Journal of Hydrology 231–232 (2000) 195–206

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Review

The role of fire and soil heating on water repellency in wildland environments: a review

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Received 5 November 1998; accepted 17 April 1999

Abstract

This paper describes the heat transfer mechanisms operating as heat moves downward in the soil along steep temperature gradients during both wildfires and prescribed fires. The transfer of heat downward in the upper part of the soil is enhanced by the vaporization and movement of water and organic compounds. Available information on the changes in the chemistry of vaporized organic compounds is summarized and discussed. An operational theory describing the formation of a highly water repellent soil condition during fire is presented. The relationship between the formation of this fire-related watershed condition and subsequent surface runoff and erosion from wildland ecosystems is explored. Worldwide literature describing fire-induced water repellency is reviewed and summarized. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Hydrologic responses; Wildfires; Water repellency

1. Introduction

Fire-induced water repellency in soils has been a continuous concern of watershed managers since its identification in the early 1960s. The formation of water repellent soil, its chemical nature, and its effect on infiltration, runoff and erosion have all captured the attention of numerous scientists and managers worldwide. Several papers in this volume describe specific cases of the effect of fire-induced water repellency on hydrologic responses. This paper, however, is intended to present only a short overview which describes: (1) the discovery of fire-induced water repellency; (2) the processes responsible for its formation; (3) the worldwide importance of this soil property; (4) the chemical nature of the substances producing it; and (5) the linkages between fire-induced water repellency and postfire hydrologic responses on wildlands.

2. Background

The excessive soil erosion following wildfires in the mountainous environment of southern California, USA has captured the interest of both scientists and land managers for over a century (Sinclair and Hamilton, 1954). Further, the flooding and erosion problems have become increasingly acute over time as more and more people continue to occupy the floodplains immediately below the steep, unstable, and chaparral-clothed San Gabriel Mountains that surround Los Angeles and nearby cities. Fire is a frequent visitor in this area and wildfires have been estimated to denude these chaparral watersheds about every 25–30 years (Biswell, 1974).

Much of the mountainous terrain in southern California is administered by the USDA Forest Service. Part of the approach in managing these brush-clothed watersheds included obtaining a better understanding

PII: S0022-1694(00)00194-3

of how frequent wildfires affected the vegetation, soils, and hydrology of these areas. Although much was known about the vegetation (Horton, 1960) and hydrologic responses (Rowe et al., 1954) of these watersheds following fire, little was known about the specific effects fire had on soil properties other than that the loss of vegetation directly exposed the soil surface to raindrop impact. The reason for the decreased infiltration after fire was initially believed to result from the loss of protective plant cover during combustion and the plugging of soil pores by ashy residue remaining on the soil surface. The decrease in infiltration, however, was later found to be affected by a repellent layer formed during the fire.

Various postfire treatments to revegetate and stabilize the soil were cooperatively evaluated by scientists assigned to the USDA Forest Service and the University of California during the late 1950s and early 1960s. One of the first studies tested the use of chemical treatments (soil stabilizers) to reduce postfire erosion (Krammes and Hellmers, 1963). During these soil investigations, it was concluded that soil wettability played an important role in postfire erosion (Osborn et al., 1964a) and that remedial chemical wetting treatment with wetting agents could potentially reduce postfire erosion (Osborn et al., 1964b).

In addition to the studies on postfire remedial treatments, detailed research on the effect of fire on the soil resource was implemented. Through a series of both laboratory and field experiments, it was shown that water repellency on these erosive watersheds was created and intensified by the soil heating occurring during a fire (DeBano, 1966; DeBano and Krammes, 1966). This soil condition dramatically reduced infiltration, created overland flow, and, as a result, accelerated erosion. This soil property had been overlooked in previous watershed investigations (Krammes and DeBano, 1965) because it was assumed that loss of cover and plugging of soil pores were the only processes responsible for postfire erosion.

3. Water repellency and fire

After fire, water repellency is typically found as a discrete layer of variable thickness and spatial continuity found on the soil surface or a few centimeters below and parallel to the mineral soil surface. If found in mineral soil, water repellency is usually covered by a layer of severely burned soil or an ash layer. Creation of this water repellent layer was described as the “tin roof” effect by earlier watershed researchers.

