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Effects of relative humidity on the water repellency of fire-affected soils

P. Jiménez-Pinilla[a,b,*], S.H. Doerr[c], S. Ahn[c], E. Lozano[a,b], J. Mataix-Solera[a,b], A. Jordán[b], L.M. Zavala[b], V. Arcenegui[a,b],

[a] *GEA (Grupo de Edafología Ambiental) Environmental Soil Science Group, Departamento de Agroquímica y Medio Ambiente, Universidad Miguel Hernández. Avenida de la Universidad s/n, 03202, Elche, Alicante, Spain*

[b] *MED_Soil Research Group. Departamento de Cristalografía, Mineralogía y Química Agrícola, Facultad de Química. Universidad de Sevilla, C/ Profesor García González, 1, 41012, Sevilla, Spain*

[c] *Department of Geography, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP, UK*

* Corresponding author: P. Jiménez-Pinilla. Tel +34 966658337; Fax: +34 966658340. E-mail: pjimenez@umh.es

Abstract

Soil water repellency (SWR) is a common feature in unburned and particularly in fire-affected soils, and can enhance several environmental risks. It can be affected by many factors such as vegetation cover, moisture content and, in fire-affected areas, the degree of heating during burning. In addition, experiments using unburned soils have shown that atmospheric relative humidity can affect their water repellency. The purpose of this laboratory study was to examine how ambient relative humidity (RH) affects SWR of burned soils, and to explore its implications for fire-affected regions. Soil samples were taken from under fire-prone, but long unburned *Pinus halepensis* and a shrub site in Gorga, Alicante (SE Spain). In order to simulate different fire severities, samples were heated for 20 minutes at different temperatures (50, 100, 150, 200, 250, 300 and 350 ºC). Samples were then equilibrated at different RHs (30, 50, 70 and 95%) in a sealed climate chamber at a constant temperature of 20ºC. The water drop penetration time (WDPT) test, molarity of ethanol droplet (MED) test, and advancing contact angle (CA) measurements were performed inside the sealed climate chamber to assess SWR for each sample and treatment. Overall, increasing heat treatments enhanced SWR, which in turn was enhanced further following exposure to high RHs. The WDPT test showed that soils under pine were water repellent at the lowest heating temperature and became strongly water repellent at the higher heating temperatures and near saturation (95% RH). Shrubland soils were mostly wettable at the onset and remained so at every RH level studied except being slightly SWR at 95% RH. A similar trend was found after MED and CA measurements. The results demonstrate that high RH contributes to enhanced SWR also in burned soils, where high temperatures had already led to a substantial enhancement of SWR. These findings suggest that SWR levels determined for fire affected areas ambient under field or laboratory conditions may underestimate the apparent SWR levels present at the high RH levels that often precede major storm events. This in turn has implications for predicting post-fire runoff and erosion events.

Key words: Hydrophobicity; Relative humidity; Contact angle; Pre-heated temperatures; Forest soils; Mediterranean calcareous soils;

