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The influence of fire history, plant species and post-fire management on soil water repellency in a Mediterranean catchment: The Mount Carmel range, Israel

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ABSTRACT

Fire is a key factor impacting soil hydrology in many Mediterranean catchments. Soil water repellency (SWR) can stimulate land degradation processes by reducing the affinity of soil and water thereby triggering a reduction in soil fertility and increasing soil and water losses. The effects of two consequent fires (1989 and 2005) on SWR were assessed in the Carmel Mountains, Israel. Fire history, plant recovery and post-fire management (14 treatments) were investigated as determining factors in a time dependent system. In total 210 locations were investigated 9 times from October 2011 to February 2012, which totals 1890 water drop penetration tests that were performed. During each visit to the field (9 times) a soil moisture content was measured for each treatment. SWR was highest in the >50 years unburnt plots, where soil under *Pinus halepensis* is most hydrophobic. In the most disturbed soils (twice burnt), many sites have a low to absent SWR even if the soil is very dry. The dynamics and fluctuations in SWR differ in magnitude under different plant species. The areas treated with CC (chipping of charred trees) showed a much higher SWR than areas left untreated. From these insights, a conceptual model of the reaction of SWR on multiple fires was developed.

1. Introduction

Since the 1960s, the number of wildfires in the Mediterranean region has increased due to rural abandonment, land-use change and the increased frequency of meteorological and climatic conditions conducive to wildfire occurrence (Pausas, 2004; Pausas and Fernández-Muñoz, 2012). However, wildfires are a key ecological agent that influences the structure and function of many ecosystems worldwide (Pausas and Schwilk, 2012). In the Mediterranean region, wildfires instigate multiple changes in the characteristics and distribution of vegetation, soil properties, and hydrological attributes of the affected areas (Shakesby and Doerr, 2006). Wildfires provoke not only the combustion of the vegetation, but also cause the charring of soil organic matter (SOM) within the uppermost soil layer. The depletion of SOM has profound effects on soil properties such as soil structure, soil permeability (García-Corona et al., 2004; Keesstra et al., 2014), with nutrient cycling, and soil chemical and biological properties, further reducing SOM (Novara et al., 2011). The spatial and temporal effects of these impacts depend upon fire severity, the topography of the burnt area, the vegetation regrowth and post-fire meteorological conditions (De Bano, 1991; Certini, 2005).

1.1. Soil water repellency (SWR)

SWR is a natural property of the soils that is found in many regions (Bodí et al., 2012a, 2012b; Gabarrón-Galeote et al., 2013; Mao et al., 2015). Soil heating during wildfires induces the formation of a water repellent layer by volatilizing hydrophobic organic compounds (Bodí et al., 2011; Dlapa et al., 2013). Some of these move deeper into the soil and condense onto cooler soil particles, producing a hydrophobic layer (Doerr et al., 2000), and determines the soil water repellency distribution from the ash layer to deeper soil horizons (León et al., 2013). Fire-induced SWR is temperature-dependent, formed between 176 and 204 °C and often destroyed when >288 °C (De Bano, 2000).

SWR is a worldwide phenomenon having been reported first under natural conditions (Huffman et al., 2001; Mataix-Solera et al., 2007),

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and on a variety of soils and an assortment of climatic conditions (Jordán et al., 2013; Hewelke et al., 2016). The coating of soil particles facilitates SWR, with hydrophobic compounds leached from organic matter accumulations from by-products of microbial activity and/or fungal growth under thick layers of litter and duff (Savage et al., 1972; Doerr et al., 2000; Pierson et al., 2008).

The formation, persistence and intensity of SWR are tightly linked with soil moisture, texture, clay fraction, pH, chemical characteristics, biological activity, soil type, organic matter amount and quality, management and land use (Bodí et al., 2013; Jordán et al., 2013; Jimenez-Morillo et al., 2016; Benito et al., 2016). Under high soil moisture content (SMC), SWR is reduced, however this is not a linear process, as a critical soil moisture threshold exists above which the soil becomes wettable. This threshold ranges from 5% (sandy soils) to >30% (clay soils) (Bodí et al., 2012a, 2012b, 2013). Vogelmann et al. (2013) observed in Brazilian soils that SWR decreased with the amount of organic content and depth; and increased with water content. According to the authors, the threshold of water content where water repellent soils became hydrophilic (^{0}h) ranged between 0.36 and 0.57 cm cm^{-3}. As the soil dries out, SWR tends to be restored (Doerr et al., 2009), which causes intra-annual, short-term variations in SWR driven by SMC (Keizer et al., 2008). On the other hand, inter-annual variations are mainly influenced by a complex matrix of factors involving chemical and biological processes (Doerr et al., 2009).

The appearance of SWR has been associated with a wide range of vegetation types including heathlands and scrublands (Cerdà and Doerr, 2007; Zavala and Jordán, 2009; Zavala et al., 2014), under pine trees (Mataix-Solera and Doerr, 2004; Buczko et al., 2005; Hubbert et al., 2006; Zavala et al., 2009; Tessler et al., 2013), deciduous trees (Buczko et al., 2002), oaks (Cerdà et al., 1995; Jordán et al., 2008, Tessler et al., 2013; Lozano et al., 2013) and beneath eucalyptus stands (Doerr et al., 1998; Keizer et al., 2008).

