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Fire Effects on Soils and Restoration Strategies

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Soil Water Repellency: A Key Factor in Post-fire Erosion

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Abstract

Soil water repellency (hydrophobicity) prevents water from wetting or infiltrating dry soil. This condition has been documented under a wide range of vegetation types and climates and particularly following forest fires. Water repellency is of considerable interest to land managers, hydrologists and soil scientists because i) it can be induced, enhanced or destroyed during burning and ii) its presence can cause a marked reduction in infiltration rate. This reduction in infiltration is commonly presumed to be the primary cause of the increases in runoff and erosion that are often observed at a range of scales following forest fires. The goal of this chapter is to provide a basic understanding of soil water repellency, its measurement, the effects of burning on soil water repellency, and its relative importance in runoff and erosion processes at different scales.

It is widely accepted that water repellency is caused by the presence of organic compounds with hydrophobic properties on soil particle surfaces. During burning such substances in the litter and topsoil can be volatized and condensed in the soil, inducing or intensifying water repellency. During very hot fires, however, these compounds can be destroyed and the soil surface is rendered wettable. In many cases fire increases repellency, which tends to be confined to the top centimeters of the soil, and often is highly variable spatially, temporally and in its degree. It is typically most pronounced under dry conditions and reduced or absent following prolonged wet conditions. The duration and amount of wetting needed to reduce or eliminate soil water repellency, however, varies with soil type, burn severity, and the persistence of soil water repellency prior to wetting.

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Burning also induces a series of other changes to soils and the vegetative cover that may be just as, or possibly even more, important in causing the observed increases in runoff and erosion following fire. These factors make it challenging to assess the role of water repellency in post-fire hydrology and erosion processes. This is particularly so at larger scales due to the high spatial variability of many factors involved and the difficulty in characterizing the counteracting role of wettable soil patches, ash, bioturbation, soil cracks, and burned-out tree roots in reducing the surface runoff engendered by strongly water repellent patches.

Research to date has demonstrated that water repellency can strongly affect post-fire runoff and erosion processes and the factors that can enhance or reduce the relative impact of water repellency in burned landscapes have been reasonably well established. Quantifying and predicting the relative contribution role of water repellency in post-fire erosion processes, however, remains a major challenge particularly at larger scales. Additional manipulative experiments and more detailed monitoring are needed to provide a better knowledge base on the extent of the impact of soil water repellency on runoff and erosion in the field under natural rainfall events at different scales.

INTRODUCTION

Soil water repellency refers to the inability of water to wet or infiltrate soil, and this phenomenon has been documented in a wide range of vegetation types and climates (Doerr et al. 2000, Dekker et al. 2005). Soil water repellency is of considerable interest to soil scientists and land managers because of its implications for increasing runoff and erosion. Much of the research on soil water repellency has focused on the effects of wild and prescribed fires, as numerous studies have suggested that soil water repellency is the primary cause of reduced infiltration rates after burning. This reduction in infiltration is commonly presumed to be the primary cause of the observed increases in post-fire runoff and erosion at the plot, hillslope and watershed scales (e.g., Sartz 1953, DeBano et al. 1970, Swanson 1981, Scott and Van Wyk 1990, Inbar et al. 1998, Robichaud et al. 2000, Shakesby and Doerr 2006).

The goal of this chapter is to provide a basic understanding of soil water repellency, the effects of burning on soil water repellency, and the effects of this soil water repellency on overland flow and erosion rates at different scales. The first part of this chapter provides an overview of the origin, occurrence and measurement of soil water repellency. We then summarize the effects of burning on the strength and persistence of soil water repellency in different vegetation types, and highlight some of the difficulties in accurately characterizing soil water repellency. The next section reviews current knowledge with respect to the role of post-fire soil water repellency in

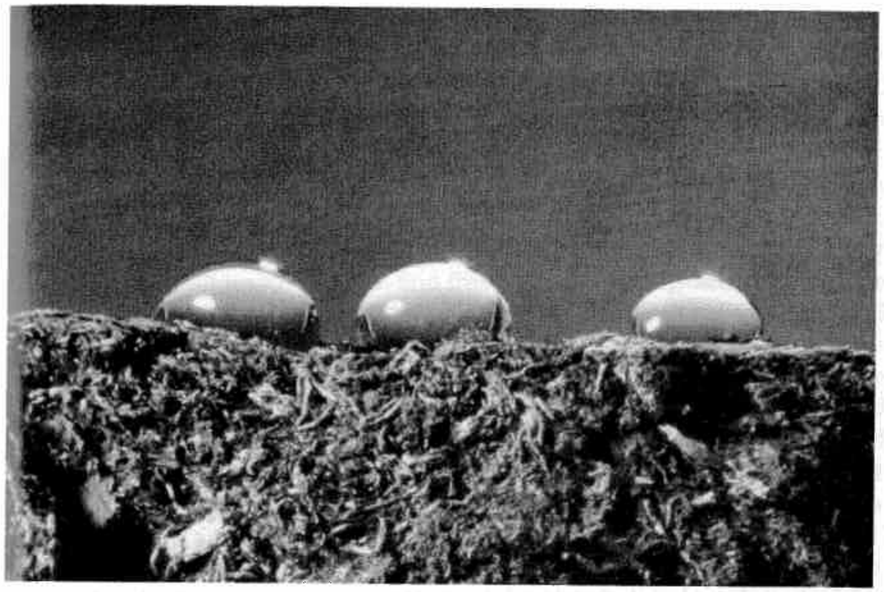

Fig. 1 Water drops resting on a highly repellent organic-rich soil (photo by Erik van den Elsen).

increasing runoff, increasing erosion, and causing land degradation. The understanding provided in the first part of the chapter is used to help explain some of the apparent disparities in the literature. The reader is referred to a series of recent reviews for more detailed information on most of the topics that are covered in this chapter (Neary et al. 1999, 2005, DeBano 2000, Doerr et al. 2000, Shakesby et al. 2000, Letey 2001, Doerr and Moody 2004, DeBano et al. 2005, Shakesby and Doerr 2006).