1 Introduction

Soil water repellency (SWR) may be defined as the condition of a soil which does not wet spontaneously when water comes in contact with the soil surface (Leelamanie et al., 2008a). This behaviour modifies infiltration and evaporation rates, erodibility and other hydrological processes of soils (Feng et al., 2001; Jordán et al., 2009; Wallis et al., 1991; Wallis and Horne, 1992). SWR is a common property of soils under many vegetation types and is often induced in previously wettable soils or enhanced by fire (DeBano, 2000; Doerr et al., 2000; Granged et al., 2011a; Jordán et al., 2013; Jordán et al., 2014). It has been shown that environmental conditions such as ambient temperature (King, 1981; Goebel et al., 2011), drying temperature (Franco et al., 1995; Dekker et al., 1998), water content (Berglund and Persson, 1996; Bodí et al., 2013; DeJonge et al., 1999; Dekker and Ritsema, 2000) and the wetting and drying history of samples (Doerr and Thomas, 2000) can strongly affect SWR. Atmospheric relative humidity (RH) is another important factor conditioning SWR. Jex et al. (1985) and Doerr et al. (2002) reported that SWR increased when soil was exposed to > 90% RH (near saturation) over a short period (< 1 day), but gradually decreased when exposed to an ambient laboratory atmosphere of ~40% RH. Leelamanie et al. (2008b) reported a positive correlation between RH and SWR at RHs between 33 and 94%. Another main factor that recently has been considered responsible of the severity of SWR is the soil surface structure (Ahn, 2014). SWR appears on low-energy surfaces where the attraction between the molecules of the solid and liquid interface is weak (Heslot et al., 1990; Roy and McHill, 2002). Under natural conditions, high-energy soil mineral surfaces are often covered by films of low-energy organic compounds (Doerr et al., 2000; Goebel et al., 2004) forming water repellent surfaces (Jiménez-Morillo et al., 2014; Leelamanie et al., 2008a) and this can be amplified by surface structure (Wenzel, 1936; Cassie and Baxter, 1944). It has been reported that the overall susceptibility to developing soil water repellency is higher in sandy and coarser textures (González-Peñaloza et al., 2013; McGuie and Posner, 1980; Roberts and Carbon, 1971) and lower in those containing clay (Crockford et al., 1991; Zavala et al., 2014). A soil surface may minimize the contact area with a water drop by its porous structure. In soils prone to develop water repellency, the upper soil layers tend to exhibit the greatest severity. This effect is usually enhanced as soil dries and water is lost from the pores, enlarging the air-solid interface, which critically increases the net contact angle (Ahn, 2014). The contact angle (CA) between the solid and water can be measured at the three-phase interface (gas-liquid-solid). According to Goebel et al. (2011) SWR occurs if CA > 0º; soils show reduced wettability with CA varying between 0 and 90º (i.e. infiltration of water into the soil matrix decreases); and values of CA > 90º indicate extreme SWR. A zero CA occurs when the surface tension of solid and liquid are equal to each other (Bachmann and van der Ploeg, 2002). Although, numerous studies have used CA to determine SWR (Carrillo et al., 1999; Bachmann et al., 2000a, b; Leelamanie et al., 2008b; Doerr et al., 2009), and some studies exist in which the effect of RH on SWR has been examined (Jex et al., 1985; Doerr et al., 2002; Leelamanie et al., 2008b). All previous studies have been carried out on unburned soils.

Fire is an important ecological agent, which has increasingly affected Mediterranean ecosystems in the last decades, leading to changes in chemical, physical and microbiological soil properties (Neary et al., 1999; Certini, 2005). Fire may induce or increase SWR in previously wettable or water-repellent soils (Doerr et al., 2000; Mataix-Solera and Doerr, 2004; Zavala et al., 2009a), but can also destroy it after intense combustion of organic matter (Arcenegui et al., 2008; Granged et al., 2011b; Jordán et al., 2010; Robichaud and Hungerford, 2000). The specific effect depends mostly on the duration of heating and temperatures reached (DeBano, et al., 1976; Doerr et al., 2004; Gordillo-Rivero et al., 2014), but also oxygen availability (Bryant et al., 2005) and soil water content (Robichaud and Hungerford, 2000; Zavala et al., 2010).

The influence of increasing temperatures and RH on SWR is of substantial importance in affecting ecosystem processes, which regulate the soil system during post-fire recovery. Given the fact that fire-affected soils often exhibit particularly high levels of SWR, the removal of the protective vegetation cover during fire can make such soils particularly susceptible to accelerated hydrological and geomorphological responses (Doerr et al., 2009). An important research gap thus exists in elucidating the effects of RH on SWR of soils that have been exposed to heating during vegetation fires.

The main aim of this study was therefore to explore the effect of different ambient RHs on SWR variations that might prevail under very dry surface conditions following a wildfire. We focused here on a Mediterranean calcareous soil under *Pinus halepensis* and mixed shrub vegetation, which is a common soil-vegetation combination subjected to fire in Eastern Spain (Mataix-Solera et al., 2002; Arcenegui et al., 2008; Mataix-Solera et al., 2013; Jiménez-Pinilla et al., 2015).

