) and then gently crushed and sieved through a 4-mm mesh sieve.

Soil bulk density, texture and organic matter content

The dry bulk density, BD (Mg m^{-3}), of the 0–5 cm surface layer was determined by oven drying the soil collected in the 8 cm diameter samplers (approximately 0.25 L volume). The volume fraction of particles having diameter d > 2 mm, f_c (m^3 m^{-3}), was recorded and the dry bulk density of the fine soil fraction, BD_f (Mg m^{-3}), determined excluding the contribution of coarse particles. The initial soil water content of the fine soil fraction, θ_{if} (m^3 m^{-3}), was determined accordingly. The particle size distribution was determined by the hydrometer method for particles having diameters, d < 74 μm and by sieving for particles with $74 \leq d \leq 2000$ μm following H_2O_2 pretreatment to eliminate organic matter and clay deflocculation using sodium hexametaphosphate and mechanical agitation (Gee and Or, 2002). A total of 14 particle size fractions were determined that allowed to estimate mean diameter, d_g, and standard deviation of particle diameter, σ_g, according to Shirazi and Boersma (1984). The clay, Cl, silt, Si, and sand, Sa, percentages were determined according to the USDA classification. Given the relatively high percentage of organic matter in the forest soils, the total organic matter, OM, content was assessed by the loss of ignition method (Nelson and Sommers, 1996).

Influence of soil moisture content on water repellency

Sieved soil samples were prepared into metallic trays having dimensions of 10.5 cm x 17.0 cm by levelling and compacting to a height of approximately 1 cm a given amount of soil to reproduce a bulk density equal to that measured on undisturbed soil samples. For each soil, two samples were prepared that represented different initial soil water contents, i.e. air-dried condition and oven-dried condition. In the latter case, the sample was dried for 24 h at 105 °C and then cooled for 2 h in a silica gel desiccator before conducting the droplet tests, i.e. WDPT and EP.

Starting from oven- or air-dried conditions, higher soil moisture contents were established in successive increments by spraying 10 g of distilled water on the surface of each sample after the end of the droplet tests. Following each water application, the samples were covered by plastic film and left to re-equilibrate at the laboratory temperature (22 ± 2 °C) for 24 h before conducting the successive droplet tests. The trays were weighted at each step to determine the gravimetric soil water content, U (g g^{-1}) by the thermogravimetric method at the end of the sequence.

To detect possible effects of the process applied to modify the soil moisture on SWR assessment, similar experiments were conducted in pressure plate extractors for a draining process. Three 10.5 cm x 17.0 cm soil samples for each soil were packed on porous ceramic plates and equilibrated into pressure plate apparatus (Soilmoisture Equipment Corp., Santa Barbara, CA) at absolute values of matric potential, ψ = 10, 100 and 1500 kPa. At each matric potential value, the soil water content was determined by the thermogravimetric method after subtracting the total weight of water added for the WDPT test. After oven drying at 105 °C, each sample was reconstructed and subject to a new drainage process into the pressure plate apparatus at the same matric potentials. This second process was applied to detect possible effect of the reuse of the same specimen on the SWR. Reuse of the same material for laboratory experiments has rarely been investigated in soil physics and hydrology but the few available data seem to suggest that stability of the results could not be guaranteed when a given soil mass is used more times (Bagarello et al., 2022).

The water drop penetration time (WDPT) test involved placing from 12 to 20 drops of distilled water, each having a 60 ± 5 μL volume, on the sample surface and recording the time for each droplet to infiltrate. Drops were placed according to a square grid of 20 mm × 20 mm by micropipette from a height of 10 mm to avoid excessive kinetic energy. According to previous investigations, infiltration time was recorded up to 3600 s (Tinebra et al., 2019) and longer infiltration times were not considered as water evaporation processes likely became non-negligible even under laboratory controlled conditions. The SWR classification suggested by Bisdom et al. (1993) was used to classify soils according to different WDPTs, that is < 5 s (wettable, W), 5–60 s (slightly hydrophobic, SLH), 60–600 s (strongly hydrophobic, STH), 600–3600 s (severely hydrophobic, SEH) and >3600 s (extremely hydrophobic, EXH). The repellency class was determined for each of the 12 to 20 droplets and the frequency distribution of the repellency classes for each established soil moisture value was calculated.

The ethanol percentage (EP) test was carried out using several mixtures of 95% denatured ethanol and deionized water having ethanol concentrations (by volume) from 1% to 36% (Letey et al., 2000). Six droplets of each mixture were placed on the sample surface according to the same arrangement followed for WDPT test and the time for infiltration recorded. Following a procedure similar to Badía et al. (2013), the EP value was calculated by linear interpolation between the two average infiltration times (i.e., higher and lower that 5 s) as the concentration of the ethanol mixture that infiltrates in exactly 5 s (de Jonge et al., 1999). According to Doerr (1998), the following classification for EP was assumed: < 3% hydrophilic or wettable (W), 3–5% slightly hydrophobic (SLH); 5–8.5% moderately hydrophobic (MOH); 8.5–13% strongly hydrophobic (STH); 13–24% very strongly hydrophobic (VSH); 25–36% extremely hydrophobic (EXH).

