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Soil water repellency. Principles, causes and relevance in fire-affected environments

Stefan H. Doerr[1] and Richard A. Shakesby[1]

[1] Swansea University, Department of Geography, Singleton Park, Swansea SA2 8PP, Reino Unido. *S.Doerr@Swansea.ac.uk*

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SUMMARY

Water repellency has often been perceived as a fire-induced feature of burnt soils, which plays a pivotal role in the typically enhanced hydrological and erosional responses of landscapes following wildfire. It is, however, also a common feature of soils under long unburnt vegetation and fire does not necessarily always alter its occurrence. This contribution aims to provide a brief review of what is currently known about the origin and principles of soil water repellency with particular emphasis on its hydrological and erosional consequences in burnt environments. The perhaps most important features of soil water repellency are that it is: i) common for many types of soils, vegetation covers and climates irrespective of fire and with its degree being highly variable; ii) mostly confined to the top few centimeters or decimeters of soil; iii) often enhanced, but in some cases unaffected or eliminated following fire, depending on the degree and duration of soil heating; and iv) seasonally variable, being most pronounced under dry conditions, but mostly reduced or absent after prolonged rainfall. Overall, the role of fire in causing water repellency has perhaps been overstated in the past; however, its contribution to enhanced hydrological and erosional responses following fire can be significant, particularly at the small-plot to hillslope scales.

INTRODUCTION

Although soils are normally thought of as being readily wettable by rainfall or irrigation, it is not uncommon for soils to behave in a water repellent (hydrophobic) manner (Figure 1). This resistance of soils to wetting when in contact with water can persist from as little as a few seconds to, in extreme cases, months (e.g. King, 1981; Dekker and Ritsema, 1994; Doerr and Thomas, 2000). Water repellent behavior is typically confined to the organically-enriched upper few centimeters or decimeters of the soil and tends to be both spatially and temporally highly variable. It can develop when soil moisture falls below a critical threshold and often disappears after prolonged wet periods (Dekker et al., 2001).

Jamison (1946) was arguably the first to demonstrate that soil water repellency reduced crop productivity and over the last two decades the use of wetting agents in horticulture and turf-grass industries (Cisar et al., 2000), or clay additions or advanced irrigation techniques in agriculture (Blackwell, 2000), have become common amelioration measures. Soil water repellency is also viewed as a key factor in enhanced hydrological and erosional hillslope and catchment responses that are often observed following wildfire (Shakesby and Doerr, 2006). During the last two decades, it has become increasingly apparent that soil water repellent behavior is relatively common. It has been reported for soils ranging from coarse- to fine-textured, from land uses including ploughed cropland, pasture, shrubland and a wide range of forest types and under climates ranging from seasonal tropical to subarctic (e.g. Wallis and Horne, 1992; Bauters et al., 2000a; Doerr et al., 2000; DeBano, 2000; Doerr et al., 2006a). Its intensity can vary considerably from extremely high, as observed under many eucalypt species (e.g. Doerr et al., 2006b; Keizer et al., 2005), to being detectable only with a purpose-built micro-infiltrometer (Hallett and Young, 1999). The view that water repellency in soils is the norm rather than the exception, with its intensity being variable (Wallis et al., 1991), has now become widely accepted.

ORIGIN AND CLASSIFICATION

Fundamental principles underlying water repellency

Figure 1. Soil water repellency preventing water drop penetration on a dry, sandy soil. Image courtesy of E. v.d. Elsen.