ORIGIN, OCCURRENCE AND MEASUREMENT OF SOIL WATER REPELLENCY

Origin of Water Repellency

It is commonly assumed that soils wet readily under rainfall or irrigation, but an increasing body of literature indicates that this is often not the case. Many soils behave in a water-repellent manner at low or moderate moisture contents under both burned and unburned conditions (Fig. 2). Schreiner and Schorey (1910) were amongst the first to document soil water repellency, as they described a soil in California that *"could not be wetted, either* [sic] *by man, by rain, irrigation, or the movement of water from the subsoil"*. Another early study showed that soil water repellency reduced the productivity of citrus orchards in Florida (Jamison 1942). Numerous other examples of soil water repellency in unburned areas can be found in the literature (Doerr et al. 2000), and during

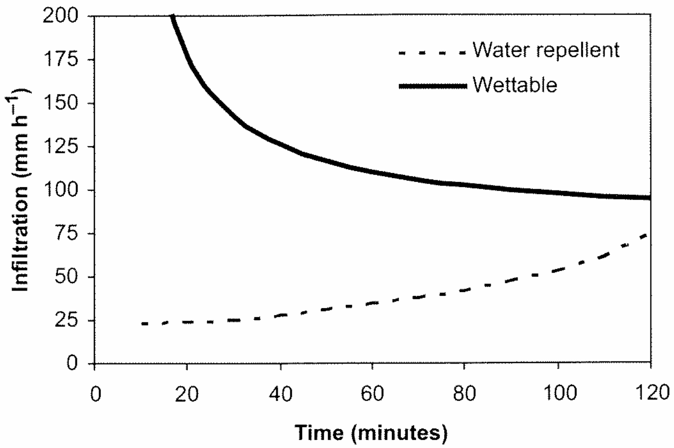

Fig. 2 Infiltration rates into water repellent and wettable soil (modified from Letey et al. 1962).

the 1990s and early 2000s it became evident that soil water repellency is widespread and not restricted to burned areas or a narrow set of other conditions.

Water repellency in unburned soils has been reported from all continents except Antarctica, for climates that range from seasonal tropical to subarctic, for soils that range from coarse- to fine-textured, and for many of land uses, including plowed cropland, grasslands, shrublands, and a wide range of forest types (e.g., Wallis and Horne 1992, Bauters et al. 2000, Doerr et al. 2000, 2006a). In some industries, such as horticulture and turf grass, wetting agents are widely used to increase soil wettability (e.g., Cisar et al. 2000).

The different techniques used to assess soil water repellency measure either the 'strength' or the 'persistence' of soil water repellency (see following section). Both properties can vary from extremely high, such as under eucalyptus plantations in Portugal (Doerr et al. 1998), to only being detectable with a purpose-built micro-infiltrometer as reported for some agricultural soils in Scotland (Hallett and Young 1999). Most scientists working on soil water repellency agree that *"water repellency in soils is the norm rather than the exception, with its degree being highly variable"* (Wallis et al. 1991). In general, soil water repellency is confined to the top centimeters or decimeters of soil where organic molecules with hydrophobic properties are present on the surfaces of soil pores. Water repellency occurs when the hydrophobic 'ends' of these molecules are oriented towards the pore space.

Molecules with hydrophobic properties are ubiquitous in the environment. Plants produce these compounds to protect leaf surfaces from desiccation, and to help repel insects or microbes. These hydrophobic molecules are relatively resistant to physical or chemical degradation, so they are common in vegetated soils and are believed to be the cause of soil water repellency (Doerr et al. 2000). Unfortunately the degree of soil water repellency cannot be predicted reliably from soil organic matter content or the amount of hydrophobic compounds (Doerr et al. 2005a). Hence it is still not completely clear why some soils exhibit soil water repellency and others do not. Specific combinations of organic compounds (Morley et al. 2005) and their inter-molecular arrangement in response to environmental conditions (Roy and McGill 2000) seem to be critical.

A review of the literature indicates that certain soil and vegetation combinations are particularly likely to develop strong soil water repellency. Coarse-textured soils are more susceptible to the development of soil water repellency than finer textured soils, and this is thus generally attributed to the much smaller particle surface area and hence the number of potential adsorption sites for organic molecules. Soils under vegetation types with oil- or wax-rich leaves, such as sclerophyllous shrubs, conifers, and eucalypts, are much more prone to develop strong water repellency than under broad-leaved deciduous forests (Doerr et al. 2000 and references therein). Under unburned conditions this soil water repellency is typically strongest at the surface of the mineral soil and drops off rapidly with depth (e.g., Huffman et al. 2001). Many of the vegetation and soil types that are likely to exhibit strong soil water repellency under unburned conditions are also particularly susceptible to wildfires. As discussed below, burning can greatly affect the magnitude and depth of soil water repellency, and burning is more likely to enhance soil water repellency in vegetation types that are prone to soil water repellency under unburned conditions.

Measurement and Classification of Water Repellency

There are many techniques for measuring and classifying soil water repellency, and these are summarized in Tschapek (1984), Wallis and Horne (1992) and Letey et al. (2000). The two primary techniques for assessing soil water repellency are the 'Water Drop Penetration Time' (WDPT) test (Van't Woudt 1959) and the 'Molarity of an Ethanol Droplet' (MED) test (also known as the 'Percentage Ethanol' or 'Critical Surface Tension' test) (Letey et al. 2000).

In the WDPT test water drops are applied to the soil being tested and the investigator simply notes how long it takes until these water drops are absorbed into the soil. A longer duration indicates stronger water repellency, and the WDPT is best considered as measuring the *persistence* of soil water repellency. In the MED test, drops with an increasing concentration of ethanol are applied to the soil to measure indirectly the apparent soil surface tension. This effectively determines how strongly the water is repelled, and this property is considered the *strength* or *severity* of soil water repellency (Letey et al. 2000). The persistence and strength of soil water repellency are often related, but the relationship is not always clear or consistent (Dekker and Ritsema 1994). Some of the more recent literature relating to these tests includes Dekker et al. (1998), Doerr (1998), Roy and McGill (2002), and Shirtcliffe et al. (2006).