Vertical extent of soil water repellency

Vertical distribution of soil water repellency was investigated by the WDPT test conducted at different soil depths of the 8 cm diameter by 5 cm height undisturbed soil cores. Previously cooled soil cores were equilibrated under laboratory temperature conditions for 24 h and then weighted for determination of volumetric water content at the time of test execution. Ten drops were applied on the soil surface after exposure and their infiltration time was measured. The same procedure was applied at other four depths, i.e., z = 1, 2, 3 and 4 cm for each core. To allow measurements on deeper layers, soil was pressed out of the core from the bottom by a plug and the upper layer was removed with a knife (Bagarello et al., 2020; Wallach et al., 2005). The experiments failed for three soil cores at z = 3 cm depth and for 14 soil cores out of the total 24 at z = 4 cm due to the rupture of the soil sample while pressing out.

RESULTS AND DISCUSSION

Soil bulk density, texture and organic matter content

The soil at sampling sites was classified as loam but the relative amounts of sand, silt and clay changed among the four sampled sites with the sites characterized by a higher steepness (sites P1 and P4) that showed a larger sand content and a lower clay content (Table 2). Silt content was relatively uniform among sites (Si = 41.3 – 49.4%) and, for a given site, among the replicate samples as detected by the standard deviation (SD) that was lower than 5.3% (Table 2). Variability of sand and clay content was particularly marked for the samples collected at site P2 (SD = 8.3 and 9.1%, respectively) and it was attributed to the presence of variable amounts of ash in the upper soil. The mean particle diameter varied according to the different particle size distributions with d_g values that ranged from 0.018 to 0.042 mm thus differing by a factor of 2.3 among the four loam soils. The standard deviation of particle diameter σ_g was largest for site P2 that showed the most sorted particle size distribution and lowest for sites P3 and P4 that showed a prevalent texture class, i.e. Si and Sa respectively.

As expected, the organic matter content of the considered forest soils was generally high but comparable with similar studies conducted on forest soils (Lozano-Baez et al., 2020). The severely fire-affected site P1 and the unaffected site P3 showed extreme values of OM (Table 2). The organic matter content of fire-affected soils depends on the combustion temperature with lower OM values found in soils that were exposed to higher fire temperature (Negri et al., 2021; Stoof et al., 2010). However, both fire temperature and duration may affect volatilization of organic matter and contrasting results were found in literature with OM content in soils affected by low or moderate fire severity that were either lower or larger than the unburned one (Chen et al., 2020). The presence of ash and/or char can also affect soil OM given that the ash contains only a fraction of the organic matter present in the less-combusted char. A possible explanation for the relatively high OM content of soil P2 is that unpredictable percentages of char, that was visible at the surface of the burned sites, were accidentally mixed with soil during collection thus determining OM values comparable to that found in the unaffected site P4.

The volume fraction of coarse fragments was relatively low (average $f_c = 0.02 - 0.06$ m^3 m^{-3}) and, for each site, greatly variable among the replicate samples as detected by SD values that ranged from 0.79 to 1.46 times the corresponding mean value (Table 2). Sites P1 and P4, that were characterized by higher sand content (Sa = 40.6 and 46.5%, respectively), showed the highest values of mean coarse fraction volumes (f_c = 0.058 and 0.050 m^3 m^{-3}, respectively). The presence of coarse fragments affected determination of soil bulk density as the BD values determined on the total sample volume were on average 1.10 times higher than the BD_f determined considering only the volume of fine fraction. In particular, mean BD values ranged from 0.728 to 0.831 Mg m^{-3} whereas mean BD_f values ranged from 0.609 to 0.802 Mg m^{-3} and the differences ($BD - BD_f$) increased at increasing f_c (R^2 = 0.97). Spatial variability of both BD and BD_f was high as detected by the SD to mean ratios that were generally over the limit of 15% considered acceptable for this soil property (Warrick, 1998).

The volumetric soil water content at the time of sampling was calculated for the fine soil fraction on the reasonable hypothesis that coarse fragments did not retain water. Mean θ_i values ranged from 0.118 m^3 m^{-3} for site P1 to 0.194 m^3 m^{-3} for site P2 with a high spatial variability of the samples collected within the same site.

Influence of soil moisture content on water repellency

Depending on the considered soil, gravimetric soil water content, U, after air drying ranged from 0.049 to 0.108 g g^{-1}. Following successive water applications, U increased up to 0.55–0.69 g g^{-1}. After equilibration in pressure plate apparatus, U ranged from 0.98 – 1.00 g g^{-1} at matric potential of 10 kPa to 0.24 – 0.49 g g^{-1} at matric potential of 1500 kPa. Volumetric soil water content, θ (m^3 m^{-3}), corresponding to each U value was calculated according to the mean bulk density of the fine fraction of the different soils (Table 2).