Over a wettable (i.e. hydrophilic) surface, water will spread in a continuous film, whereas over a hydrophobic surface, it 'balls up' into individual droplets. If the surface is a porous medium like sand or soil, water infiltration is inhibited (= water repellency; Figure, 1). The affinity between water and solid surfaces originates from mutually-attractive forces (adhesion) and the attraction between the water molecules (cohesion). The underlying principles are briefly considered here. A water molecule comprises an oxygen atom with a partial negative charge and two hydrogen atoms with a partial positive charge. The hydrogen and oxygen atom bonds are positioned 105º apart, giving the water molecule a strongly dipolar structure (Parker, 1987). The attraction of these positive and negative ends causes water molecules to form aggregates, held together by hydrogen bonds. Water adheres to most natural surfaces because their positively- or negatively-charged ions attract the negative or positive ends of a water molecule, respectively. The dipole character of water, however, also results in a comparatively strong force counteracting the attraction to charged surfaces. Within a liquid, the net force acting on an individual molecule is zero as it is surrounded by other molecules and their forces. Beyond the surface of a liquid, however, no similar molecules exist to oppose the attraction exerted by the molecules within the liquid. Consequently, the surface molecules experience a net attractive force towards the interior, which promotes the reduction of the surface area of water. Thus, if opposing forces are minimal, liquids will assume a spherical shape (i.e. that of a droplet). To enlarge the surface of a liquid, work is necessary. This work is related to the surface tension (y) or surface free energy of the liquid. Most liquids have surface tensions between 20 and 40 Nm x 10^{-3} at 20^{O}C, but that of water is comparatively high at 72.75 Nm x 10^{-3} (Parker, 1987). The same principle applies to solid surfaces, although their nature inhibits deformation into a spherical shape. The surface tension of solids therefore leads to lateral forces at the surface. Hard solids such as soil minerals can have surface tensions between 500 and 5000 Nm x 10^{-3}, increasing with hardness and melting point (Zisman, 1964). For water to spread on a solid, the adhesive forces between them must exceed the cohesive forces within the body of water. Thus, surfaces with a surface-free energy >72.75 Nm x 10^{-3} attract water and are therefore hydrophilic. The higher the surface tension of the solid, the stronger is the attraction. All principal soil minerals have a much higher surface-free energy than water and are therefore hydrophilic (Tschapek, 1984), whereas soft organic solids, such as waxes or organic polymers can exhibit ? values below 72.75 Nm x 10^{-3} and are thus hydrophobic (Zisman, 1964).

Origin of water repellency in soils

The wettability of a flat surface is determined by the property of its outermost molecular layer. Thus, in principle, a single layer of hydrophobic molecules can render a hydrophilic mineral surface hydrophobic (Zisman, 1964), although in practice, hydrophobic compounds may be absorbed to soil mineral surfaces as globules rather than uniform monolayers (Cheng et al., 2008). The amount of hydrophobic compound required to induce water repellency in soil is nevertheless very small. For example, Ma'shum et al. (1988) induced severe water repellency in 1000 g of medium-sized sand using only 0.35 g of hydrophobic compound. Soil water repellency can also be caused by the presence of hydrophobic interstitial matter. If hydrophobic particles are present in the pore spaces of hydrophilic matrix, the wettability of the composite material is reduced. For example, severe water repellency has been induced by intermixing as little as 2-5 % by weight of solid organic matter to wettable sand (McGhie and Posner, 1981).

When considering the water repellency of textured media (such as soils) compared to flat surfaces, it is important to recognize the effect of surface roughness and morphology. When water comes in contact with a rough granular surface, a fraction of the water surface will be in contact with solid material, with the remainder being in contact with the air between granules. Air is very hydrophobic and a granular surface can therefore become substantially more water repellent than a flat surface with identical surface chemistry. This phenomenon has been described as 'super-hydrophobicity' and is perhaps better known from other biological surfaces such as the lotus leaf, but also applies to soils (McHale et al., 2005).

The biological origin of hydrophobic compounds in soils is undisputed. Such compounds are naturally abundant in the biosphere and may be gradually released into the soil, for example, as root exudates (Dekker and Ritsema, 1996; Doerr et al., 1998), from soil fauna fungi or microbes (Hallett and Young, 1999; Schaumann et al., 2007), or directly from decomposing organic matter (McGhie and Posner, 1981). Depending on vegetation cover present and soil temperatures reached, a rapid release or redistribution of hydrophobic compounds often accompanies the burning of vegetation, leading to a distinct hydrophobic layer at the soil surface or at some depth in the soil profile (DeBano et al., 1976; Doerr et al., 2006b).

The specific types of compounds suggested to be a cause of soil water repellency include, alkanes, fatty acids and their salts and esters and other related compounds such as phytanes, phytols and sterols (Ma'shum et al., 1988; Roy et al. 1999; Franco et al., 2000; Horne and McIntosh, 2000; Morley et al., 2005). The presence of these compounds, however, does not necessarily lead to the expression of water repellency in soils. In has been demonstrated that comparable amounts of such compounds occur also in wettable soils (Doerr et al., 2005; Morley et al., 2005). It has been suggested that these compounds only cause hydrophobicity when they form a specific molecular arrangement (Roy and McGill, 2000; Morley et al., 2005), which in turn is influenced by soil physical and chemical properties (Doerr et al., 2000; Graber et al., 2009).