Both the WDPT and the MED tests provide quantitative data, but the subsequent classification or characterization of these data vary with the investigator's objectives and perception of what constitutes low or high soil water repellency (Table 1). WDPT thresholds as short as 1 (Roberts and Carbon 1971) and 5 sec (Bisdom et al. 1993) have been used to distinguish between wettable and water repellent soils. The U.S. Department of Agriculture, Forest Service (1995) uses only 3 categories, as a WDPT of less than 5 sec indicating no water repellency, 5 to 40 sec as moderately water repellent, and a WDPT greater than 40 sec is characterized as strongly water repellent. The different definitions of the various water repellency classes used can hinder the comparison of results among studies. One widely used set of water repellency classes for the WDPT test is presented in Table 1.

The comparability and statistical analyses of WDPT data also are complicated because the maximum time of observation varies among studies, and the maximum time of observation effectively truncates the data. For practical reasons most studies do not make observations for more than 600 sec. In many studies WDPTs of less than 600 sec have been reported, however, higher values are also commonly found in burned and also unburned soils (e.g., Dekker et al. 2001, Doerr et al. 2006a, b).

Table 1 Water Drop Penetration Time (WDPT) class intervals in seconds (upper limit) and associated repellency persistence rating.

WDPT interval	<=5	10 30 60	180 300 600	900 1800 3600	18000 >18000
Persistence rating [1]	-	slight	strong	severe	extreme

[1] based on Bisdom et al. (1993)

The reported values also can vary with the exact methodology used to collect and analyze the data. Most studies use multiple drops to ascertain the WDPT for a given sample, but the reported value can vary depending on whether one uses the maximum observed value, the mean, or the median. The median is generally considered to provide the most accurate index of soil water repellency because the mean can be greatly affected by one or a few drops with very long penetration times. Furthermore, a few very high values may not be of much practical significance because of the typically high spatial variability in soil water repellency.

The MED test is less commonly used by field practitioners but is preferred by many researchers because the observation times are much shorter and it may exhibit less variability (e.g., Huffman et al. 2001). Table 2 provides the molarity and surface tension values for the most commonly used volumetric concentrations of ethanol, and two different schemes for converting the MED values to a categorical classification of soil water repellency.

The analysis of MED data is complicated because one typically uses a set of predetermined solutions to assess soil water repellency as indicated in Table 2. Since only certain concentrations are used, the MED data are discrete rather than continuous and should be analyzed using nonparametric statistics. It also is important to note that the surface tension of water decreases quite markedly as temperature increases, so the surface tension values in Table 2 are only applicable at 20°C.

Table 2 Ethanol concentrations, Molarity of an Ethanol Droplet (MED) values, apparent surface tension (γ), and two associated descriptive classifications used in water repellency testing.

% Ethanol (vol.)	Molarity (MED)	γ (mNm^{-1})	Severity rating [1]	Severity rating [2]
0	0	72.1	none	low
1	0.17	66.9		
3	0.51	60.9		
5	0.85	56.6	slight	
8.5	1.45	51.2	moderate	
13	2.22	46.3	strong	moderate
18	3.07	42.3	very strong	severe
24	4.09	38.6		very severe
36	6.14	33.1	extreme	

[1] after Doerr (1998); [2] after King (1981)

Both the WDPT and the MED tests provide useful characterizations of soil water repellency, but it is very difficult to use either of these measurements to predict infiltration rates and the wetting behavior of bulk soil material directly (Dekker et al. 1999, Lewis et al. 2005, Doerr et al. 2006b, Cerdà and Doerr 2007). More studies are needed to link the measured soil water repellency to the infiltration rate as measured at the point scale with infiltrometers, the small plot scale using rainfall simulators, and runoff rates at the small watershed scale.

Changes to Water Repellency during Burning

Burning induces or enhances soil water repellency by volatilizing the hydrophobic organic compounds in the litter and topsoil. The simultaneous development of a pressure gradient in the layer being heated causes some of these compounds to be driven upwards into the atmosphere while some are forced downwards. The decline in soil temperature with depth means that these compounds will condense onto cooler soil particles at or below the soil surface (DeBano et al. 1976). The heat generated by burning, in addition to redistributing and concentrating the naturally-occurring hydrophobic substances in the soil and litter, is also thought to make these compounds more hydrophobic by pyrolysis and conformational changes in their structural arrangement (Doerr et al. 2005b). Burning also is believed to facilitate the bonding of these substances to soil particles (Savage et al. 1972, Giovannini 1994). Laboratory studies show that soil water repellency is intensified at soil temperatures of 175 to 270°C, but is destroyed at temperatures above 270 to 400°C. The duration of heating can also affect the degree of soil water repellency with longer heating during influencing the temperature at which these changes occur (e.g., DeBano et al. 1976, Doerr et al. 2004). When there is insufficient oxygen, the combustion of the hydrophobic compounds and hence the temperature at which soil water repellency is destroyed it may rise to 500 to 600°C (Bryant et al. 2005).

These principles mean that the effects of burning on soil water repellency can be highly variable, as fires can induce soil water repellency in soils that were largely non-repellent, and either enhance or reduce pre-existing water repellency. The effect of burning depends primarily on the amount and type of organic matter consumed, the duration and amount of soil heating, and the amount of oxygen available during burning (DeBano and Krammes 1966, Robichaud and Hungerford 2000, Doerr et al. 2004, Bryant et al. 2005). Figure 3 illustrates some of the different soil wettability scenarios due to burning, which include:

i) burning can induce a low level of soil water repellency in a formerly non-repellent surface soil (e.g., Reeder and Jurgensen 1979, Cerda and Doerr 2005);
ii) a weakly water repellent soil can develop a stronger water repellent layer at or near the soil surface after burning; this has been observed after moderate and high severity fires in pine forests in the western USA (e.g., Huffmann et al. 2001, Woods et al. 2007; Fig. 3a);
iii) a high surface heating can destroy a strong or weak surface water repellency while creating increased repellency a few centimeters below the surface; this has been reported for hot chaparral fires in the western USA (e.g., DeBano 1971; Fig. 3b); and eucalypt fires in Australia (Doerr et al. 2006b; Fig. 3c);
iv) a soil that is strongly water repellent in both the surface and subsurface layers may have similar or weaker water repellency after burning when the heating was not sufficient to destroy the surface repellency and does not enhance a strong pre-existing subsurface water repellency. This has been observed in relatively wet eucalyptus stands in Portugal (Doerr et al. 1998) and in conifer forests of the northwestern USA (Doerr et al., submitted).