2 Material and methods

2.1 Sampling site, soil sampling and experimental design

The sampling site is located in a formerly cultivated area in Gorga (N 38º 43′44′′, W 0º 22′58′′; 545 masl), province of Alicante (SE Spain), with a Mediterranean climate type and approximate annual average rainfall of 500 mm. Vegetation type is mainly composed of *P. halepensis* forest and an understory stratum formed by Mediterranean shrubs, including *Quercus coccifera*, *Rosmarinus officinalis*, *Cistus albidus* and *Erica arborea*. The soil is classified as a Lithic Xerorthent (Soil Survey Staff, 2014), developed over limestone with a silt loam texture (49.7% sand, 40.7% silt and 9.6% clay). Surface soil samples (0 - 2.5 cm depth) were collected beneath either well-demarcated pine or shrub areas after carefully removing any superficial litter by hand. Samples were stored in plastic bags, transported to the laboratory, air dried at room temperature (~25 ºC) for one week and then carefully sieved through a < 2-mm mesh.

Soil samples were homogenized before the heating procedure. Then triplicate soil samples (~30 g) were heated at selected temperatures under controlled laboratory conditions (50, 100, 150, 200, 250, 300 and 350 ºC), during 20 minutes in ceramic crucibles using a muffle furnace (Nabertherm, P320, Bremen, Germany). This range of temperatures was selected in order to simulate different potential heating scenarios of wildfires and also in agreement with previous studies which have shown notable heat-induced increases in SWR (Neary et al., 1999; Bachmann et al., 2003; Doerr et al., 2005a; Mataix-Solera et al., 2011). For each case, the furnace was pre-heated to the desired temperature and each sample was heated separately. The experiment includes also unheated control samples.

2.2 Exposure to selected relative humidities and associated water repellency measurements using WDPT and MED tests

For each experiment, each heated soil sample was divided into 3 subsamples (10 g, approximately), which were then put in petri dishes (5-mm diameter and 7-mm depth), and placed inside a climate chamber (SANYO Gallenkamp, model PLC CF4; range: 30-90% RH and -40 to 180 ºC temperature) and subsequently exposed for equilibrium under a different prescribed atmospheric conditions of 30, 50, 70 and 95% RH at 20 ºC. Each sample type, in triplicate, was kept for 48 hours inside the chamber prior to the water repellency assessments, to ensure the entire sample was fully adjusted to the selected humidity. Soil samples remained within the sealed climate chamber throughout the experiments, with manipulations and measurements conducted by using gloves attached to sealed portholes in the chamber window. This ensured that samples remained under constant environmental conditions and without any other environmental variables affecting them.

Persistence of SWR was assessed using the water drop penetration time (WDPT) test, which measures how long SWR persists on a porous surface. Given that SWR usually decays with prolonged water contact, it relates to the hydrological implications of reduced wettability as the amount of surface runoff is affected by the time required for the infiltration of raindrops (Wessel, 1988; Doerr, 1998). It involved placing three drops of distilled water (~0.02±0.05 mL) onto the soil sample surface. In each case, the time (in seconds) required for a complete droplet infiltration was recorded and a SWR persistence class assigned according to Bisdom et al. (1993) (Table 1).

Severity of SWR was also assessed inside the chamber using the molarity of an ethanol droplet (MED) test (expressed as % ethanol; Doerr et al., 1998) (Table 2). This test is an indirect measure of the surface tension of the soil surface and indicates how strongly a water drop is repelled by a soil at the time of application (King, 1981; Doerr, 1998). It involved placing 3 droplets (~0.02±0.05 mL) using an applicator of water-ethanol solution (0, 1, 3, 5, 8.5, 13, 18, 24, 36 % ethanol) (Table 2) onto the soil samples surfaces. The number of droplets that penetrate the soil within 5 seconds (Crockford et al., 1991) was recorded for each ethanol solution and the solution that allowed more than one drop to penetrate was then taken to assign a SWR severity class (Doerr, 1998) (Table 2).