Measurement and classification of soil water repellency

There are a number of techniques for measuring and classifying soil water repellency (see Wallis and Horne, 1992; Hallett and Young, 1999; Letey et al. 2000; Bachmann et al., 2003). One of the most common methods, the 'Water Drop Penetration Time' (WDPT) test (Van't Woudt, 1959) is briefly described here. It involves placing droplets of distilled water onto a sample surface and recording the time for their complete infiltration (Figure 1). This test, which can be carried out on field-moist samples in the field or air-dry samples in the laboratory, broadly determines how long water repellency persists in the contact area of a water droplet and is particularly relevant for estimating the likely response of a soil surface to rainfall or irrigation. This *persistence* or stability of water repellency is usually somewhat, but not always well, related to the apparent surface tension (i.e. the *severity* of water repellency) of soil (Dekker and Ritsema, 1994; Doerr, 1998; Scott, 2000). Water repellency *severity* will determine how strongly a droplet initially balls up when in contact with the soil and can be determined indirectly by contact angle or critical surface tension measurements (see Letey et al., 2000). Contact angles can, however, change rapidly if the *persistence* of water repellency is low. The apparent surface tension of the soil is particularly relevant when modeling flow processes through the soil matrix.

Perception of what constitutes high or low level water repellency *persistence* varies widely. To distinguish between wettable and water-repellent soils, an arbitrary WDPT threshold of 5 s (Bisdom et al., 1993; Table 1) has been used widely, although considerable effects on water movement at the centimeter-scale have been shown to be caused by lower levels of repellency (Hallett et al., 2004). WDPT values found in the literature are generally presented in categories rather than distinct values and are not always directly comparable because, for practical reasons, this test is often terminated well before droplet penetration occurs. In many studies to date, WDPTs exceeding one hour have been recorded (= classed as extreme persistence; Table 1), but *persistence* can in some cases reach levels such that even ponded water may not infiltrate for periods exceeding one month (Doerr and Thomas, 2000).

Table 1. Water Drop Penetration Time (WDPT) class intervals in seconds (upper limit) and associated repellency *persistence* rating. Based on Bisdom et al. (1993).

WDPT Interval (s) ≤	≤ 5	10	30	60	180	300	600	900	1800	3600	18000	>18000
Persistence rating	-	slight			strong			severe			Extreme	

Although the aforementioned laboratory tests allow a general classification of soils according to hydrophobicity *persistence* and *severity,* these measurements do not always relate well to the actual wetting behavior of field soils for which infiltrometer measurements or rainfall simulations may provide additional insight (Doerr et al., 2006a).

OCCURRENCE OF SOIL WATER REPELLENCY

Distribution of water repellency

Soil water repellency has been reported in well over 1000 studies, which have focused on soils ranging from coarse- to fine-textured, land uses including ploughed cropland, pasture, shrubland and a wide range of forest types and from climates ranging from seasonal tropical to subarctic (e.g. Wallis and Horne, 1992; Bauters et al., 2000a; Doerr et al., 2000; DeBano, 2000; Doerr et al., 2006a). Although the occurrence of soil water repellency is normally not assessed within general soil surveys and hence little is known about its wider distribution, the view that it is the norm rather than the exception, with its degree being variable (Wallis et al., 1991), is now widely accepted. Regional-scale surveys in the Netherlands (Dekker et al., 2000) and the UK (Doerr et al., 2006a) indicate that water repellency is particularly common under grass, shrub and conifer forest land. There are also many reports of high levels of water repellency being naturally common under many eucalypt species (e.g. Doerr et al., 2006b; Keizer et al., 2005). Furthermore, it is well established that peat, once dried out, can become highly water repellent (Fuchsmann, 1986). Coarser-scale studies suggest, for example, that in The Netherlands, 75 % of the crop- and grassland exhibit water repellency (Dekker and Ritsema, 1994) and that in southern Australia 5 million hectares of land are affected, leading to production losses of up to 80 % in Australian agriculture (Blackwell, 2000). In some sectors, such as horticulture and sports turf (e.g. golf greens, playing fields) wetting agents are widely used to increase soil wettability (e.g. Cisar et al., 2000). Where recycled waste water is used for crop irrigation, it has recently been recognized that this practice can impart water repellency and result in uneven water distribution (Wallach and Graber, 2007).

Fire effects on water repellency

A substantial body of research has also focused on the presence of water repellency following wildfire where it is thought to play a key role in the often enhanced hydrological and erosional responses of burnt terrain. In such environments, soil water repellency is often considered to be fire-induced although it is clear that it can also be present without the influence of burning (Shakesby et al., 1993; DeBano, 2000). For example, the presence of soil water repellency following fire is used as an indicator for high soil burn severity according to assessment procedures in the western USA (USDA, 2000). However, recent work by Doerr et al. (2009) suggests that most soils under conifer forests in this region also exhibit high water repellency levels under long unburned conditions.

