Geomorphology 125 (2011) 186–192

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Post fire induced soil water repellency—Modeling short and long-term processes

Dan Malkinson [a,b], Lea Wittenberg [a,*]

[a] Department of Geography and Environmental Studies, University of Haifa, Haifa 31905, Israel
[b] The Golan Research Institute, University of Haifa, Haifa 31905, Israel

ARTICLE INFO

Article history:
Received 3 December 2009
Received in revised form 2 September 2010
Accepted 15 September 2010
Available online 1 October 2010

Keywords:
Hydrophobicity
Mathematical model
Soil water repellency
Water drop penetration test
Wildfires

ABSTRACT

Soil water repellency has direct implications to hydrological as well as geomorphological processes, especially in fire-prone ecosystems. Five predominant mechanisms have been described as generating water repellency in soils: fungal and microbial activity, growth of particular vegetation species, organic matter, heating of the soils by wildfires and soil characteristics. Herein we synthesize among these mechanisms and propose a general model describing the long-term properties of water repellency in soils. Using non-linear regression analysis methods we compare among different variants of the model in order to assess the relative role of vegetation on water-repellency dynamics. We suggest that following a wildfire event hydrophobic peak soil properties are dictated by vegetation properties, but that the rapid decrease is not associated with the vegetation. Following wildfires, the recovery of the ecosystem commences and water-repellency is characterized by increased predominance of the biotic activity. Thus, the general pattern of a rapid decrease and a long-term increase in water repellency can be described by a mathematical model presented herein.

1. Introduction

The phenomenon of changes in soil wettability and hydrophobicity has been long reported and studied. Publications reporting such changes date back to the earlier parts of the 20th century (Schreiner and Shorey, 1910; Schantz and Piemeisel, 1917), and since then numerous studies have been published regarding this phenomenon. Dekker et al. (2005) report on an exponential increase in the number of publications relating to this topic, during the last several decades, and over 2100 publications were published by 2009 related to fire and water repellency. Doerr et al. (2000), in their seminal review of the causes and characteristics of soil water repellency (WR), classify the factors generating hydrophobicity to five predominating categories: fungal and microbial activity, growth of particular vegetation species, organic matter, heating of the soils by wildfires and soil characteristics. While these factors have been studied extensively, attempts to investigate and describe the long-term (decadal) changes of water repellency at a given site are lacking. Further, it is not possible to use a single parameter or individual soil (or vegetation) characteristics to predict accurately the occurrence or the degree of soil WR (McKissock et al., 1998)

The underlying approach presented herein is comprised of a literature review of the mechanisms generating WR, and the development of a general mathematical model synthesizing between them. Further, we present a case study of sampling water repellency in areas burnt in different events during a 16 year period, at the Carmel Mountain in northern Israel, and discuss it within the framework of the model.

1.1. Soil properties and water repellency

WR following forest fires in Mediterranean climatic regions has often been reported under pine forests, eucalyptus forests and natural maquis (Ferreira et al., 2000; Mataix-Solera and Doerr, 2004; Tessler et al., 2008). These studies, however, have generally been confined to acidic soils (Doerr et al., 1998; Scott, 2000; Huffman et al., 2001). Whether WR occurs also in burnt or unburnt alkaline soils (pH>7), under pines is less certain (Mataix-Solera and Doerr, 2004). One of the principal causes of soil WR is the presence of organic matter (OM) (Jaramillo et al., 2000). Direct mechanisms and relations, however, between WR and OM content are not fully understood and several processes have been previously suggested to elucidate the effect of OM on WR. For example, OM is thought to increase aggregate stability by lowering the wettability and increasing the cohesion of aggregates (Chenu et al., 2000); this is influenced mostly by both the quality and quantity of OM in the soil (Piccolo, 1996). Whilst several studies reported on improvement in aggregate stability with the increase of OM, others indicated that it is the composition of OM and especially the humified fractions that are responsible for aggregate stabilization rather than the total amount of OM (Dutarte et al., 1993). Increased aggregate stability generated from OM is attributed to the hydrophobic properties and stronger intermolecular associations of the OM (Haynes and Swift, 1990; Haynes, 1993). Several organic fractions were shown to be responsible for the hydrophobicity of soils: humic

* Corresponding author. Tel./fax: +972 4 8249605.
E-mail address: leaw@geo.haifa.ac.il (L. Wittenberg).

0169-555X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.09.014

acids (Giovannini et al., 1983; Jouany and Chassin, 1987), aliphatic fractions (MacGhie and Posner, 1980; Ma'shum et al., 1989), or plant litter debris (Mataix-Solera et al., 2008). It has not been demonstrated, however, to which extent clay–OM associations have hydrophobic properties, nor whether they contribute to soil aggregate stability.

Adhikari and Chakrabarti (1976), using OM-free soils, showed that addition of humic acid increased soil WR. This phenomenon was not the result of any binding action of OM within the soil; rather, it was probably due to the formation of a hydrophobic complex film on the soil. Thus, various components of OM, depending on the hydrophobic or hydrophilic substances, might yield different, and even opposite, correlation trends between OM and degrees of hydrophobicity.