The WDPT values under dry condition were not influenced by the initial drying procedure (i.e., air or oven drying) and, despite the higher initial volumetric water content of the air-dried samples, the median infiltration time was the same, or nearly the same, for soil of sites P1, P2 and P4 (Table 3). None of these soils exhibited repellency at air- or oven-dried conditions being individual WDPT values always lower than 5 s. Under the same initial conditions, the soil of site P3 was classified as strongly hydrophobic (STH) given the median drop infiltration time was 362 s for oven-dried and 406 s for air-dried conditions (Table 3). Moreover, 58% and 67% of droplets, respectively, fell in the STH class (Figure 2). Oven drying of soil samples sometimes resulted in much higher SWR levels (Franco et al., 1995; Ma'shum and Farmer, 1985) and Doerr (1998) suggested that, in the experimental estimation of SWR, soil samples should be air-dried rather than oven-dried in order to avoid the possibility of enhancing their degree of hydrophobicity. For the considered soils, the two treatments (i.e., air- or oven-drying) did not affect the assessment of SWR given soils that were wettable after air-drying remained the same after heating at 105 °C. Similarly, for soil P3 classification of SWR did not change and also the frequency distribution of WDPT values was very similar between the two treatments (Table 3, Figure 2). A similar result was observed by King (1981) who found SWR was essentially unchanged as soil moisture contents were increased from oven-dry to air-dry.

Successive wetting did not change wettability of soils P1 and P2 as the median WDPT was equal to 1 s for water content up to 0.22 – 0.23 g g^{-1} and the maximum water droplet infiltration time was 4 s (data not shown). It was concluded that soils P1 and P2 were permanently wettable at the soil surface and, thus, they were excluded from the subsequent ethanol percentage experiments aimed at assessing SWR intensity. It is probable that high fire temperatures caused combustions of hydrophobic substances and the ash that remained on the soil surface contributed to increase soil wettability (Bodí et al., 2011; Cerdà and Doerr, 2008).

Independently of the wetting or drying procedure, the water repellency of unburned sites P3 and P4 depended on the soil moisture content and clearly exhibited a maximum SWR at intermediate θ values (i.e., $\theta = 0.25$ m^3 m^{-3} for P3 and $\theta = 0.17$ m^3 m^{-3} for P4) whereas for soil moisture conditions close to field capacity ($\psi = 10$ kPa) SWR was slight or null (Figure 2). Doerr et al. (2006) found that the maximum moisture content for which extreme water repellency (WDPT > 3600 s) occurred was 20% v/v for loamy soils. Furthermore, they observed a significant decrease or even the elimination of repellency under dry conditions that casted doubt on the general applicability of a lower moisture threshold for SWR. A single-peak curve with maximum water repellence at intermediate U values in the range 0.04–0.10 g g^{-1}, and wettable conditions for soil water content near zero was also reported by de Jonge et al. (1999) for sandy soils in Denmark. They also showed that the finer fractions were water repellent up to soil water contents as high as 0.30 to 0.40 g g^{-1} thus explaining why the maximum SWR occurred at higher moisture contents for the finer soil P3. Our results are also consistent with the finding of Doerr et al. (2006) as below a threshold for which the maximum repellency occurs, soil moisture may be not a reliable predictor for repellency persistence given both water repellent (soil P3) and wettable conditions (soil P4) may occur (Figure 2).

Table 2. Percentage of clay (*Cl*), silt (*Si*) and sand (*Sa*) according to USDA classification, mean particle diameter (d_g), standard deviation of particle diameter (σ_g), organic matter content (*OM*), volume of coarse fraction (f_c), bulk density of the total soil sample (*BD*) and of fine fraction (BD_f) and initial moisture content (θ_i) for the soils of the considered sampling sites. Values in parenthesis are standard deviations (sample size $N = 4$ for soil texture, $N = 6$ for soil bulk density and initial moisture content).

	Site P1	Site P2	Site P3	Site P4
***Cl* (%)**	17.7 (1.4)	24.5 (9.1)	18.8 (1.5)	12.2 (2.9)
***Si* (%)**	41.8 (1.1)	43.4 (2.1)	49.4 (2.3)	41.3 (5.3)
***Sa* (%)**	40.6 (2.4)	32.2 (8.3)	31.8 (1.6)	46.5 (5.7)
USDA	Loam	Loam	Loam	Loam
d_g **(mm)**	0.031 (0.002)	0.021 (0.011)	0.018 (0.002)	0.042 (0.013)
σ_g	12.1 (0.4)	13.2 (1.6)	9.0 (0.7)	9.3 (1.2)
***OM* (%)**	19.7	23.5	36.4	23.4
f_c **(m^3 m^{-3})**	0.058 (0.046)	0.024 (0.025)	0.021 (0.031)	0.050 (0.033)
***BD* (Mg m^{-3})**	0.728 (0.075)	0.772 (0.117)	0.831 (0.174)	0.787 (0.034)
BD_f **(Mg m^{-3})**	0.609 (0.133)	0.732 (0.144)	0.802 (0.143)	0.703 (0.036)
θ_i **(m^3 m^{-3})**	0.118 (0.028)	0.194 (0.048)	0.141 (0.015)	0.132 (0.040)

Table 3. Statistics of WDPT tests conducted on samples oven-dried at 105 °C for 24 h and air-dried at 22 ± 2 °C for 15 days (N = number of replicates; W = wettable; STH = strongly hydrophobic).