Notwithstanding the above findings, the heat generated by burning, can redistribute and concentrate the naturally-occurring hydrophobic substances in the soil, and is also thought to make these compounds more hydrophobic by pyrolysis and conformational changes in their structural arrangement (DeBano, 2000). Laboratory studies have shown that soil water repellency is intensified when soil temperatures reach 175-270°C, but is destroyed at temperatures above 270-400°C. The duration of heating can also affect the degree of soil water repellency with longer heating times reducing the temperature at which these changes occur (e.g. DeBano et al., 1976, Doerr et al., 2004). When there is insufficient oxygen, the temperature at which soil water repellency is destroyed may rise to 500-600°C (Bryant et al., 2005). Apart from the influence of burning conditions, factors such as the type and quantity of vegetation present or soil properties such as organic matter characteristics, clay content or mineralogy) can influence the effects of fire on water repellency (Arcenegui et al., 2007; Mataix-Solera et al., 2008). The effects of burning on soil water repellency can therefore be highly variable, with fire potentially inducing water repellency in soils that were largely non-repellent, or either enhancing or reducing pre-existing water repellency. Examples of various effects of fires on water repellency reported from different environments are given in Figure 2. 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 layer 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. Finally, short-term changes in soil moisture can greatly affect soil water repellency as discussed below.

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 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.

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.

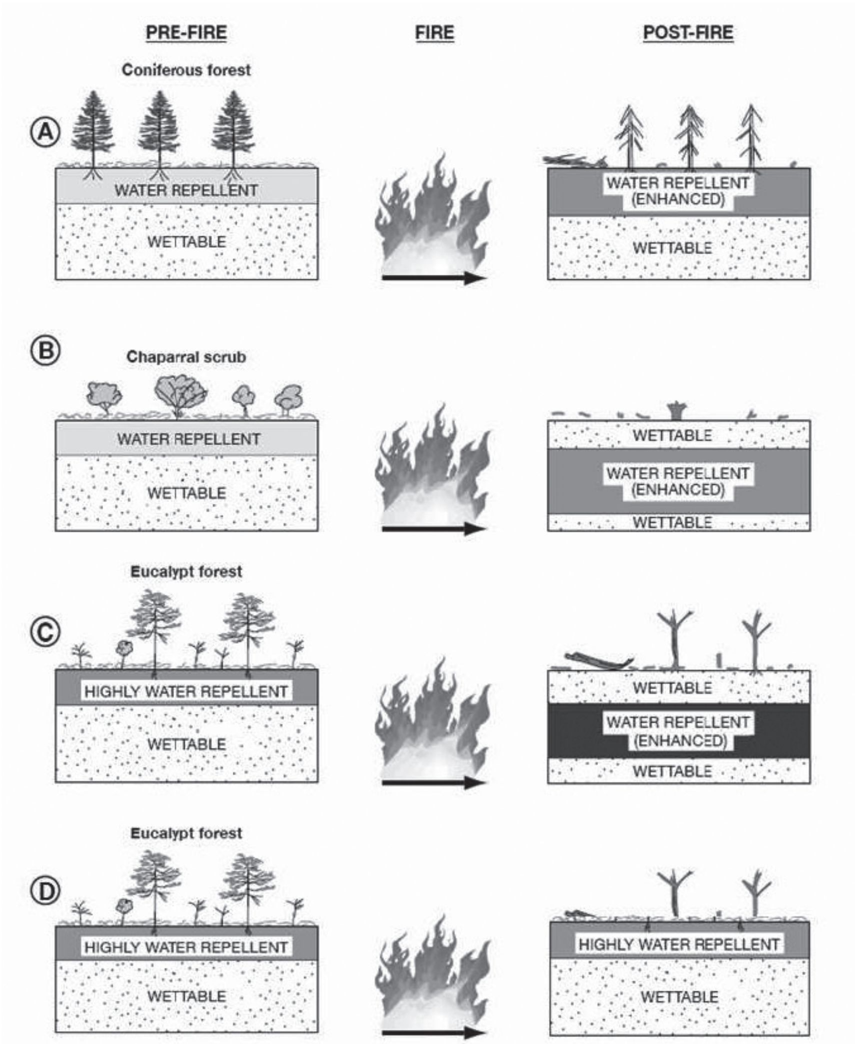

Figure 2. Effects of wildfire on soil water repellency reported from different environments. (A) temperate or Mediterranean coniferous forests (e.g. Scott, 2000; Ferreira et al., 2000; Woods et al., 2007); (B) Californian Chaparral (e.g. DeBano, 1971); (C) temperate eucalypt forests, severe fire (e.g. Doerr et al., 2006) and (D) temperate eucalypt forests, moderate fire (e.g. Lane et al., 2006).