2.3 Additional water repellency assessments using advancing contact angle measurements

The advancing contact angle (CA) of a water droplet on a soil can also be used to determine the severity of SWR (Letey, 2000; Leelamanie, 2008a). In surface science, a CA of 90º is usually taken as demarcating water repellent and wettable conditions on flat media (Letey, 2000). For porous granular media such as soils, it has been suggested that reduced wettability is present for 0º < CA < 90º; and values of CA > 90º indicate extreme SWR (Goebel et al., 2011; Fig. 1). More specifically, Shirtcliffe et al. (2006) found that the critical contact angle for penetration was 52-61° using soil models and test liquids (pentane and hexane), but years before Bán et al. (1987) had determined CA even lower (49.5-57.7°) using ethanol and sulphur pellets, polyamide and polytetrafluoroethylene. CA measurements were included in this study as third measure of SWR (i) to provide wider comparability of the SWR data obtained here and (ii) as CA measurements have not been included in any previous study in which the effect of RH on SWR had been examined.

To measure the CA of a sample, a monolayer of soil particles was immobilized on a microscope glass slide (1.5 cm × 3 cm) using double-sided adhesive tape to accomplish a plain homogeneous surface (Bachmann et al., 2000b). Samples were then placed on a tray inside the sealed climate chamber and exposed to the selected RH’s as in the previous experiments, except that samples were only exposed for 24 hours given that only a monolayer of soil was used.

We also included two different hydrophobic control ‘model soil’ materials in this experiment: spherical glass beads to represent smooth-spherical particles (obtained from Whitehouse Scientific, UK); and natural quartz sand (collected from fluvial deposits, South Wales, UK) to represent textured-angular particles typical of soils. Both materials were used in two different size ranges: 710-850 μm and 1120-1180 μm and were chemically hydrophobized using chlorotrimethylsilane as described in Ahn et al. (2013), resulting in static (temporally stable) water repellency. They were then packed as closely as possible and immobilized on the glass slides as described above.

It is now well established that hydrophobicity can be enhanced by the micro-topography of a surface when compared to flat surfaces (McHale et al., 2005). For particle arrays as presented by a soil surface, the texture of the particle surface itself seems to have a significantly greater influence in the amplification of the CA (i.e. and hence SWR) than the coarser-scale particle-based structure or particle shape (Bachmann et al., 2006; Ahn, 2014). Hence these 'model soil' materials, varying in surface texture (glass beads: spheres with no particle surface texture and sand: textured-angular particles), were included to explore the fundamental physical impact of RH and surface texture on SWR behaviour for a static (i.e. chemically more stable) hydrophobic coating that is expected not to be altered by microbial activities. .

For CA assessment, drops of distilled water were placed onto the surfaces of soils and chemically treated materials using a 1-mL syringe with a blunt tip needle (19 gauge Luer-Lock blunt ended needles, Sylmaste, UK). The advancing contact angles of sessile drops were recorded by a video camera (30 fps) while the water drop was being gradually enlarged (~10-100 μL). The left and right hand side contact angles of each advancing moment were determined using the software *ImageJ* (Version 1.48, National Institutes of Health, USA) and averaged, and then 3-5 advancing CAs were averaged from each sample in triplicate. All samples remained in the sealed climate chamber throughout the experiments, as described above.

2.4 Statistical analysis

The normal distribution of SWR data was checked using the Kolmogorov-Smirnov test. As normality of SWR data was rejected ($p < 0.05$), WDPT data were transformed (Ln) to allow a better data display given their large variability. Mann-Whitney U test was used to check the statistical differences between SWR data at each temperature treatment regarding to unheated (control) samples for every RH studied ($p < 0.05$). Statistical analyses were performed by IBM® SPSS (© SPSS Inc., 1989) version 22 for Windows software package.

3 Results

3.1 Heating effects on soil water repellency at a standard humidity (50% RH)

Heating has a similar effect for both persistence (WDPT test) and severity (MED and CA tests) of water repellency for samples at a standard laboratory RH of 50%. For the WDPT test, an apparent slight increase in SWR for pine soils was observed at 50 ºC compared to the control samples (unheated), and also an apparent decrease between 100 and 200 ºC, although in both cases, no significant differences were observed ($p > 0.05$) (Fig. 2a). For the highest heating temperatures (300-350 ºC), a substantial increase in SWR was observed, with significant differences ($p < 0.05$) , with the peak occurring at 350 ºC (Fig. 2a). SWR was not found at 50% RH in shrub soils for any heating treatment (Fig. 2b).