A hypothesis describing the formation of a water repellent soil layer in soils was developed during the mid and late 1960s (DeBano, 1981). This hypothesis evolved as a product of numerous field observations, laboratory tests and field research studies. The results of preliminary field observations suggested that water repellency might well be an important factor responsible for the accelerated erosion experienced during the first few years following wildfires (Krammes and DeBano, 1965). An initial laboratory study showed that water repellency could be intensified by heating a soil–organic matter mixture in a muffle furnace at different temperatures for different lengths of time (DeBano and Krammes, 1966). It was hypothesized that a more efficient coating of mineral soil particles occurred at lower temperatures and for shorter periods of heating than in the case of longer periods of heating at higher temperatures that destroyed the organic substances responsible for the water repellency.

Laboratory tests of changes in water repellency resulting from different times and temperatures of heating were combined with measured temperatures during prescribed fires and wildfires to develop the hypothesis describing how a water repellent layer is formed beneath the soil surface during a fire (DeBano, 1981; DeBano et al., 1998). According to this hypothesis, organic matter accumulates on the soil surface during intervals between fires (Fig. 1A). During these intervals, the upper soil horizons become water repellent due to the drying out of the mixture of partially decomposed organic matter and mineral soil. The addition of hydrophobic substances due to the leaching of decomposing plant parts on the soil surface may also contribute to the prefire water repellency. Fungal growth also is a dynamic source of hydrophobic substances, particularly in the organic-rich upper soil horizons.

The combination of combustion and heat transfer during wildfires produces steep temperature gradients in the surface layers of the mineral soil (Fig. 1B). During a fire, temperatures in the canopy of burning chaparral brush can reach over 1100°C (Countryman, 1964). Temperatures can reach about 850°C at the

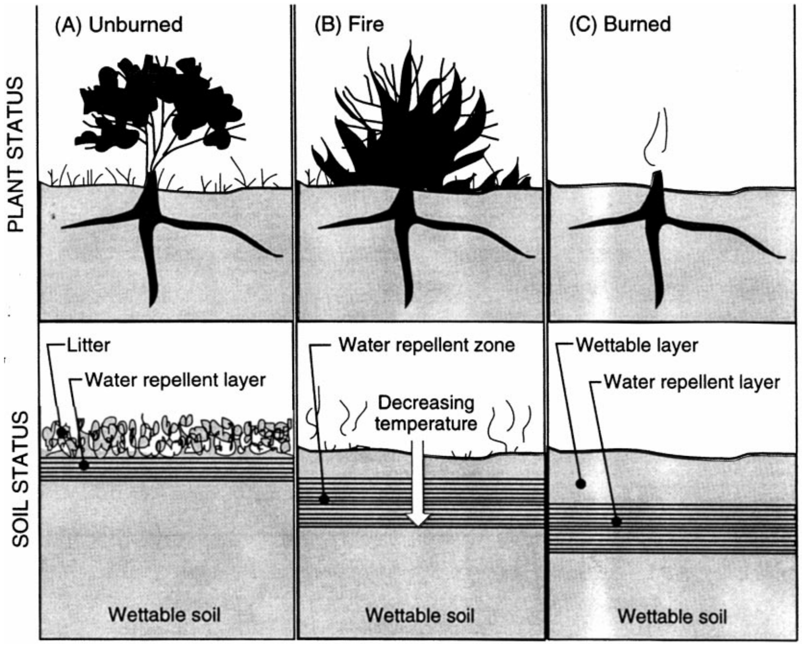

Fig. 1. (A) Soil water repellency in unburned brush is found in the litter, duff, and mineral soil layers immediately beneath the shrub plants. (B) When fire burns, hydrophobic substances are vaporized, moving downward along temperature gradients. (C) After the fire has passed, a water repellent layer is present below and parallel to the soil surface on the burned area (adapted from DeBano, 1981).