	Site P1		Site P2		Site P3		Site P4	
	Oven	Air	Oven	Air	Oven	Air	Oven	Air
θ_i **(m^3 m^{-3})**	0.003	0.057	0.004	0.054	0.006	0.087	0.003	0.035
N	12	12	12	12	12	12	12	12
min (s)	1	1	1	1	21	49	1	1
max (s)	1	1	1	1	703	763	2	3
median (s)	1	1	1	1	362	406	1.5	2
SWR class	W	W	W	W	STH	STH	W	W

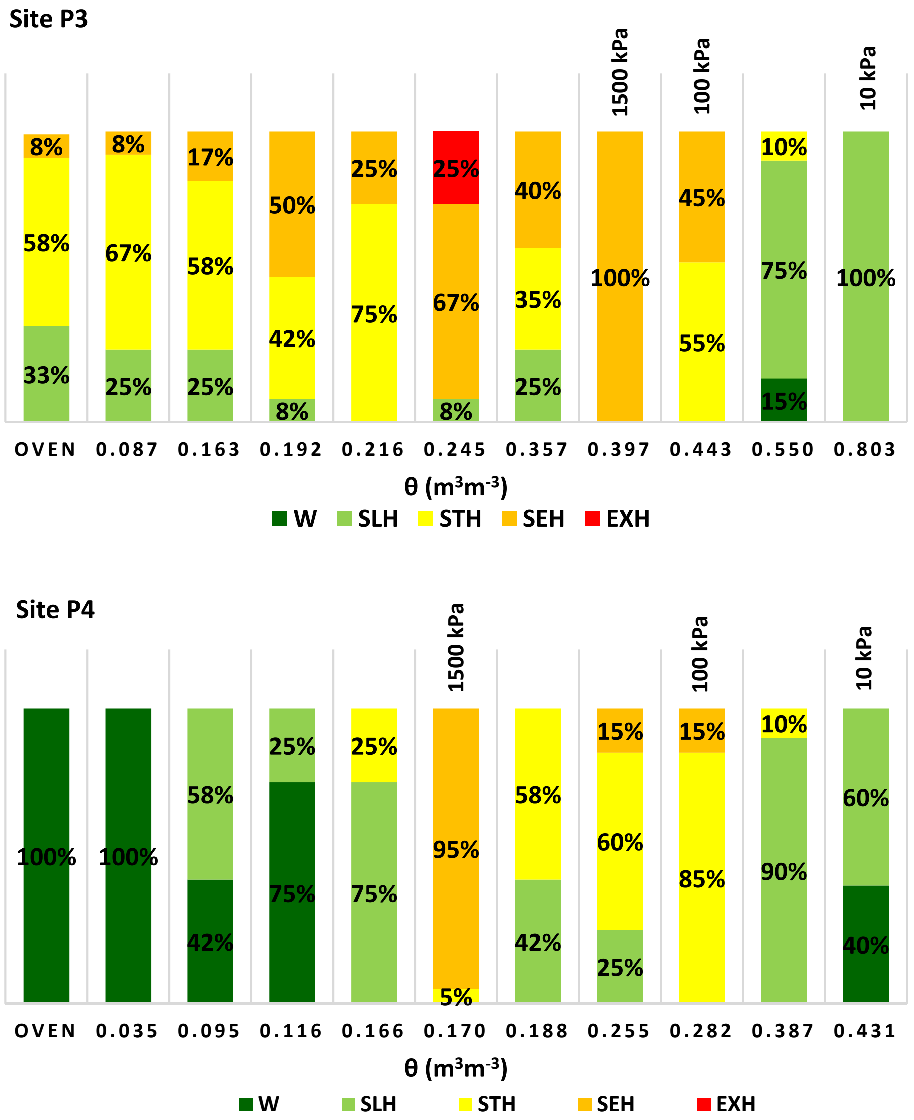

Fig. 2. Classification of SWR persistence according to Bisdom et al. (1993) at different volumetric water contents for soil of the unburned sites P3 and P4 of Moarda forest (W = wettable; SLH = slightly hydrophobic; STH = strongly hydrophobic; SEH = severely hydrophobic; EXH = extremely hydrophobic).

The wetting or drying process had a detectable influence on determination of SWR persistence given that, at similar moisture content values, WDPT was generally higher for the drying than the wetting process. For example, both soils were severely hydrophobic (SEH) at the wilting point (ψ = 1500 kPa) that corresponded to θ = 0.397 m^3 m^{-3} for soil P3 and θ = 0.170 m^3 m^{-3} for soil P4. For similar θ values achieved through a wetting process (i.e., 0.357 and 0.166 m^3 m^{-3} for soils P3 and P4, respectively), SWR classification shifted below by at least one class (i.e., STH/SEH for soil P3 and SLH/STH for soil P4). Due to soil retention curve hysteresis, water is held more strongly in the soil pore system during a drying process than a wetting one (i.e., more negative matric potential for a given θ value). As the WDPT measures the time required for the contact angle to change from > 90° to approximately 90°, our results suggest that the stronger are soil-water interaction forces the slower is the re-orientation of the amphiphilic molecules responsible of initial SWR (Doerr et al., 2000).