Numerous other scenarios can fall between these, and different scenarios can occur within the same fire depending on the conditions prior to the fire and fire behavior.

The apparent effects of burning on soil water repellency can also vary with the methodology used. For example, the position of the soil surface may be defined as the surface of the residual ash or litter after burning or the top of the mineral soil. In the former case the surface is most likely to be characterized as non-repellent because ash is typically hydrophilic rather than hydrophobic. If the ash and residual litter is first swept away, the surface is much more likely to be characterized as water repellent. The identification of the mineral soil surface can also be problematic when there is a gradual boundary between the organic and mineral layers. The surface repellency can also change quite quickly as the wettable ash and any wettable mineral layers are removed by wind or overland flow. The relationship between burn severity and soil water repellency can vary because of differences in how different investigators characterize burn severity and soil water repellency (see previous section). Finally, short-term changes in soil moisture can greatly affect soil water repellency as discussed below.

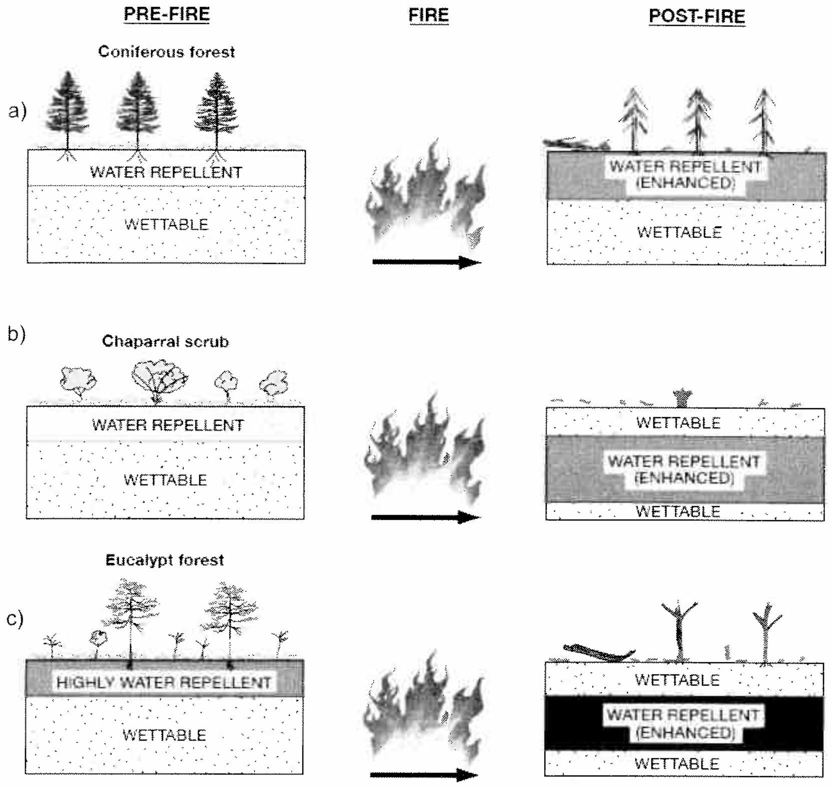

Fig. 3 Soil water repellency changes following fire for moderate or high soil burn severity conditions in: a) coniferous forest in the northwestern USA; b) Californian chaparral; and c) Australian eucalypt forest. Darker shading represents more severe repellency.

Changes to Water Repellency in the Post-fire Period

The effects of burning on soil water repellency follow directly from the combustion of the organic matter and the associated soil heating. However, soil water repellency also can change very rapidly in response to changes in soil moisture, and somewhat slower as the fire-induced changes in soil water repellency decay towards pre-fire conditions or a new status according to the amount and type of post-fire vegetation. Any effort to predict the effects of burning on infiltration and erosion must clearly distinguish between this longer-term recovery and the shorter-term changes due to variations in soil moisture.

Both burned and unburned soils become less repellent or completely lose their water repellency as soil moisture increases. A water repellent soil can resist wetting for periods ranging from a few seconds to days or even months (e.g., King 1981, Dekker and Ritsema 1994, Doerr et al. 2006b), but the strong pressure gradient and the presence of macropores or other preferential flow paths means that water will eventually enter the soil. At a certain soil moisture content (i.e., critical threshold) the soil changes from being water repellent to wettable (Dekker et al. 2001). This soil moisture threshold can be less than 5 percent (per volume) for dune sands with a low organic matter content to more than 30 percent for finer textured soils (Doerr and Thomas 2000, Dekker et al. 2001, Benavides-Solorio and MacDonald 2005). One study has suggested that the soil moisture threshold increases with increasing burn severity, but the mechanism for this relationship is unknown (MacDonald and Huffmann 2004).

Once a water-repellent soil dries out, the soil water repellency is gradually or immediately re-established. Observations by one of the authors in Colorado suggest that in burned areas this repellency may be slightly weaker than prior to wetting, so a series of wetting and drying cycles may eventually eliminate the soil water repellency induced by burning (L.H. MacDonald, unpublished data). The exact processes involved in this are not fully understood, but changes in the spatial configuration of the hydrophobic molecules such as those suggested by Roy and McGill (2000) and Morley et al. (2005) are thought to be important.

The longer-term changes in soil water repellency after burning are due to a variety of physical and chemical processes. The duration of fire-induced increases in soil water repellency is an important concern for resource managers, but relatively little is known about the factors that control the changes in post-fire soil water repellency over time. There are several reasons for this, including: i) the relative paucity of longer-term studies on post-fire soil water repellency; ii) the large variability in results amongst those studies that have been conducted; iii) the short-term changes in soil water repellency due to changes in soil moisture are not always separated from the 'true' recovery to pre-fire conditions; iv) the variation amongst investigators in terms of what constitutes soil water repellency; and v) the difficulty of identifying and characterizing the effect of the different processes on the longevity of post-fire soil water repellency.