The MED tests showed a similar pattern with WDPT tests for both pine and shrub soils (Fig. 3a and 3b, respectively). Nevertheless, significant differences ($p < 0.05$) were found on SWR pine samples from 250 ºC to 350 ºC campared to the unheated samples. SWR was not detected by MED tests in pine soils heated at 150 and 200 ºC (Fig. 3a).

The results of CA measurements showed a similar pattern with the WDPT results. CA measurements at 50% RH showed a general trend of increasing SWR with heating temperatures showing the largest CA at the highest heating range, where significant differences were found from 200 to 350 ºC with regarding to unheated (control) samples ($p < 0.05$) (Fig. 4).

3.2 Relative humidity effects on soil water repellency persistence (WDPT test)

Persistence of SWR in pine soils increased with RH for all heating temperatures. The WDPTs were longest at the highest RH (95%) for the most of heating treatments (Fig. 2). Particularly, for the heating treatments at 300 °C, the ln WDPT increased from 5.1 s at 50% RH to 8.6 s at 95% RH, and for the treatment at 350 °C, the ln WDPT increased from 5.1 s at 50% RH to 8.4 s at 95% RH (Fig. 2a), being in both cases significantly different ($p < 0.05$). For these samples for the 300 °C and 350 °C treatments were 'severely water repellent' (ln WDPT 6.4-6.8 s in Table 1) at 30% RH (Fig. 2a), whereas 'extremely water repellent' (ln WDPT > 8.2 s in Table 1) at 95% RH (Fig. 2a).

Shrub soils were wettable at the onset (ln WDPT < 1.6 s) and remained stable at each considered RH except at 95% RH, where the samples heated at 250 °C and 300 °C were 'slightly water repellent' (ln WDPT 1.8-3.4 s in Table 1; Fig. 2b), and there were statistically significant differences ($p < 0.05$).

3.3 Relative humidity effects on soil water repellency severity (MED and CA tests)

For the MED test, an influence of RH on SWR was observed mainly for the pine soils, showing a consistently increasing severity of water repellency with increasing RH (Fig. 3). At 30 and 70% RH, severity of SWR ranged between very wettable and strongly water repellent (classes 1 to 6; Table 2), with the highest values occurring for the highest temperature treatments (Fig. 3a), and where also statistically significant differences were detected for both RHs at 250 ºC and 300 ºC ($p < 0.05$). At 95% RH (Fig. 3a), SWR ranged between moderately and extremely water repellency (classes 5 to 9; Table 2), and the increase of SWR detected at 300 ºC was statistically significant different ($p < 0.05$).

In contrast, the influence of RH on SWR was not shown from the shrub soils at low RH levels, as the shrub soils were wettable at the onset (ethanol < 0%), and remained so at every RH level monitored except at 95% RH. Even at 95% RH, only the samples heated at 250, 300 and 350 ºC (Fig. 3b) were 'slightly water repellent' (class 4; Table 2), and with no significant differences ($p > 0.05$).

The CA measurements were only conducted on samples taken from the pine site as only these showed a resistance to wetting sufficient for conducting CA measurement ($LN_{WDPT} > 1.6$ s). Shrub soils had rapid infiltration of water droplet, and thus, CAs were not technically measurable.

The CA measurements for the pine soils also showed an effect of RH at all heating temperatures at 30 and 70% RH (Fig. 4). The most noticeable increase in CA was found in the samples heated between 250 and 350 ºC, particularly for 30 and 70% RH (Fig. 4), where significant differences were also detected ($p < 0.05$). The highest CA was observed at 95% RH after all heating treatments (Fig.4), finding significant differences ($p < 0.05$) from 200 ºC forward.

3.4 Relative humidity effects on 'model soils': glass beads and sand

Both glass beads and sand showed a similar pattern where CA increased with RH (Fig. 5). CAs observed on glass beads of different sizes ranged from 77.91º (66.5º, 85.6º) to 100.9º (88.5º, 107.9º) (Fig. 5a), and on sands from 117.7º (100.0º, 126.0º) to 125.9º (118.3º, 128.9º) (Fig. 5b). The CAs of glass beads at different relative humidities all indicated water repellency (according to the classification of Goebel et al., 2011). The CA of the glass beads of size 1120-1180 μm at 95% RH was 100.9º (88.5º, 107.9º), indicating a fully water repellent behaviour (CA > 90º) (Fig. 5a). The sand of both size groups also had consistent water repellent behavior (CA > 90º). The CA was 123.2º(111.3º, 127.1º) for size 710-850 μm and 125.9º(118.3º, 128.9º) for size 1120-1180 μm (Fig. 5b). Regarding the differences between two sizes of sands, we observed that CAs were slightly larger for the smaller particles (710-850 μm) compared to the larger ones (1120-1180 μm) at 30, 50 and 70% RH, and the opposite at 95% RH (Fig. 5b).