Most studies have indicated a relatively short phase (a few months after the fire to 3 years) of fire-induced SWR (Cerdà and Doerr, 2005; Doerr et al., 2009; MacDonald and Huffman, 2004; Pereira et al., 2014), with a maximum duration of 6 years recorded in alpine forest following a severe fire in Oregon (Dyrness, 1976). The increase in SWR after a fire event is often followed by a sharp decrease to lower values than the natural level due to erosion and leaching of hydrophobic components. Continuing accumulation of SOM and the recovered soil biotic activity facilitate a gradual increase in SWR; in Mediterranean soil, these processes might last a couple of decades (Tessler et al., 2013). After recurrent fires, however, SWR rehabilitation is more complicated, and may take an even longer time period (Malkinson and Wittenberg, 2011; Tessler et al., 2013).

1.2. Recurrent fires

The current scientific literature is mainly concerned with the effects of a single fire event, at several spatio-temporal scales; with little attention paid to the role of recurrent fires, or even long-term fire studies with the exceptions being Cerdà and Doerr (2005) and Lasanta and Cerdà (2005). Studies have addressed the compound effects of recurrent fires in relation to vegetation regeneration, runoff and sediment production and hydrophobicity dynamics (Malkinson et al., 2011; Tessler et al., 2013), soil changes (Martín et al., 2012; Novara et al., 2013; Tsibart et al., 2014), ash properties (Pereira et al., 2014) and restoration and rehabilitation strategies (Fernández et al., 2012).

The Mediterranean ecosystem is well adapted to wildfire and exhibits a high resilience capability. However, short intervals between burnings may lead to prominent changes in soil properties, vegetation composition and structure (Malkinson et al., 2011). After recurrent fires, the ecosystem, rehabilitation is more complicated, and may take decades to return to pre-fire condition (Tessler et al., 2013). Previous studies conducted at Mt. Carmel indicated that in sites where the last fire occurred 4–10 years earlier, vegetation cover was mostly composed of shrubs and dwarf-shrubs with *Pistacia lentiscus* and *C* = *Cistus salvifolius*, as the dominant species. With the increasing number of short-interval fires, the relative cover of herbs and sub-shrubs markedly increased. Additionally, in the recurrent fire plots a decrease in the general tree cover was monitored.

This study explores SWR as a process that results from multiple and interacting factors, including fire history, vegetation recovery, and post-fire management, as determining factors in a time dependent system. It examines the long-term (decadal) influence of wildfires on SWR under various factors including: (i) plant species, (ii) fire history (one/twice burned recently and burnt >50 years ago), and (iii) post-fire management practices (CC/natural regrowth). In addition, it assesses the short-time scale variation in SWR after rainfall events and subsequent wetting–drying cycles and how these dynamics differ for the conditions of the sites depending on their history and plant cover.

2. Materials and methods

2.1. Study area

The study area is located on the Mount Carmel range in northwestern Israel (Fig. 1; 35°W, 32°N; Wittenberg et al., 2007a). The climate in this part of the Mediterranean has wet cool winters and dry hot summers. The rainy season generally starts at the end of September and ends at the end of May. Mean annual precipitation ranges from 500 mm at the coast to 750 mm in the uplands (Wittenberg et al., 2007b). Soil is characterized as brown or gray rendzina; rich in chalk and limestone (Tessler et al., 2008). The experiments took place on the northern slopes of the range where the lithology and the topography are homogeneous and were subjected to wildfires in 1989 and 2005 (Fig. 1; Kutiel, 1994; Inbar et al., 1998; Tessler et al., 2008, 2013).

A typical Mediterranean maquis covers Mount Carmel, characterized by a blend of high-standing plants, shrubs and trees which are well adapted to recurring wildfires (Naveh and Carmel, 2003). Shrubs such as *P. lentiscus* L., *C. salviifolius* L. are growing alongside tree species such as *Quercus calliprinos* Webb, *Arbutus andrachne* L. and *Pinus halepensis* Mill. *P. halepensis* Mill. is an obligatory seed regenerator as regrowth relies on the production of seeds. Heat triggers the opening of the otherwise closed cones from which seeds are released. Other plants such as *P. lentiscus* L. are obligatory root resprouters, but are more resistant to fire damage. They resprout in the following season taking full advantage of the rich starch reserves located in their root systems. While *C. salviifolius* L. is an example of a facultative root resprouter that can either regrow from the root crown or by seed germination.

Over a five year span (2003–2007), an average of 1000 ha of forested Israeli land was burnt every year (FAO, 2010). After the 1989 and 2005 wildfires, two types of management practices were adopted in the Mount Carmel area. The most common practice in the region was the removal of all burnt vegetation ('clear-cut' (CC)) using heavy machinery. Burnt trunks were felled and removed out of the burnt site and the balances were chipped and distributed over the soil. Most trees were logged to avoid the accumulation of potential fire fuel. However, small portions of the area were left untouched allowing vegetation to naturally regrow.

2.2. Research setup and measurement methods

On the northern slopes of the Mount Carmel ridge, four research plots were delineated (Fig. 1) in an area that was subjected to a number of fire events: burnt once (1989) – one plot; twice (1989 and 2005) – two plots; or not burnt during the last 50 years (control site) – one plot. Furthermore, within each of the burnt plots, we identified areas where post-fire management practices differed: parts of each plot were CC, and others were left to naturally regenerate. Within the research plots, we selected tree species representative of the local vegetation; *P. halepensis*, and *P. lentiscus*, and the dominant shrub *C. salviifolius*.