Most studies indicate that the increase in soil water repellency due to burning will break down within a few months to a couple of years. The longest documented duration of post-fire soil water repellency was in a severely burned pine forest in Oregon, USA, where the fire-induced soil water repellency apparently persisted for 6 years (Dyrness 1976). In less severely burned sites the post-fire soil water repellency persisted for 3 to 4 years (Dyrness 1976). On the other hand, 65 percent of the soil area that was water repellent after a fire in a mixed species forest in Michigan, USA was wettable a year later (Reeder and Jurgensen 1979). A low-severity fire in mixed chaparral in California almost doubled the frequency of measurements indicating moderate to extreme surface repellency, but the frequency of water repellency returned to pre-fire values in less than two months (Hubbert and Oriol 2005).

The longevity of post-fire soil water repellency can be highly variable, even for a particular vegetation type and geographic area. Huffmann et al. (2001) reported that fire-induced repellency persisted for at least 22 months in pine stands in Colorado, USA, while in a nearby location affected by a high-severity wildfire, the soil water repellency returned to pre-fire conditions within one year (MacDonald and Huffman 2004). In a Sardinian scrubland, the moderate pre-fire surface repellency was reduced after an experimental burn, but recovered to pre-fire levels within three years (Giovannini et al. 1987). Similarly, a severe fire in a *Pinus halepensis* stand in Spain destroyed the pre-fire soil water repellency, but this returned within three years (Cerda and Doerr 2005). A moderate to severe fire in an Australian eucalypt forest resulted in a patchy destruction of, or increase in, surface soil water repellency and increased the already high subsurface water repellency. Subsequent measurements showed no significant decline in the area of wettable surface soil one and two years after the fire, but there was a progressive decline in extreme water repellency in both the surface and subsurface soil (Doerr et al. 2006b).

Relatively little is known about the different processes that control the changes in post-fire soil water repellency over time. Observations after the 2002 Hayman wildfire in Colorado showed that the fire-induced soil water repellency was longer lived at 3 cm depth than at the soil surface (MacDonald and Rough, 2005). The faster breakdown of soil water repellency at the soil surface was attributed to the physical disruption caused by freeze-thaw cycles, but it also could be due to the greater biological activity associated with vegetative regrowth or the armoring of the soil surface with larger particles. One study in a shrubland in Idaho, USA, showed that the differences in solar insolation with slope aspect affects soil moisture, and the resulting differences in soil moisture will affect both the soil water repellency and post-fire vegetative regrowth (Pierson et al. 2002). More detailed studies are needed to determine i) the duration of fire-induced soil water repellency in different vegetation types and ii) the relative roles of physical, chemical, and biological factors in breaking down post-fire soil water repellency.

EFFECTS OF SOIL WATER REPELLENCY ON HYDROLOGY AND EROSION

The primary hydrologic and erosional effects of soil water repellency include: i) lower infiltration rates (Fig. 2) and a corresponding increase in the likelihood and amount of infiltration-excess (Hortonian) overland flow; ii) more spatial variability in infiltration and soil moisture fluxes, causing an uneven distribution of soil moisture; iii) increased surface erosion due to the increase in overland flow; and iv) increased susceptibility to wind erosion due to drier soil conditions and reduced cohesion of soil particles. The reduction in infiltration can also have secondary effects, such as hindering the germination and growth of vegetation, which can prolong fire impacts on runoff and erosion rates (see reviews by DeBano 2000, Doerr et al. 2000, Shakesby et al. 2000, and Shakesby and Doerr 2006).

Soil water repellency is of particular concern in burned areas because it can be much stronger and more persistent (in terms of WDPT) than in unburned areas (Fig. 4). Water repellency is typically implicated as the main cause of the increase in overland flow and erosion after burning (DeBano 2000, Martin and Moody 2001), but the effect of soil water repellency on runoff and erosion is complicated by other fire-induced changes such as the loss of the protective litter layer, the change in soil structure and cohesion due to the loss of soil organic matter, the potential reduction in infiltration due to soil sealing, and the reduction in interception due to the loss of overstory vegetation (e.g., Shakesby et al. 1993). This is illustrated in Figure 5, where all these factors may have contributed to the occurrence of this overland flow event in post-fire terrain. The hydrological and erosional effects of soil water repellency in unburned and burned areas are discussed in more detail in the following sections.

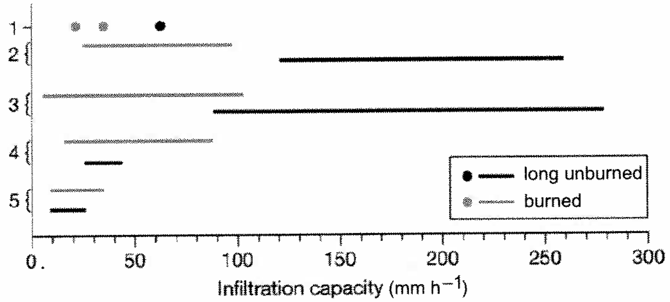

Fig. 4 Infiltration capacities measured after wildfire and on comparable unburned terrain according to various authors. Lines represent ranges of values and points represent individual values. 1) pine, Arizona, USA (Campbell et al. 1977); 2) pine and mixed conifer, Washington, USA (Martin and Moody 2000); 3) pine and eucalypt, Portugal (Shakesby et al. 1993); 4) pine and oak scrub, Israel (Kutiel et al. 1995); and 5) oak scrub, Spain (Imeson et al. 1992) (from Shakesby and Doerr 2006).

Fig. 5 Overland flow transporting burned soil, ash and charred debris during intense rain following wildfire in eucalypt forest in the Victorian Alps, southeast Australia in 2003 (photo by Rob Ferguson).