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 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, whilst 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 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 et al., 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. 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.

Other factors affecting water repellency occurrence

Apart from the major factors linked to water repellency occurrence such as vegetation type and fire occurrence outlined above, there are a number of other environmental or soil specific factors that can affect water repellency. Coarse-textured soils are generally thought to be more susceptible to the development of soil water repellency than finer-textured soils. This is generally attributed to their relatively smaller particle surface area, which requires less organic material to generate a hydrophobic coating (DeBano, 2000) and clay hence additions have been used successfully to reduce repellency in sandy soils (Blackwell, 2000; Figure 2). The specific mineralogy of the clay applied is of importance here (McKissock et al., 2000; Lichner et al., 2006) and the aforementioned soil surface topography effect (super-hydrophobicity) may also be of relevance. Finer textured soils, however, have also been reported to exhibit high levels of water repellency (Dekker and Ritsema, 1996). This is thought to arise when substantial amounts of hydrophobic organic matter are present (DeBano, 2000; Doerr et al., 2000). Water repellency appears to be more common in acidic compared to calcareous soils (Mataix-Solera et al., 2007). The more widespread occurrence of acidic soils may be a compounding factor. However, it is also thought that the lower fungal activity and less organic matter content typical of neutral or alkaline soils make them less prone to water repellency development (Hallett and Young, 1999; Mataix-Solera et al., 2007). Thus, for example, high pH treatments have been used to reduce water repellency on golf greens (Karnok et al., 1993).

Perhaps the most critical factor affecting the occurrence of water repellency in soils that are prone to water repellency is soil moisture. Water repellency can be temporally highly variable. Depending on its level of *persistence*, it tends to disappear after prolonged contact with water and typically reappears when soil moisture falls below a critical threshold (Dekker et al., 2001). A fundamental factor thought to be critical in this ‘switching’ behavior is the specific molecular arrangement of the organic coating on soil particle (or soil pore wall) surfaces. At low soil moisture contents, the hydrophobic ends of the organic molecules would tend to be oriented away from the surface towards the soil pore space, imparting water repellency. During prolonged water contact, these molecule ends ‘fold’ onto the particle surface, thereby exposing more hydrophilic areas and ultimately making the soil wettable (Tschapek, 1984; Roy and McGill, 2000; Morley et al., 2005). Whether or not this is the main reason for the 'switching behavior', several studies have shown that water repellency is not present above a critical soil water threshold. In sandy soils, this threshold can be at a water content of a few volume percent (Dekker et al., 2001; Täumer et al., 2005), but for finer-textured soils, thresholds in the region of 20-30 % have been reported (Doerr and Thomas, 2000; Doerr et al., 2006a). What happens below this threshold is not entirely clear. Although water repellency typically recovers when soils dry out, this effect may be delayed (Crockford et al., 1991; Leighton-Boyce et al., 2005) and some soils may remain wettable after drying (Doerr and Thomas, 2000). This makes the prediction of water repellency occurrence particularly challenging.

HYDROLOGICAL AND GEOMORPHOLOGICAL EFFECTS OF SOIL WATER REPELLENCY

The primary hydrologic and erosional effects of soil water repellency include: (a) lower infiltration rates and a corresponding increase in the likelihood and amount of infiltration-excess (Hortonian) overland flow; (b) more spatial variability in infiltration and soil moisture fluxes, causing an uneven distribution of soil moisture; (c) increased surface erosion aided by the increase in overland flow; and (d) increased susceptibility to wind erosion due to drier soil conditions and reduced cohesion of soil particles.

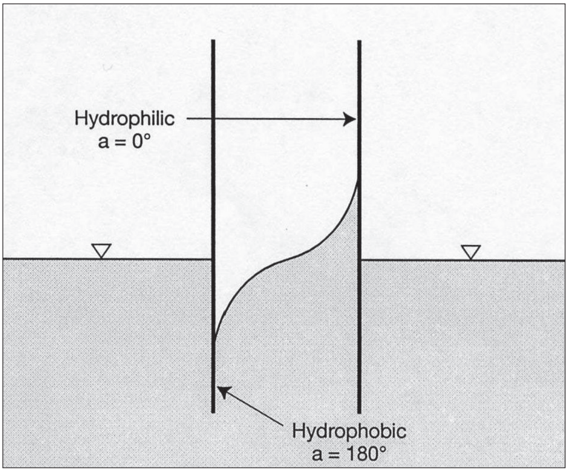

Figure 3. Shape of the meniscus of water between a hydrophilic and a hydrophobic plate with liquid-solid contact angles of 0º and 180º respectively (adapted from Bauters et al., 2000b).