soil–litter interface. But, temperatures at 5 cm in the mineral soil probably do not exceed 150°C because dry soil is a good insulator (DeBano et al., 1979). Heat produced by combustion of the litter layer on the soil surface vaporizes organic substances, which are then moved downward in the soil along the steep temperature gradients until they reach the cooler underlying soil layers, where they condense. Incipient water repellency at different soil depths could also be intensified in place by heating, because organic particles are heated to the extent that they coat and are chemically bonded to mineral soil particles. Movement of hydrophobic substances downward in the soil occurs mainly during the fire. After fire has passed, the continued heat movement downward through the soil can re-volatilize some of the hydrophobic substances resulting in thickening the water repellent soil layer or fixing the hydrophobic substances in situ (Savage, 1974). The final result is a water repellent layer below and parallel to the soil surface on the burned area (Fig. 1C).

The above described investigations also provided some general relationships between water repellency and soil temperature, which showed: (1) little change in water repellency occurs when soils are heated less than about 175°C (DeBano, 1981); (2) intense water repellency is formed when soils are heated between 175 and 200°C (DeBano, 1981; March et al., 1994); (3) destruction of water repellency occurs when soils are heated between 280 and 400°C (DeBano et al., 1976; Giovannini and Lucchesi, 1997; March et al., 1994; Savage, 1974). Further, the water repellent layer produced during fire can vary widely because of differences in fire and soil characteristics. Fire behavior, fire severity and temperature gradients developing in the soil during a fire, all affect the formation of a water repellent layer (DeBano et al., 1976; DeBano, 1981). Soil properties that affect water repellency include: amount and type of organic matter present (DeBano, 1981; Imeson et al., 1992; Doerr et al., 1998); soil texture (DeBano, 1981); soil water content (DeBano et al., 1976; Robichaud, 1996); and the general soil–plant environment.

4. Worldwide distribution

The relationship between soil heating and water repellency was reported at the first international conference on water repellency (DeBano and Letey, 1969) in Riverside, California, and in earlier publications (DeBano, 1966; DeBano and Krammes, 1966). As a result, the awareness of water repellency was heightened, and numerous reports in other wildland environments of the United States soon began appearing. During the two decades between 1960 and 1979, water repellency was reported in: ponderosa pine forests following fire in Arizona (Zwolinski, 1971; Campbell et al., 1977); mixed conifer forest in California (Agee, 1979); Arizona chaparral (Scholl, 1975); high elevation forests in the Cascades of Oregon (Dyrness, 1976); forest soils in upper Michigan (Reeder and Jurgensen, 1979); forested environments of the Sierra Nevada Range of Nevada and California (Hussain et al., 1969); the sagebrush type found in the Great Basin of USA (Salih et al., 1973); and several vegetation types throughout the western United States (DeBano, 1969). Water repellent soils have also been reported in soils where large accumulations of fuels, such as logging residues, are burned (DeByle, 1973) and under camp fires (Fenn et al., 1976). Although most of the reports between 1960 and 1979 were from the United States, fire-induced water repellency was reported in New Zealand pumice soils (John, 1978), and in Japan (Nakaya et al., 1977).

The interest in the effect of fire-induced water repellency continued through the 1980s until the present time and in the USA it has been reported in: the Pacific Northwest (Boyer and Dell, 1980; McNabb et al., 1989), Idaho (Campbell and Morris, 1988), Nevada (Everett et al., 1995), and southern California and Arizona (Wells, 1982, 1987). Fire-induced water repellency was also continuing to capture the attention of scientists in other parts of the world, including: British Columbia (Henderson and Golding, 1983), southern Chile (Ellies, 1983), England (Mallik and Rahman, 1985), Italy (Giovannini and Lucchesi, 1983; Giovannini et al., 1983, 1987, 1988), South Africa (Scott, 1989), Turkey (Sengonul, 1984), Portugal (Walsh et al., 1994; Doerr et al., 1998), and Spain (Sevink et al., 1989; Almendros et al., 1990; March et al., 1994; Martinez-Fernandez and Diaz-Pereira, 1994; Molina et al., 1994).