Hydrological Effects of Soil Water Repellency

One of the most striking consequences of soil water repellency is the reduction in the infiltrability (or infiltration rate); extremely water repellent soils may show very little wetting during rainstorms. For example, 40 to 46 mm h^{-1} of simulated rain caused minimal wetting of some strongly water repellent forest soils in Portugal (Walsh et al. 1998), even though the infiltration capacities of these same soils were around 80 mm h^{-1} in the laboratory when rendered non-repellent (Doerr et al. 2003). In laboratory experiments these soils remained dry despite having a ponded water layer for more than three weeks (Doerr and Thomas 2000). DeBano (1971) found that in the first five minutes the infiltration into a water-repellent soil was only one percent of the value when wettable; the maximum infiltration rate was 25 times less than a similar soil rendered hydrophilic by heating (see Fig. 2). Empirical data indicate a positive and significant relationship between soil water repellency and the amount of runoff from rainfall simulations (Robichaud 2000, Benavides-Solorio and MacDonald 2001, 2002), but few studies have rigorously isolated the effect of soil water repellency on infiltration and runoff. A recent study found that the application of wetting agents caused a 16-fold increase in infiltration from simulated rainfall on bare soils in eucalypt stands with strong soil water repellency (Leighton-Boyce et al. 2007).

A moderate reduction in infiltration rates due to soil water repellency would be expected to have minimal effect if the infiltration rate is still greater than rainfall intensities. In areas with distinct wet and dry seasons, an increase in soil water repellency may only be important for the first few storms, as once the soil wets up the water repellency is eliminated until the soil dries out. In snowmelt-dominated areas, soil water repellency is rarely a problem because snowmelt rates tend to be low relative to rainfall intensities, and the initial snowmelt would typically be expected to wet the soil beyond the critical soil moisture threshold. This explains why there is virtually no surface runoff or erosion during the winter and spring from severely burned areas in the central and northern Rocky Mountains, USA (Benavides-Solorio et al. 2005). Soil water repellency can have a much greater effect on infiltration and runoff under dry conditions when the soil moisture is below the critical threshold (Shahlaee et al. 1991, Walsh et al. 1994, Soto and Díaz-Fierros 1998, Doerr and Thomas 2000, Dekker et al. 2001). In an Australian eucalypt forest, exceptionally dry conditions were reported to enhance repellency and cause an increase in the overland flow coefficient from 5 to 15 percent (Burch et al. 1989).

Comparison of infiltration capacities from burned and unburned sites in Fig. 4 show the possible range in response. In two of the five studies, burning had no apparent effect on infiltration capacities, while burning greatly decreased infiltration rates in the other three studies. Post-fire soil water repellency is of greatest concern when it is sufficient to cause a shift in the dominant runoff process from subsurface stormflow to overland flow. In most unburned forests and shrublands the infiltration capacity is greater than rainfall intensities, and storm runoff is dominated by subsurface stormflow or saturation overland flow (Dunne and Leopold 1978, Hewlett 1982). In certain vegetation types burning can reduce the infiltration rate to the extent that even moderate rainstorms may exceed the infiltration rate. In the lower montane forests in Colorado, for example, summer thunderstorms with intensities of 60 to 65 mm h^{-1} generate no surface runoff or erosion, but in the first two years after burning, rainfall intensities of only 8 to 10 mm h^{-1} generate extensive surface runoff and erosion (Moody and Martin 2001, Benavides-Solorio and MacDonald 2005, Kunze and Stednick 2006). This remarkable difference, however, can not only be attributed to post-fire water repellency, but also to other fire effects such as vegetation removal as outlined in more detail in the next section. Overland flow generated as a result of post-fire soil water repellency is generally characterized as infiltration-excess or Horton overland flow (Horton 1933), but the presence of a wettable surface layer above a strongly repellent layer can induce a shallow layer of saturation overland flow (Walsh et al. 1994, Doerr et al. 2006b).

The reduction in infiltration after burning is exacerbated by the concomitant loss of interception and storage losses in the vegetation and litter, and this also acts to increase the amount of runoff. In high-severity fires, there also is a loss of surface roughness, and this increases the velocity of the overland flow and hence the size of peak flows. The exposure of the mineral soil surface to rainsplash, sheetwash, and rill erosion also may induce soil sealing, which further reduces the infiltration rate (Shakesby and Doerr 2006).

The net effect of these changes is that the size of peak flows can increase by one or more orders of magnitude (Robichaud et al. 2000, Neary et al. 2005). For example, there was a 5- to 15-fold increase in summer peakflows after burning for a chaparral site in Arizona (Robichaud et al. 2000), and a comparable increase was observed after burning for summer convective storms in a ponderosa pine forest in Colorado (Kunze and Stednick, 2006). Scott (1993) also noted an increase of up to two orders of magnitude in peak flows following burning in South Africa. In a burned pine forest in South Africa stormflows were 7.5 percent of precipitation as compared to 2.2 percent in unburned areas, and this difference was attributed to saturation overland flow in the wettable surface layer (Scott and Van Wyk 1990).

Other studies have shown little increase in runoff after burning because the change in infiltration was not sufficient to induce infiltration-excess overland flow (see, for example, Anderson et al. 1976). In oak woodlands in northeast Spain, burning increased the water-holding capacity of moderately water repellent soils by stabilizing water-retaining pores (Imeson et al. 1992). After several years these pores were lost by compaction and the infiltration capacity was reduced, but overall there was little difference in infiltration rates between the burned and unburned soils.

Burning can also affect the amount of runoff when much of the overstorey vegetation is killed, as this will reduce interception and transpiration rates. In areas with at least 450 to 500 mm of annual precipitation, annual water yields will increase. This increase, however, is typically smaller than the potential change in the size of peak flows because annual water yields are driven primarily by changes in evapotranspiration while peak flows are driven by the change in runoff processes on a storm by storm basis (Anderson et al. 1976). Similar to what is observed following forest harvest, the fire-induced increases in annual water yields tend to be greatest in humid ecosystems with denser pre-fire vegetation and high pre-fire evapotranspiration rates (Anderson et al. 1976, Robichaud et al. 2000).