4 Discussion

4.1 Heating effects on soil water repellency at different pre-established laboratory relative humidities

An overall increasing trend of both persistence (determined using the WDPT test) and severity (MED and CA tests) of SWR with increasing heating temperature was detected from pine soils at a standard RH of 50%. More specifically, SWR increased somewhat at the lowest heating temperature (50 ºC) compared to unheated samples (Fig. 2a, 3a, 4). The SWR increasing can be caused by increased alignment of hydrophobic molecule chains (Doerr et al., 2005b). This was followed by a slight reduction for 100 and 150 ºC treatments. The reason for this is unclear. Following heating at 200-300 ºC a strong increase in SWR was observed (Fig. 2a, 3a, 4) which is in agreement with established knowledge based on previous laboratory studies, which have shown intesification of SWR when soil temperatures reach 175-270 ºC (Doerr and Shakesby, 2009). Amongst the suggested causes for strong increases in SWR by heating are migration of hydrophobic material from interstitial organic matter onto soil particles (Franco et al., 1994) and chemical changes such as the relative increase in long chain (<C20) fatty acids aromatic compounds (Atanassova and Doerr, 2011). Krammes and DeBano (1965) found that SWR is destroyed at temperatures between 280 and 400 ºC, with the specific destruction temperature being closer to 280 ºC for shorter heating durations (Doerr et al., 2004). In the current study, however, heat treatments at 350 ºC seem to be remained below the threshold for SWR destruction.

Shrub soils remained wettable after all heating treatments, highlighting the importance of vegetation type on the development of water repellency. It has been previously reported in burned (Arcenegui et al., 2007; Mataix-Solera et al., 2008) or unburned soils (Jordán et al., 2008; Martínez-Zavala and Jordán-López, 2009; Zavala et al., 2014).

4.2 Relative humidity effects on the persistence and severity of soil water repellency

Persistence and severity of SWR were substantially enhanced at the highest RH applied in our experiments. At 95% RH, SWR in pine soils exhibited the highest values for each heating temperature (Fig. 2a, 3a, 4), and the shrub soils that were wettable at all other RHs turned into slightly water repellent at 95% (Fig. 2b, 3b).

A notable increase in SWR also occurred for pine soils at 70% RH compared to the standard atmosphere of 50% RH, particularly when considering SWR severity measured by MED test. This was evident in all samples irrespective of heating temperatures (Fig. 3a). These results demonstrate a considerable enhancing influence of high RHs (near atmosphere saturation: 95% RH) on SWR persistence and severity of already water-repellent soil. This fact suggests that air humidity is a key control of SWR. It supports findings from previous work on a variety of unburned soils (Jex et al., 1985; Doerr et al., 2002; Leelamanie and Karube, 2007; Leelamanie et al., 2008b), and demonstrates that this also applies to heat-affected soils. Given the relatively rapid change observed also in previous laboratory tests, Doerr et al. (2002) proposed that physicochemical rather than microbiological processes may be responsible for this soil behaviour. They suggested that the prior interactions between soil components and water vapour at high RH may be of significant influence, as a considerable quantity of energy is released, which might be disrupting the mineral and organic hydrophobic bonds within the soil. They speculated that, similar to heating effects, the condensation and adsorption of water vapor onto soil associated with an increase in RH might lead to reorientation of the hydrophobic organic molecule chains, expanding more strongly into pore spaces, thereby enhancing SWR.