During the 1990s, detailed studies on fire-effects began addressing the effect of different fire intensities on soil heating (Valette et al., 1994) and water repellency (Giovannini and Lucchesi, 1997). The effects of fire on overall soil quality (Giovannini et al., 1990; Giovannini, 1994) and aggregate stability (Molina et al., 1994) were also investigated. One study reported the relationship of soil hydrophobicity to depth and particle size in burned and unburned eucalyptus forests (Doerr et al., 1996). Interest was being focused on the spatial variability of water repellency (Doerr et al., 1998) and on the relationship between the spatial distribution of water repellency and the erosion potential produced during prescribed burning (Robichaud, 1996).

5. Chemistry of fire-induced water repellency in soils

In the late 1960s and early 1970s, several studies were conducted in an attempt to identify the substances responsible for heat-induced water repellency (Savage et al., 1969, 1972; Savage, 1974). The objective of this effort was to chemically characterize the hydrophobic substances causing water repellency so that chemical wetting agents could be specifically synthesized to more effectively counteract the extreme hydrophobic conditions produced during wildfires. Although non-ionic wetting agents were found to be effective treatments to reduce runoff and erosion in many cases, the rates and methods of application were being determined largely by trial and error when prescribing treatment for burned watersheds.

Alterations of organic substances occur both during their volatilization and after they have condensed on mineral soil particles. The volatilized fractions released during the heating of organic matter from chaparral soils in California produced only a slight water repellency when added to non-repellent sand, but when this treated sand was heated to 300°C for 10 min it became highly water repellent (Savage et al., 1972). It was proposed that the substances moving from burning organic matter may have been produced by pyrolytic reaction rather than a simple volatilization of organic matter and that these substances were produced in the greatest quantities above 350°C (Savage et al., 1972). Although these pyrolytic substances themselves produced little water repellency, further fractionation produced three fractions that were capable of causing water repellency in a wettable sand, particularly if they were heated for a few minutes at 200–300°C. A detailed analysis of the three fractions producing water repellency showed that one was an aliphatic hydrocarbon that contained a large proportion of oxygen as carbonyl groups. From these experiments it was concluded that 50–95% of the substances moving from burning litter into sand were capable of causing water repellency (Savage, 1974).

Humic and fulvic acids have been examined as possible sources of water repellency in both fire (Giovannini and Lucchesi, 1984; Almendros et al., 1988, 1990) and non-fire (Wallis and Horne, 1992) environments. Coordinated use of differential thermal analysis and infrared spectrophotometric techniques revealed that soil water repellency may be due to a fraction of the organic matter that had a low degree of humification and that was made up of a compound identified as an ester between phenolic acids and polysaccharide-like substances (Giovannini and Lucchesi, 1984). Another soil heating study showed that the oxygen-containing functional groups in organic matter were particularly sensitive to thermal treatment (Almendros et al., 1990). The overall changes detected in the humic acid fractions were used to develop a conceptual model, which showed that substantial amounts of humic acids were converted into alkali-insoluble substances that contributed to the soil humus fraction during natural fires.

In summary, research on fire-induced water repellency has not revealed specific hydrophobic substances, nor have the precise changes occurring during heating been determined. This conclusion is not unexpected, however, because chemistry of the hydrophobic substances produced by heating of organic matter would be expected to be extremely complex due to the infinite number of organic compounds that can be acted upon by fire to produce organic substances responsible for fire-induced water repellency.

6. Effect on hydrologic processes and watershed responses

The interest in infiltration, runoff, and erosion following wildfires developed simultaneously with the effort directed toward understanding the mechanisms responsible for producing fire-induced water repellency. During the 1970s, consideration of post-fire erosion resulting from fire-induced water repellency was restricted to a few erosional studies reported in the southwestern United States (Rice and Osborn, 1970; Cleveland, 1973; DeBano and Conrad, 1976). The interest in extending the principles of water repellency to erosion and hydrologic performance at a watershed level gained further worldwide attention during the 1980s and 1990s, with reports being published for: Australia (Topalidis, 1984), Portugal (Shakesby et al., 1993; Walsh et al., 1994), Spain (Imeson et al., 1992; Diaz-Fierros et al., 1994), South Africa (Scott, 1989; 1993, 1997; Scott and Van Wyk, 1990; Scott and Schulze, 1992), and the United States (Wells, 1981; 1987; Robichaud, 1996).