Conclusive investigations into the larger-scale effects of soil water repellency are hindered by the high spatial variability in soil water repellency and infiltration rates. Intensive sampling of soil water repellency along burned transects in Colorado and Montana indicated an autocorrelation length of only about 2 m (Woods et al. 2007), and this high spatial variability is consistent with the results of most other studies (e.g., Huffman et al. 2001, Hubbert et al. 2006). In unburned soils the probability distribution of infiltration rates typically follows a lognormal distribution and also shows a relative low level of spatial correlation (e.g., Loague and Gander 1990). This suggests that the generation of overland flow is spatially heterogeneous, and as spatial scale increases there is a greater likelihood of encountering patches at the extreme end of the probability distribution where there are relatively high infiltration rates. In burned areas the overland flow generated from severely water repellent patches may infiltrate farther downslope in less

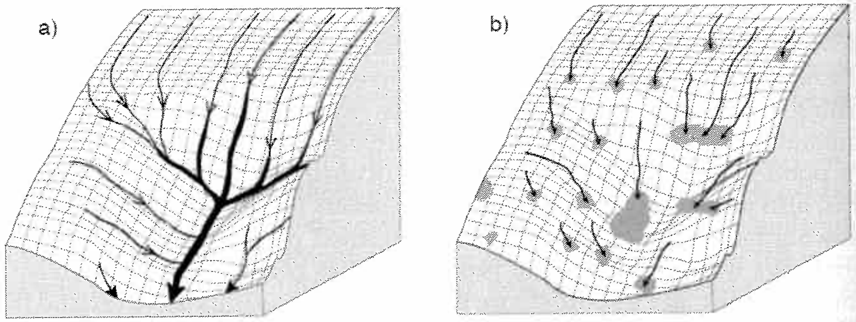

Fig. 6 The possible influence of variation in the spatial contiguity of water repellency on Hortonian overland flow in a catchment with a) a uniformly repellent soil and b) a repellent soil interrupted by 'sink' areas in the form of wettable patches or macropores. Overland flow (arrows) generated on repellent areas is shown intercepted by sinks (shaded areas) (modified from Shakesby et al. 2000).

severely burned patches, through macropores created by burned-out roots, or in areas that were burned at a similar severity but are less water repellent (Shakesby et al. 2000, Woods et al. 2007). Figure 6 compares the runoff pathways on a uniformly water repellent hillslope with a hillslope that has a water repellent soil interrupted by hydrologic 'sinks' in the form of macropores or wettable patches. In the first case, the volume and depth of overland flow increases uniformly in the downslope direction, while in the latter case some of the runoff only flows as far as the nearest sink. The continuity and connectivity of water repellent areas is believed to be an important control on hydrological impacts of soil water repellency in both burned and unburned areas (Doerr and Moody 2004, Hubbert et al. 2006, Woods et al. 2007).

The temporal and spatial variability of soil water repellency is only one reason for the difficulty in determining the effects of soil water repellency on runoff rates at the watershed (catchment) scale as compared to the point and plot scales. In many cases, it is very difficult to accurately measure runoff at the watershed scale after burning because of the very high sediment and debris loads. There can also be problems in characterizing the precipitation and snowmelt inputs at the watershed scale, as well as the spatial variation in other controlling factors, such as soil depth, soil type, and vegetation (Miller et al. 2003). The difficulty of measuring soil water repellency at the watershed scale means that the hydrologic effects of soil water repellency usually have to be inferred by comparing runoff rates under different conditions. A comparison of storm hydrographs from similar rainstorms on an unburned forested watershed in Portugal showed that peak and total runoff did not significantly differ between dry antecedent (i.e., repellent) and moderately moist antecedent conditions (less or non-repellent), but the time to peak was considerably reduced (Doerr et al. 2003). Data from burned ponderosa pine forests in Colorado indicate that surface runoff and erosion rates can be nearly as high one year after burning as immediately after burning (Benavides-Solorio and MacDonald 2005, Kunze and Stednick 2006), even though the soil water repellency was substantially weaker a year after burning. These results suggest that soil water repellency can increase storm runoff at the watershed scale as well as at the point and plot scales, but soil water repellency is only one of the many factors that affect the amount and timing of runoff. The complexity of runoff responses precludes simple generalizations, and better procedures are needed to predict the effects of burning on post-fire soil water repellency and infiltration (Doerr and Moody 2004). A general review of post-fire hydrologic changes at the watershed scale can be found in Shakesby and Doerr (2006).

Effects of Soil Water Repellency on Soil Erodibility and Erosion

In general, the greatest influence of soil water repellency on erosion is its potential for increasing overland flow. As the amount of overland flow increases, so does its depth and velocity, and hence the ability of the water to scour and transport particles by sheetwash (Meeuwig 1970). The concentration of overland flow into small rivulets can initiate rill erosion (e.g., Doehring 1968, Wells et al. 1987, Benavides-Solorio and MacDonald 2005), and the topographic convergence of water at larger scales can result in gully, bank, and channel erosion (e.g., Moody and Martin 2001). Pre- and post-fire data from the Colorado Front Range show that the first storms after a high-severity fire caused an extensive rill network to develop in previously unchanneled swales, and sediment yields to increase from zero to around 10 Mg ha^{-1} yr^{-1} (Libohova 2004).

Soil water repellency can also directly affect erosion rates by altering the erodibility of the soil by either wind or water action. Laboratory tests have shown that raindrops on water repellent soils produce fewer, slower-moving ejection droplets than raindrops on wettable soils, but the droplets from water repellent soils had more sediment (Terry and Shakesby 1993). With successive drops, the surface of the water repellent soil remained dry and non-cohesive, and the soil particles could be displaced by rainsplash despite the overlying film of water. In contrast, the simulated rainfall caused the surface of the wettable soil to become sealed and compacted, and this increased the resistance of the soil to detachment by rainsplash. These results have been replicated by simulated rainfall experiments on long-unburned, water repellent soils in the laboratory (Doerr et al. 2003) and in the field (Leighton-Boyce et al. 2007), though they have not yet been verified for natural rainfall on bare, newly burned surfaces.

In burned areas, it is very difficult to determine the effect of soil water repellency on surface erosion rates because moderate and high severity fires also remove the protective litter layer and expose the mineral soil surface to rainsplash. By definition, high severity fires consume some of the organic matter in the surface layer of the mineral soil, and the resulting disaggregation of the soil particles greatly increases the susceptibility of the surface soil to rainsplash, sheetwash, and rill erosion. The removal of the litter layer also reduces the surface roughness and increases the velocity of overland flow, which will further increase the surface erosion rates. In steeper terrain that burned at high severity, a wettable surface soil layer can become saturated, and the increased pore pressures will decrease the shear strength and lead to the downslope movement of soil by mass failure (DeBano 2000) and miniature debris flows (e.g., Wells 1981, Gabet 2003). Detailed measurements in the Colorado Front Range indicate that about 80 percent of the sediment produced from 0.1 to 0.5 ha plots can be attributed to rill incision (Pietraszek 2006). The concentration of flow necessary to produce rills can also be facilitated by anthropogenic modifications such as roads and paths (e.g., Atkinson 1984, Scott and Van Wyk 1990, Zierholz et al. 1995), skid trails or cable rows resulting from post-fire salvage logging (Chase 2006), or improperly installed contour-felled logs (Wagenbrenner et al. 2006).