For the drying process, an effect of the repeated use of the same specimen was also observed. Rewetting the sample generally resulted in a decrease of the soil water repellency at a given applied matric potential value (Figure 3). The median WDPT value for soil P3 decreased by a factor of 2.8 – 5.4, depending on the considered ψ value, and the differences between the two WDPT values (i.e., wetting, W1, and rewetting, W2) increased at increasing the matric potential value (Table 4). For soil P4, a different trend was observed with WDPT decreasing by factor of 5.0 at the lower matric potential of the sequence (ψ = 10 kPa) and practically no effect for ψ = 1500 kPa. Further research is clearly needed to unravel the interaction between SWR and soil moisture fluctuations. Leaching of soluble amphiphilic hydrophobic compounds during the pressure plate extraction could be hypothesized as a cause of the reduced SWR upon repeated use of the same materials (Alagna et al., 2017; Vogelmann et al., 2013). Doerr and Thomas (2000) showed that complete re-establishment of hydrophobicity after wetting needs a new input and/or redistribution of hydrophobic substances, mainly related to biological activity in the root zone during, or after, the soils dry out. This was not the case of our sieved soil samples that went through two repeated wetting cycles. Imposition of a wetting and drying cycle greatly reduced water repellency of sand soils ameliorated with 1 – 2%

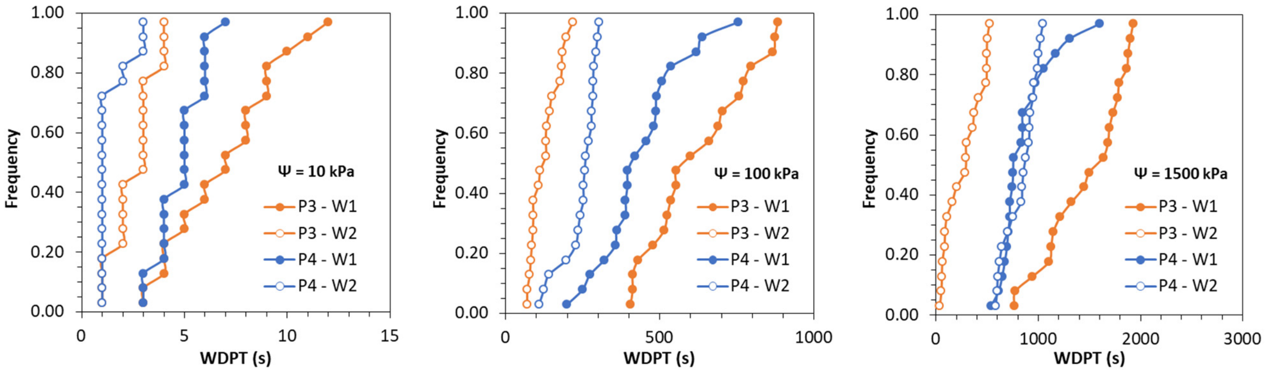

Fig. 3. Frequency distributions of WDPT data collected at matric potential values of 10, 100 and 1500 kPa for soils P3 and P4 used only once (W1) or twice (W2).

Table 4. Statistics of WDPT tests conducted at given matric potential values on soil samples after wetting (W1) and re-wetting (W2).

Site P3						
	10 kPa		**100 kPa**		**1500 kPa**	
	W1	W2	W1	W2	W1	W2
θ (m³/m³)	0.803	0.787	0.443	0.463	0.397	0.304
N	20	20	20	20	20	20
min (s)	3	1	405	70	764	36
max (s)	12	4	883	218	1928	523
median (s)	7	2.5	577	121	1566	288
Site P4						
	10 kPa		**100 kPa**		**1500 kPa**	
	W1	W2	W1	W2	W1	W2
θ (m³/m³)	0.431	0.431	0.282	0.292	0.170	0.195
N	20	20	20	20	20	20
min (s)	3	1	199	108	537	582
max (s)	7	3	754	303	1604	1045
median (s)	5	1	408	258	758	866

clay addition due to the ability of the clay particle to remain dispersed over the surface of sand grains (McKissock et al., 2000). Thus, the larger clay content of soil P3 could explain the different response of the two soil to replicated wetting-drying cycles.

For the two soils that showed hydrophobicity (i.e., soil P3 and P4), the ethanol percentage inducing immediate (< 5 s) infiltration of the droplet (EP) increased at increasing soil water content up to a maximum that corresponded with that determined with the WDPT test applied to the wetting process (Figure 4). A significant linear regression between EP and θ was found for both soils. According to the classification of SWR intensity proposed by Doerr (1998), under oven- or air-dried conditions soil P3 was classified as very strongly hydrophobic whereas the soil P4 was hydrophilic (Figure 4). A similar assessment of SWR was obtained by the WDPT test that classified soil P3 as strongly hydrophobic and soil P4 as wettable at very low moisture contents. As the soil moisture content increased, classification of SWR intensity for soil P3 changed to extremely hydrophobic for $\theta \geq 0.17$ m^3 m^{-3} and classification of soil P4 changed to slightly hydrophobic for $0.10 \leq \theta < 0.15$ m^3 m^{-3} and then to moderately hydrophobic for $\theta \geq 0.15$ m^3 m^{-3} (Figure 4).