During the course of the above studies, a general understanding of the effect of water repellency on individual hydrologic processes (e.g. infiltration, runoff and erosion) developed as a result of measurements that were taken on field study sites exposed to either natural or simulated rainfall. These studies were done on different sized areas that varied from small plots to large watersheds.

6.1. Hydrologic responses

The hydrologic responses to water repellency most studied are: infiltration, runoff, rill formation, raindrop splash and streamflow parameters. The effect of a water repellent layer near, or at, the soil surface of burned watersheds has been fairly easy to model conceptually and test in the laboratory, but has proven extremely difficult to model physically under field environments because of the large temporal and spatial variability found under natural conditions on large-scale watersheds. The following discussion of individual hydrological processes first describes a conceptual framework; supplemental information obtained during laboratory and field experiments is then added to describe more closely the wildland environments.

6.1.1. Infiltration and runoff

Some anomalies occur during infiltration into a water repellent soil during laboratory studies. One such anomaly is that the uptake of water during infiltration is slower at the beginning of infiltration and increases over time which is contrary to infiltration into a wettable soil where the converse is true (Letey et al., 1962; DeBano, 1975). A second anomaly is that in water repellent soils, faster infiltration rates occur in moist soils compared to dry soils (Gilmour, 1968). This second anomaly arises because initial soil moisture content affects the initial severity of the water repellent condition and is related to the concept of "potential" and "actual" water repellency (Dekker and Ritsema, 1994).

The above relationship describes water flow when the soils are uniformly water repellent or wettable. However, when a soil profile contains a layer of water repellent soil beneath a thin wettable layer (as is often found on burned watersheds that contain a wettable ashy surface layer), the water repellent layer affects infiltration in much the same way as a coarse-textured layer would in a wettable soil profile. If the water repellent layer lies beneath a layer of wettable soil, the wetting front moves through the wettable layer rapidly until it reaches the water repellent layer, after which the infiltration rate drops to that of the water repellent soil. The infiltration rate remains depressed until the wetting front passes through the water repellent layer into the underlying wettable soil; then the rate begins to increase (DeBano, 1975). The depth to the water repellent layer also affects infiltration rates so that a layer near the surface is more effective in restricting infiltration than a deeper layer (Mansell, 1969).

The idealized model of infiltration into a soil having a uniformly distributed water repellent layer, such as that described above, grossly oversimplifies field environments because of the large spatial and temporal heterogeneity of soil water repellency patterns and the soil surface microtopography. Studies on agricultural soils indicate that uneven microtopography of the soil surface and a heterogeneous spatial distribution of water repellency within the soil profile lead to a redistribution of surface water and concentrate water flow through the soil in discrete wettable soil fingers (Ritsema, 1998). The same differential flow undoubtedly occurs frequently in wildland soils because of the highly complex and variable spatial patterns found in natural environments.

6.1.2. Hillslope runoff and erosion

Some debate still occurs about the importance of fire-induced hydrophobicity on runoff and erosion from small plots and watersheds. In a study on small hillside plots under eucalyptus forest in Australia, it was concluded that the fire-induced water repellency produced localized runoff and sediment movement only on hillslopes, but did not appreciably affect the performance of the entire watershed (Prosser and Williams, 1998). Another study of plots covered with 8-year-old scrub species in Spain showed that fire intensities affected erosion, and sediment delivery was 8 times greater on plots burned at high intensities than on unburned controls (Soto and Diaz-Fierros, 1998). Other plot studies suggested that the hydrologic responses to fire-induced water repellency depended upon soil dryness (Walsh et al., 1994). The increased runoff was attributed to an increase in the severity of water repellency at lower soil water contents during the dry season.