Wetting agents are perhaps the best way to isolate the unique role of soil water repellency in hydrology and erosion, and Osborn et al. (1964) found that post-fire rills developed only on plots that were untreated (i.e., water repellent). On the other hand, removing the litter cover on hillslope-scale plots in a ponderosa pine forest in Colorado caused similar amounts of rilling and surface erosion as a high severity fire (L.H. MacDonald, unpublished data). This, together with the high correlation between surface cover and post-fire erosion rates (Pietraszek 2006), suggests that the amount of vegetation cover is a more important control on post-fire erosion rates in the Colorado Front Range than fire-induced soil water repellency.

In some environments and soil types rill networks may not develop, and this can be due to several reasons. First, the shear stress exerted by flowing water is several orders of magnitude lower than the force exerted by rainsplash (Hudson 1995, also see Chapter 16) and may not exceed the critical shear stress for particle entrainment. Once concentrated flow develops, the depth of water may protect the soil surface from rainsplash and erosion rates may be higher in the interrill areas. In other cases rill networks may not develop on water repellent burned soils due to the interception of overland flow by cracks, burned-out root holes, and burrows from insects and animals (Burch et al. 1989, Booker et al. 1993, Shakesby et al. 2003).

At larger hillslope scales the role of soil water repellency in increasing erosion is uncertain. There is no shortage of studies that document large increases in post-fire channel erosion and sediment yields in small to moderate-sized watersheds (see review by Shakesby and Doerr 2006), and these increases are readily attributable to the increase in runoff. However, there is considerable uncertainty with respect to the specific effect of soil water repellency in increasing surface runoff as opposed to other factors, and this uncertainty also applies to the effect of soil water repellency on larger-scale erosion rates.

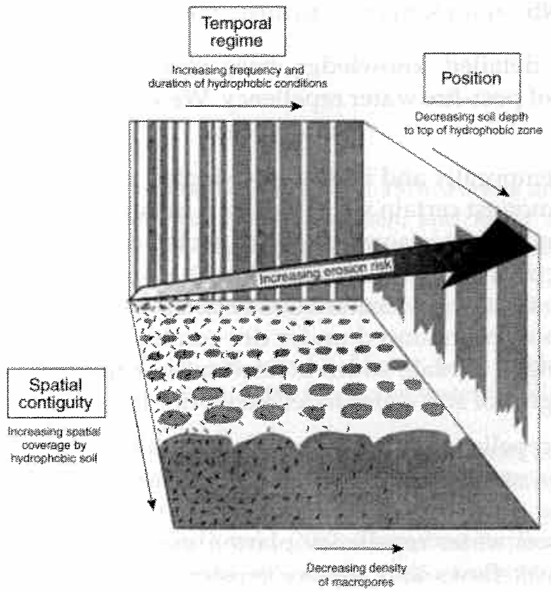

Fig. 7 A conceptual model of the effect of three soil water repellency attributes (temporal variation, spatial contiguity and thickness of wettable soil overlying water repellent soil of undefined depth) on erosion risk. Grey tones represent repellent conditions and unshaded areas represent wettable conditions. Other obvious factors that have a positive relationship with erosion risk, but are not included in this figure to retain its clarity, are the persistence and severity of soil water repellency, the intensity and duration of rainstorms, vegetation cover and slope angle. These are assumed to be unvarying here (modified from Shakesby et al. 2000).

Conceptually, in addition to the amount of protective vegetative cover, the effect of soil water repellency on surface erosion rates depends on not only the strength and persistence of soil water repellency, but also its spatial and temporal frequency and its spatial contiguity (Fig. 7). Several of these characteristics depend on other factors, such as soil texture, the seasonal timing of precipitation and its effect on soil moisture, and the dominant cause of runoff (i.e., snowmelt or rainfall).

The final issue is the effect of soil water repellency on wind erosion. As in the case of water-driven surface erosion, burning can greatly increase wind erosion rates, and much of this increase can be attributed to the removal of the protective vegetation and litter cover. Soil water repellency can also play a role in wind erosion in both burned and unburned areas, as it reduces the surface soil moisture, which reduces soil particle cohesion and lowers the threshold wind velocity for particle detachment and entrainment (Whicker et al. 2002).

CONCLUSIONS

A reasonably detailed knowledge base now exists on the origin and characteristics of post-fire water repellency. We know that post-fire soil water repellency is:

i) spatially, temporally and in its degree highly variable;
ii) common amongst certain vegetated soils irrespective of burning;
iii) often enhanced, but in some cases unaffected or eliminated following fire depending on the degree of soil heating;
iv) confined to the top few centimeters or decimeters of soil; and
v) typically most pronounced under dry conditions, but reduced or absent after prolonged rainfall, which in turn varies with soil type, burn severity, and the degree of soil water repellency prior to wetting.

Soil water repellency is a common characteristic of post-fire soils, and in some cases it is much stronger and more persistent than in the same soils prior to burning. The observed decreases in infiltration after burning suggest that post-fire soil water repellency plays a major role in causing the large increases in peak flows and surface erosion that are observed after high severity fires. The problem is that burning induces a series of other changes to the surface soils and vegetative cover that may be just as, or possibly even more, important in causing the observed increases in runoff and erosion. It is also much more difficult to determine the role of soil water repellency at larger scales due to the high spatial variability and the difficulty of characterizing the counteracting role of wettable soil patches, ash, bioturbation, soil cracks, and burned-out tree roots for reducing the surface runoff engendered by strongly water-repellent patches. Additional manipulative experiments and more detailed monitoring are needed to determine the extent to which soil water repellency has a measurable impact on runoff and surface erosion in the field under natural rainfall events at different scales.

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