Therefore, the two droplet tests for assessment of SWR persistence (i.e., WDPT) and intensity (i.e., EP) yielded congruent results as P3 was in general classified as more hydrophobic than P4 whereas both droplet tests detected similar dependency of SWR on soil moisture content (i.e., both WDPT and EP values that increase at increasing θ). Unfortunately, the EP test was not conducted for θ values greater than 0.25 and 0.19 m^3 m^{-3}, respectively, thus impeding to detect a possible decline on the SWR intensity at higher water content values.

Most hydrophobicity studies have been based on one of these two tests and the existence of a relationship between the two experimental methods is questionable due to the different physical meaning of EP and WDPT tests. Dekker and Ritsema (1994), in an extensive study on Dutch sand dunes, found a limited correlation between the two tests. Doerr (1998) found that long persistence of hydrophobicity (WDPT > 1 h) was associated to high EP values. Zavala et al. (2009) found significant correlation between persistence and intensity of SWR for sandy soils under evergreen forests. Significant correlation between log(WDPT) and EP for two loam soils and a clay loam soil widely diffused in Northeast Spain was reported by Badía et al. (2013). For the soil moisture range explored with our soils, a clear positive trend was observed between Log WDPT and EP with R^2 values of 0.636 and 0.850 for soil P3 and P4, respectively (Figure 5). For soil P4, a significant regression equation between the two tests can be proposed ($p < 0.01$): Log WDPT = 0.100 + 0.2567 · EP, in which WDPT is in seconds and EP is a percentage.

Vertical extent of soil water repellency

The median WDPT at the surface of undisturbed samples of soil P1 was 1 s and 75% of applied droplets (N = 60; 10 drop

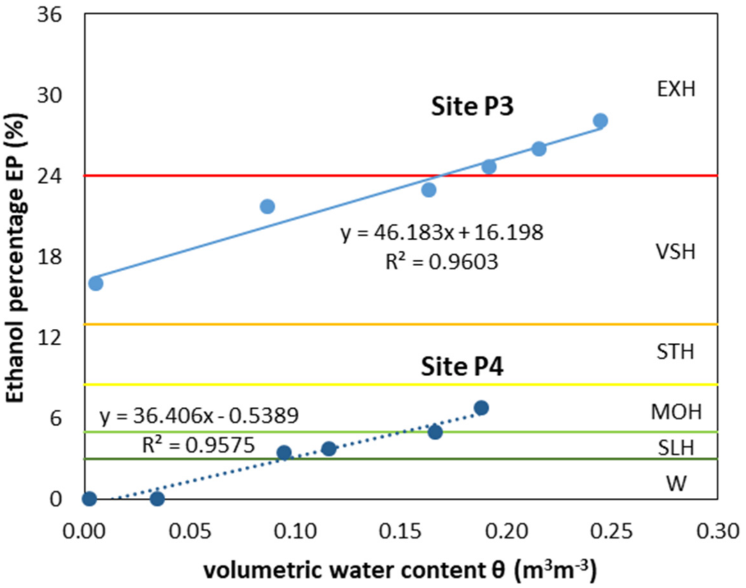

Fig. 4. Ethanol percentage vs. volumetric water content for the soils of unburned sites P3 and P4 (W = wettable; SLH = slightly hydrophobic; MOH = Moderately hydrophobic; STH = strongly hydrophobic; VSH = very strongly hydrophobic; EXH = extremely hydrophobic).

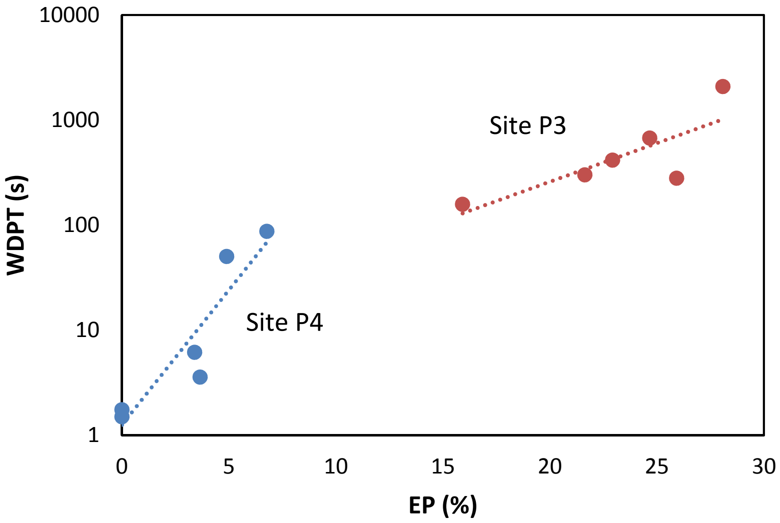

Fig. 5. Linear regression between the intensity (EP test) and persistence (WDPT test) of water repellency for the soils of unburned sites P3 and P4.

lets × 6 soil cores) infiltrated in less than 5 s (Figure 6). Strong hydrophobicity (STH) occurred only occasionally with maximum WDPT = 90 s. Also soil P2 showed median WDPT = 1 s and it was classified as wettable (i.e., WDPT < 5 s) in 88% of cases with only a single droplet infiltration time exceeding 60 s. The mean water content of the fine fraction at the time of sampling, θ_i, was 0.12 m^3 m^{-3} for soil P1 and 0.19 m^3 m^{-3} for soil P2 (Table 2). Therefore, the undisturbed soil core results were consistent with those obtained on repacked soil since both soils were wettable at their surface for an intermediate soil water content.

