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

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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 min at different temperatures (50, 100, 150, 200, 250, 300 and 350 °C). Samples were then equilibrated at different RHs (30, 50, 70 and 95%) in a sealed climate chamber at a constant temperature of 20 °C. 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.

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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, 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.,

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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; McGhie 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 >0°; soils show reduced wettability with CA varying between 0 and 90° (i.e. infiltration of water into the soil matrix decreases); and values of CA >90° 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, 2013; Arcenegui et al., 2008;Jiménez-Pinilla et al., 2015).

2. Materials and methods

2.1. Sampling site, soil sampling and experimental design

The sampling site is located in a formerly cultivated area in Gorga (N 38° 43′44″, W 0° 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 °C) 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 °C), during 20 min 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 °C temperature) and subsequently exposed for equilibrium under a different prescribed atmospheric conditions of 30, 50, 70 and 95% RH at 20 °C. Each sample type, in triplicate, was kept for 48 h 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 s (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 et al., 2000; Leelamanie et al., 2008a). In surface science, a CA of 90° is usually taken as demarcating water repellent and wettable conditions on flat

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