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; Shakesby and Doerr 2006).

Hydrological effects of water repellency

The most frequently reported effect of soil water repellency is reduced infiltration (e.g. Van Dam et al., 1990, Imeson et al., 1992; Doerr et al., 2003) and thus increased overland flow (e.g. McGhie and Posner, 1980; Witter et al., 1991; Crockford et al., 1991). For example, the infiltration capacity of a water repellent soil was found to be 25 times lower than for a similar soil rendered hydrophilic by heating (DeBano, 1971). Owing to the reduced surface tension of the soil pore walls, a water repellent soil matrix will have a *positive* soil water potential. This effectively leads to a capillary depression effect illustrated in figure 3. Infiltration into a relatively dry water repellent soil matrix will therefore only occur if a ponding depth (hydraulic head; entry pressure) sufficient to exceed the positive soil water potential is reached. The necessary ponding depth may decrease with time if water repellency decays during water contact. These factors acting in combination usually result in infiltration rates *increasing* during rainfall. This contrasts with 'normal' soil behavior, where infiltration rates *decrease* over time (Letey et al., 1962; Kirkham and Clothier, 2000). The lack of capillary rise in water repellent topsoil, on the other hand, leads to reduced evaporation from the subsoil, which may be of advantage to plant communities in drier regions (Doerr et al., 2000).

On a water-repellent soil surface in the field, rainwater will pond and, if rainfall is sufficient and surface detention is exceeded, Hortonian (infiltration-excess) overland flow will occur. The frequency of 'gaps' through this layer (such as structural or drying cracks, root holes and burrows, and patches of wettable or less repellent soil) will then determine whether overland flow is widespread or only local (Figure 4A). Under some conditions, for example where intense soil heating during a wildfire has destroyed water repellency in the top few centimeters of the soil (see DeBano, 1971), rainfall infiltrating such a topsoil may pond above the water-repellent layer (Figure 4B). The commonly observed temporal variability of water repellency also needs to be considered here.

Thus reductions in infiltration capacity and increases in overland flow can be expected to be most pronounced following prolonged dry periods, when water repellency tends to be most severe. For example, Burch et al. (1989) recorded infiltration capacities in Australian eucalypt forest of 0.75-1.9 mm h^{-1} when dry, but 7.9-14.0 mm h^{-1} when wet. In many areas, water repellency-linked overland flow may therefore be confined to storm events following dry weather (Sevink et al., 1989; Walsh et al., 1994). The rapid response of Hortonian overland flow in a water-repellent soil following dry weather contrast sharply with the muted overland flow in moderately wet weather, when soils are generally wettable (Jungerius and De Jong, 1989; Ferreira et al., 2000).

Another common observation in soils prone to water repellency is enhanced preferential flow, which is the concentrated vertical movement of water via preferred pathways through the soil. It may originate for a variety of reasons such as cracks and biopores, textural discontinuities and unstable wetting fronts, which may result from soil layering, air entrapment etc. (Ritsema et al., 1993). In stony, water-repellent soils, water movement may be facilitated along sand-stone interfaces and preferential flow may take place where there are contiguous stone-to-stone connections (Urbanek and Shakesby, 2009). Although not restricted to water repellent soils, repellency can be particularly effective at preventing or hindering downward water movement, directing it into structural or textural preferential flow paths (Figure 4A/2 and 4B) and creating an unstable irregular wetting front. Consequently soils may not wet completely with the passage of a wetting front (DeBano, 1971), and water may be channeled via biopores (Shakesby et al., 2007), cracks and pipes, thereby by-passing the water-repellent soil matrix (e.g. Burch et al., 1989; Ferreira et al., 2000). Walsh et al. (1995) considered that macropores and cracks could explain why even large storms produced little overland flow for extremely water repellent mature pine and eucalypt forest soils in Portugal. Irrespective of the dominance of enhanced overland or subsurface flow, the reduced soil water storage capacity in catchments affected by soil water repellency is likely to increase flooding particularly in cases where long dry periods are followed by large rainstorm events. This situation can be further exacerbated following the removal of a protective vegetation and litter cover by clearance or fire (Figure 5). Following fire, water repellency has often been considered to be the major factor causing enhanced hydrological (and erosional – see next section) responses. The consensus amongst many researchers, howe-