In this study, the heated samples, in which SWR had already been increased through the effect of temperature, showed further enhanced SWR by high RHs. Considering that high temperature treatments up to 300 ºC would have led to a substantial reduction in any viable soil microbial population (Guerrero et al., 2005; Mataix-Solera et al., 2009), thereby limiting the growth of both bacteria (Díaz-Raviña et al., 1996) and also fungi (Widden and Parkinson, 1975), the intensified SWR by RH does not seem to be driven by increased microbial activity within a relatively short-duration of exposure to high humidities (Doerr et al,. 2002).

It is also noteworthy that a slight increase in SWR was observed for pine soils at 30% RH, compared to the standard atmosphere of 50% RH. This was less consistent across the heat-treated soils and was evident predominantly from WDPT and MED tests (Fig. 2a, 3a), and also from CA test for control treatment (Fig. 4). This behaviour might be related to a conclusion of Moody and Ebel (2012), in where the time scale for rewetting of fire-affected soils under “hyper-dry” conditions is much slower (days to weeks) than the time scale of rainstorms (minute to hours). RHs of 30% can be considered a threshold for hot dry summer weather conditions in the Mediterranean climate (Harpaz et al., 2014), and this behaviour may therefore be relevant to the study region.

4.3 Assessments of relative humidity effects on ‘model soils’: glass beads and sand

The observed increase in SWR severity of hydrophobic ‘model soil’ samples after a short exposure (24 h) to relatively high RHs (> 50%) (Fig. 5a, b) suggests that the enhanced water repellency with RH observed here is a generic effect by a physical mechanism. The ‘model soils’ were hydrophobized with a chemically relatively stable compound, and thus there is lowest possibility for microbial activities to get involved for these materials.

It supports the conclusion already stated above that physical rather than microbial processes are responsible for enhanced SWR at high RH.

4.4 Implications of enhanced soil water repellency for pre-heated soils with relative humidity

SWR is a widespread phenomenon with the capacity to condition hydrological and geomorphological processes (Whelan et al., 2015). It can reduce infiltration rates (Wallach and Graber, 2007) and water retention capacity (Naasz et al., 2005). Important environmental consequences of the reduced infiltration rate include increased soil erosion, enhanced overland flow and non uniform wetting fronts with fingered flow (Burch et al., 1989; Imeson et al., 1992; Ritsema et al., 1993; Jordán et al., 2008; Zavala et al., 2009b). These environmental impacts can affect important ecosystem processes such as soil organic matter decomposition, plant regeneration, succession of vegetation and microbial activities. The intensity of these effects depends upon the severity and spatial variability of SWR (Jungerius and de Jong, 1989; Ritsema and Dekker, 1994) and its severity and persistence (Zavala et al., 2009b). The enhanced SWR by high RH found in this study, therefore, can result in more intensive environmental change than the generic SWR under dry conditions. In nature, high RH conditions often precede precipitation events or wetting front advances in the soil, which in turn could increase SWR (Doerr et al., 2002; Zavala et al., 2009b).

The results of the current study suggest that this will also be the case for soils in which water repellency was enhanced by soil heating during fire. Considering that the removal of the protective vegetation cover by fire increases the susceptibility of burned hillslopes to accelerated hydrological and erosional responses (Shakesby and Doerr, 2006), the enhancement of SWR at high RH may be even more influential in recently burned compared to unburned environments.

5 Conclusions

To the authors' knowledge, this is the first study in which RH effects on SWR have been examined for heat-affected (burned) soils. It was found that heat-affected soils also show the enhanced SWR that has been previously reported for soils not affected by heating. This effect was observed at 70% RH and was most pronounced at 95% RH. The effect of RH was shown in all heat-treated samples, and most pronouncedly in the samples heated at high temperatures (250-300 ºC) that already had a substantial increase in SWR. The fact that the latter soils, as well as model soil particles treated with a hydrophobic coating, behaved in this manner suggests that physicochemical rather than microbial effects are responsible for the rapid increases in SWR induced by RH. The finding that soils in which SWR has already been enhanced by heating exhibit further increases with RH emphasizes the importance of considering RH when investigating the environmental impact of SWR in burned areas. Furthermore, a fire burns off protective vegetation and litter, and makes burned areas even more vulnerable to hydrological and erosional responses. Enhanced SWR at high RH could, therefore, be of greater significance than in unburned vegetated terrain.

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