In addition to OM, soil mineral properties have been demonstrated to determine WR properties. Soil clay content, and type, can significantly affect soil response to heating. Mataix-Solera et al. (2008) demonstrate that calcareous soils with high kaolinite contents remained wettable through all heating treatments, while soils with low kaolinite were potentially water repellant. Mataix-Solera and Doerr (2004) reported on a reasonable correlation between OM and water drop penetration test (WDPT) times for ten soil samples, taken from calcareous and thus an alkaline soil, from fire-affected pine forests in southeastern Spain. DeBano (1991) suggested that soils containing more than 2% OM will exhibit some degree of WR following heating, but exceptions to this have been found (e.g., Arcenegui et al., 2008). Consequently, it has been suggested that formation of WR may depend on other soil properties, such as grain size distribution (DeBano, 1991), OM/clay ratio and the mineralogy of the clays (Lichner et al., 2006; Mataix-Solera et al., 2008). For example, in the Mediterranean region terra rossa soils are less likely to become water repellent by burning owing to the relatively low soil OM/clay ratio and the high proportion of kaolinite in the clay fraction compared to other soils of the region (Mataix-Solera et al., 2008). Soil WR is also associated with coarse-textured, sandy soils (Doerr et al., 2000). Coarser particles are more susceptible to developing WR because of their smaller surface area per unit volume. Previous findings (DeBano, 1991) suggested that WR is commonly found in soils with less than 10% clay content. Recent studies, however, indicate that WR is also common in soils with 25–40% clay content, as long as the clay aggregates and thus reduce the relative surface area of the particles (Doerr et al., 2000).

1.2. Fire and hydrophobicity

The relationship between fires and soil hydrophobic properties has been investigated experimentally and in field studies. DeBano's (1981) review of WR in soils describes the mechanism through which WR is formed in heated soils. Experiments indicated that release of aliphatic hydrocarbons as a result of heating the organic material, generates water repellent compounds. During a forest fire, the heat released during combustion vaporizes organic substances, some of which migrate downwards into the soil where they condense and coat mineral particles (DeBano, 2000). Maximal production of hydrophobic compounds is generated when soils are heated to temperatures of 176–204 °C. Temperatures of 250 °C, however, are required to fix these compounds onto soil particles in order to form a water repellent layer (DeBano, 1981), whereas at higher temperatures these compounds are destroyed. Since a strong temperature gradient is formed in the soil during a fire event, the hydrophobic compounds vapor may migrate to deeper depths in the soil, or formed there, if enough organic matter is present (Letey, 2001).

Ample evidence on the relationship between fires and changes in soil properties is also available from field studies and observations (Hubbert et al., 2006). It should be noted, however, that WR values observed at areas in which fires were prescribed are usually lower compared to values obtained from wildfires (Ferreira et al., 2005). Accordingly, Coelho et al. (2004) found WR values to be lower in prescribed-burn sites compared to areas burned by wildfires.

Ferreira et al. (2005) investigated the effects of wildfires on hydrological processes at a range of spatial scales following wildfires. Rainfall simulators were used in 0.24 m^2 plots to assess erosion and overland flow. At larger scales, 16 m^2 plots were used to measure overland flow, and runoff was compared between burned and unburned forested catchments. In all spatial scales the response variables (overland flow and runoff) increased with increasing fire severity. At the watershed level such results may not be consistent for several reasons. It is possible that the extent of the wildfire compared to the watershed is not large enough to generate a response at the watershed scale. Another reason may be the existence of heterogeneous water repellent patches, dispersed among wettable patches which serve as infiltration sinks, or rocky outcrops which may consist of fractures through which water can penetrate to deeper soil layers.

1.3. Time and hydrophobicity

Following a wildfire event and the generation of a hydrophobic layer due to the heating of organic compounds in the soil, studies demonstrated the relatively rapid diminishing of the WR phenomenon. Huffman et al. (2001) found that within a three-month period following a wildfire in a *Pinus ponderosa* forest in the Colorado Front Range, WR significantly weakened, but persisted for at least 22 months. Hubbert and Oriol (2005) also demonstrate the short duration of fire induced WR, which diminished within two months following a fire event. Reeder and Jurgensen (1979) report that WR persisted for approximately a year following a wildfire event in 65% of an area burned in Michigan. The short-term duration of fire induced water repellency has not been observed consistently in all cases. Dyrness (1976) reports on the persistence of WR of up to six years following a forest fire in Oregon.

1.4. Long term changes in water repellency

Long-term studies assessing changes in soil hydrophobicity are lacking. As time passes from the fire event biotic activity proliferates in the system, as vegetation and microfauna populations recover and microbial activity in the soil increases. Vegetation recovery may affect WR in two manners. First, with the growth and maturation of the vegetation OM accumulates, and this, in turn, may lead to increased WR as described above. Additionally, soils under particular plant species exhibit stronger hydrophobicity. Typically, this occurs in soils beneath evergreen vegetation, such as different pine and eucalyptus species (Doerr et al., 2000). Other factors which may increase WR with time are bacterial and fungal activity, which are typically associated with the accumulation of OM in the soil. Hallett (2008) found a positive correlation between fungal biomass in soils and WR. Hence, following a fire event, the importance of these factors may increase, as the biological activity increases over time.

The short-term decrease in WR results from the breakdown of hydrophobic compounds which are formed during the heating of the soil in times of fire. As time passes, soil OM increases, humus accumulates, and fungal activity intensifies. These processes which have been reported to be positively associated with hydrophobicity (Wallach et al., 2006), operate at much longer time scales compared to fire generated WR.

The processes reviewed previously have been extensively discussed in the literature. The objective of this study was to synthesize among them by conducting a serious of field measurements in conjunction with developing a mathematical model.