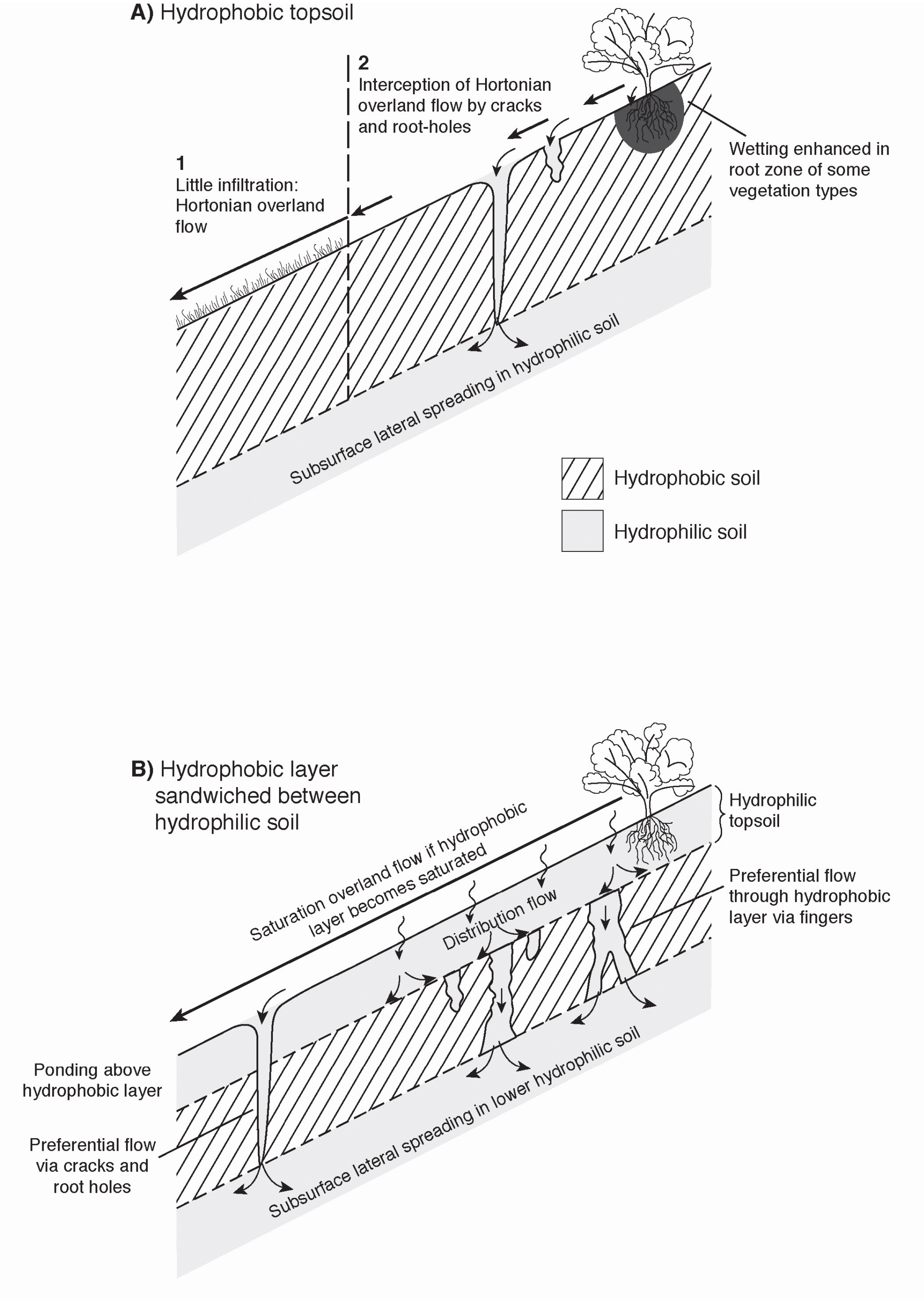

Figure 4. Illustration of possible hydrological responses of soil with (A) a water repellent layer located on the surface, and (B) a repellent layer sandwiched between wettable soil (adapted from Doerr et al., 2000).

Figure 5. Enhanced overland flow during intense rain in burnt eucalypt forest terrain in the Victorian Alps, south-east Australia in 2003 (photo courtesy of Rob Ferguson).

ver, is that the loss of vegetation cover is perhaps the most important factor. This notion is supported by recent research from Colorado (Larsen et al., 2009).