In agreement with the results discussed in the previous section, the soils of the two unburned sites (soils P3 and P4) showed hydrophobicity at the soil surface. The median WDPT at site P3 was 16.5 s thus being classified as slightly hydrophobic (SLH). However, this soil characteristic showed a large spatial variability with 23% of droplets that infiltrated in more than 600 s (SEH) and 5% in time larger than 3600 s (EXH) (Figure 6). Hydrophobicity was even more pronounced at the surface of site P4 as the soil was classified as wettable only in 10% of cases whereas 41% of droplets signaled severe or extreme SWR.

The results of the WDPT tests conducted at the surface of the unburned sites were only partially in agreement with the results of the same tests for repacked soil samples under the same initial moisture content. Indeed, for the surface layer of undisturbed soil P3 ($\theta = 0.14$ m^3 m^{-3}), even if SWR occurred for the majority of the applied droplets, the most frequent SWR class was W (Figure 6). For a comparable water content of $\theta = 0.16$ m^3 m^{-3}, WDPT tests conducted on repacked samples more univocally signaled occurrence of SWR with 58% of droplets falling in STH class (Figure 2). For soil P4 ($\theta = 0.13$ m^3 m^{-3}), the surface of undisturbed sample was from strongly to severely hydrophobic (Figure 6) whereas it was from wettable to slightly hydrophobic for repacked soil conditions under a similar moisture content of $\theta = 0.12$ m^3 m^{-3} (Figure 2). The surface of the