On a grass-covered sandy soil in Holland, Ritsema et al. (1993) used tracers to record distribution flow within a thin (<2.5 cm) wettable topsoil, which supplied water via columns of less repellent soil (preferential flow paths) in an otherwise extremely repellent layer to the wettable subsoil, where the water spread laterally. This has been termed 'fingered flow' (Ritsema and Dekker, 1994). The fingers formed only after dry weather when soil moisture levels in the sandy, repellency-prone layer were below a 'critical' value of 4.75 % (vol.). The fingers ranged from 10-50 cm in diameter (expanding in wetter weather), and were the sole means of water transport for several hours during sustained rainfalls. Such fingers have been shown to recur at the same places in successive storms following intervening dry weather, possibly aided by preferential leaching of hydrophobic substances from the finger pathways (Ritsema et al., 1998). In a study in Germany, wet and adjacent dry areas where seasonally persistent in a grass-covered and partially water repellent soil (Täumer et al., 2005). Preferential flow in general is thought to be reinforced by soil water hysteresis between wetting and drying phases, a feature of wettable soils but more pronounced in water-repellent ones (Ritsema et al., 1998). Water repellency-induced fingered flow can lead to considerable variations in water content in an initially repellent soil such that zones of very dry soil can abut directly against zones of wet soil. For example, Dekker and Ritsema (1996) found differences in soil moisture of up to 28 % (vol.) between closely-spaced samples in both clay and sandy soils. Such differences do not only result in the widely reported poor seed germination and plant growth. Any type of preferential flow path formation can also lead to accelerated leaching of surface-applied agrichemicals and an increased risk of surface and groundwater contamination (Hendrickx et al., 1993, Ritsema et al., 1993).

Effects of water repellency on soil erosion

In general, the most important way in which soil water repellency can influence erosion lies in its potential for contributing to an increase the proportion of rainfall going to overland flow. As the amount of overland flow increases, its depth and velocity also increases and with it the ability of the water to detach and transport particles, initially by sheetwash (Shakesby et al., 2000). Then, as the overland flow becomes concentrated into small rivulets, this can initiate rill erosion (Benavides-Solorio and MacDonald, 2005). At a larger scale, convergence of overland flow in concave parts of hillslopes in plan form can lead to the formation of gullies, and to channel bank and bed erosion (e.g. Moody and Martin, 2001). Soil water repellency can also directly affect erosion rates by altering the erodibility of the soil. Laboratory tests have shown that individual water drops falling on a water-repellent soil produce fewer, slower-moving ejection droplets than those on wettable soils, but the splash ejection droplets developed on the former carried 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 continued to be displaced by rainsplash despite the retention of an overlying film of water. In contrast, drops falling on the surface of the wettable soil sealed and compacted it, which increased its resistance to detachment by rainsplash. Aggregate stability, in contrast, has been shown to be higher in water-repellent soils, which may counter the above effect to some degree in soils that exhibit aggregation (Giovannini and Lucchesi, 1983; Mataix-Solera and Doerr, 2004). At hillslope and watershed scales, the role of soil water repellency in increasing erosion is less certain. Its overall impact is likely to be reduced where areas with macropores or wettable soil patches promote interception of overland flow generated on water-repellent areas.

Soil water repellency can also play a role in other forms of erosion. Wind erosion can be enhanced as a result of its effect on surface soil moisture, which reduces soil particle cohesion and lowers the threshold wind velocity for particle detachment and entrainment (Whicker et al. 2002). Dry ravel (the rapid, dry particle-to-particle sliding of sediment through gravity) is a form of mass movement which is strongly associated with post-fire water-repellent conditions, particularly in chaparral vegetation of western USA (Wells, 1986). Formation can occur of small-scale debris flows related to failure of a saturated layer of wettable soil only a few millimeters thick overlying a subsurface water-repellent zone (Gabet, 2003). The links between larger debris flows and water-repellent soils seem to be less certain (Cannon, 2001).

CONCLUSIONS

Two decades ago, soil water repellency would have been viewed as a curious aberration by many soil scientists, whereas now it has become a widely acknowledged soil property which is typically: i) highly variable spatially, temporally and in its degree; ii) common for many types of soils, vegetation covers and climates; iii) confined to the top few centimeters or decimeters of soil; iv) enhanced, but in some cases unaffected or eliminated following fire, depending on the degree of soil heating; and v) most pronounced under dry conditions, but reduced or absent after prolonged rainfall, which in turn varies with factors such as soil type 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 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. However, 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.

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