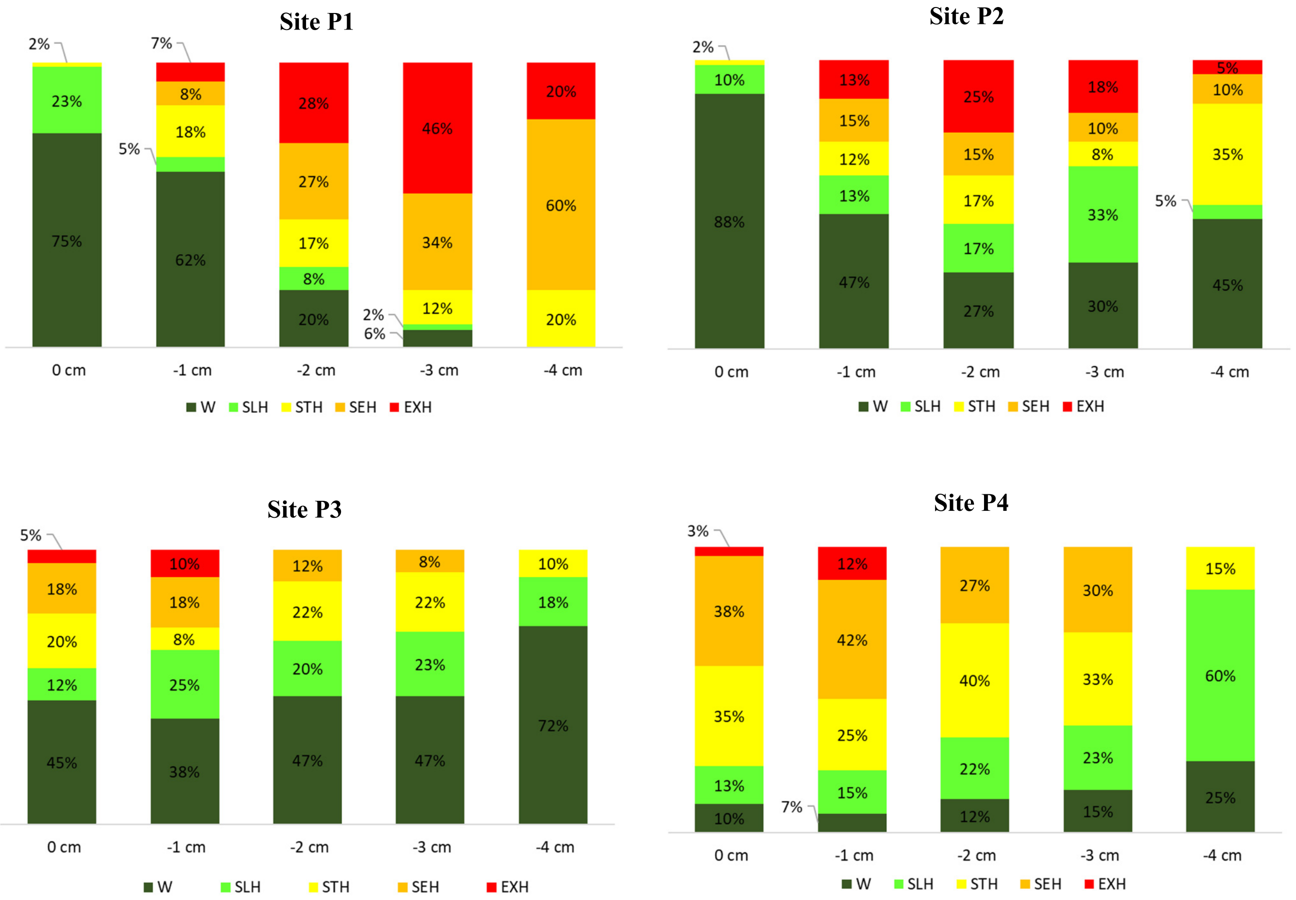

Fig. 6. Classification of the persistence of SWR at different depths of the undisturbed samples collected at the forest sites of Moarda (W = wettable; SLH = slightly hydrophobic; STH = strongly hydrophobic; SEH = severely hydrophobic; EXH = extremely hydrophobic).

undisturbed soil samples was characterized by micro roughness and heterogeneities that probably affected drop infiltration time and resulted in a large variability as detected by classification that spammed into all the five SWR classes (from W to EXH) (Figure 6). Conversely, the surface of the sieved samples was more levelled and smooth and this resulted in a more uniform infiltration time. In this case, WDPT values fell, at the most, in two neighbor SWR classes.

Analysis of WDPT data collected at the different depths of undisturbed soil cores showed a counteractive trend for the soils of burned and unburned sites (Figure 6). For soil P1, the SWR increased with depth and was maximum at z = 4 cm where 100% of droplets infiltrated in more than 5 s. Signs of extreme water repellency (WDPT > 3600 s) were observed starting from a depth of 1 cm and they were particularly remarkable at 3 cm depth where about 50% of droplets showed extreme SWR. Despite being less pronounced, a similar trend in SWR was observed at site P2. In this case, the maximum SWR was observed at 2 cm depth where 25% of droplets signaled extreme water repellency. It is worth to note that a relevant number of droplets (27 – 47%) infiltrated in less than 5 s independently of the considered depths and all the five SWR classes were represented for $z \geq 1$ cm thus confirming the high spatial variability that characterized SWR at these sites. A similar vertical distribution of SWR was observed in the first 2 cm a coarse loamy soil under a Pine-Oak forest affected by a low to moderate fire severity (Chen et al., 2020).

For sites P3 and P4, an increase in SWR was observed between the soil surface and z = 1 cm, then water repellency gradually decreased with depth and almost disappeared at z = 4 cm. Also for these soils, the spatial variability of SWR was particularly high in the first centimeters.

Soils of unburned sites (P3 and P4) are more representative of the natural SWR that characterizes forest soils with high, or extremely high, hydrophobicity at the surface which reduces with depth (Alagna et al., 2017; Iovino et al., 2018). Vertical distribution of SWR in sites P1 and P2 is representative of the effects of fire as combustion of the surface organic material eliminates natural background hydrophobicity whereas induces SWR deeper into the soil profile (DeBano, 1981; Doerr et al., 2009). As the SWR layer depth is mostly determined by temperature gradient (Tessler et al., 2008), it can be argued that surface temperatures were comparatively higher in site P1 than site P2. Spatial variability of SWR was maximum at the surface in the natural soils and at a small depth (z = 2 – 3 cm) below the surface in the soil of burned sites.

CONCLUSIONS

With the aim to investigate some open issues related to occurrence of post-fire soil water repellency in Mediterranean forests, the influence of soil water content, wetting-drying process, sampling disturbance, reuse of the same specimen and vertical distribution of hydrophobicity were investigated in two natural and two burned sites of the Moarda forest that was affected by a large wildfire in summer 2020. The main conclusions can be summarized as below:

- independently of the initial soil water content and the sampling disturbance (i.e., sieved or undisturbed), the surface layer of the burned sites was classified as wettable by the WDPT test;

- SWR in the surface layer of the natural unburned soils was maximum at intermediate soil water contents ($\theta = 0.17 - 0.25$ m^3 m^{-3}) and reduced, or even disappeared, either for higher and lower water contents;
- undisturbed soils cores were characterized by higher SWR spatial variability than sieved samples probably as a consequence of surface roughness and heterogeneities;
- an influence of the wetting or drying process on the SWR assessment was detected given that, at similar moisture contents, WDPT was generally higher for the drying than the wetting process;
- for the drying process, rewetting the same specimen generally resulted in a decrease of the SWR at a given applied matric potential;
- the EP and WDPT tests yielded congruent SWR classification for the two natural soils;
- wildfire altered the natural vertical distribution of SWR and the maximum hydrophobicity layer moved from surface to a depth of 2 – 4 cm depending on the considered site.

The occurrence of a strongly hydrophobic layer at shallow depth in burned soils, while the surface layer remains wettable, enhances the risk of mood floods. Indeed, infiltrating rainfall is hindered to move deeper by the subsurface water repellent soil layer thus causing a rapid saturation of the surface layer with increased runoff and sediments transfer down the hillslope. Controlled fire experiments, both under laboratory or field conditions, are recommended to assess the effects of other factors like soil temperature gradient, organic matter content and composition, presence of ash and/or unburned char that are expected to influence the vertical SWR distribution.

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