6.1.3. Watershed responses

Predicting watershed responses by using information gained from conceptual models, laboratory studies, field observations and runoff and erosion data from small plots is extremely difficult because expanding these relationships to a watershed scale further increases the variability of these heterogeneous and highly complex natural systems. One useful technique for evaluating watershed responses to different treatments is to use paired watersheds with the control and treated watersheds having been calibrated against each for several years before and following a treatment (in this case, prescribed fire or wildfire). Reports of several studies done in South Africa illustrate how watershed level studies can be designed and the responses evaluated when studying watershed responses to fire-induced water repellency (Scott and Van Wyk, 1990; Scott and Schulze, 1992; Scott, 1993, 1997). These studies involved coordinated measurements of streamflow response, sideslope erosion, and soil water repellency. The results of studies done on *Pinus radiata* watersheds that had been burned showed that during the first year following the fire, total streamflow, quick flow volumes, peak flow rates, and the watershed response ratio all increased as a result of the fire (Scott and Van Wyk, 1990). The second year responses were somewhat less (Scott, 1997). Soil loss by overland flow from the plots during the first year following fire increased from 10 to 26 t/ha, and both suspended sediment and bedloads increased about four-fold following the fire. Wettability of the soils was decreased significantly and the most severe water repellency was found deeper in the soil.

In a separate experiment in South Africa, the effect of prescribed fires and wildfires was studied on watersheds supporting indigenous native fynbos, *P. radiata* forest, and *Eucalyptus fastigata* forest (Scott, 1993). One of the two fynbos watersheds was prescribe-burned and the second burned by a wildfire during the wet season. Fynbos is a vegetation type found in South Africa that is dominated by sclerophyllous (evergreen and leathery-leafed) shrub species. Both of the forested watersheds were burned by an intense wildfire during the dry season. The forested watersheds experienced significant increases in storm-flows and soil loss. In contrast, the fynbos watersheds showed no change in storm-flow although annual flow increased 16% because of reductions in transpiration and interception. Water repellency measurements suggested that the storm-flow responses were partly generated by increased surface runoff into the stream channel that occurred as a result of reduced infiltration into water repellent soils on the hillslopes.

A third study utilized a nested watershed design, supplemented with hillslope plots and water repellency measurements (Scott and Schulze, 1992). This study was designed to evaluate the effects on storm-flow and hillside erosion of a high-intensity wildfire that burned a eucalyptus forest. The fire markedly increased storm-flows and caused high soil losses from the hillslopes. The increased overland flow was linked to the widespread presence of water repellency. Measured soil losses of the hillslopes, however, were about five times that measured at the stream gaging stations because a healthy riparian area acted as an effective buffer, which trapped large amounts of eroded soil and ash.

6.2. Erosional processes

Two important erosion processes occur following fire when water repellent soils are present—rill formation and raindrop splash. Rill formation occurs when rainfall exceeds infiltration rates and surface runoff occurs. Soil material moved by rill erosion accumulates in channels at the base of steep slopes and remains there until increased stream-flow moves it downstream (Wells, 1987). The greatest movement of sediment occurs when rill formation is accompanied by sufficient sideslope runoff to move the debris stored in the channels.

6.2.1. Rill formation

A striking feature on freshly burned watersheds during the first postfire rainstorms is an extensive rill network, which is related to water repellency (Wells, 1981, 1982, 1987). The sequence of rill formation follows several well-defined stages. First, the wettable soil surface layer is saturated during initial infiltration (Fig. 2A). The water infiltrates into the wettable surface until it encounters a water repellent layer (Wells, 1981). This process occurs uniformly over the landscape so that when the wetting front reaches the water repellent layer, it can neither drain downward nor laterally. As rainfall continues, water fills all available pore space until the wettable soil layer becomes saturated. Because pores cannot drain, pore pressures build up immediately above a water repellent layer. This increased pore pressure reduces intergranular stress among soil particles, and as a result, decreases shear strength in the soil mass and produces a failure zone at the boundary between the wettable and water repellent layers where pore pressures are greatest (Fig. 2B). Pore pressure continues to increase and shear strength decreases until it is exceeded by the shear stress of gravity acting on the soil mass. When this happens, a failure occurs and a portion of the wettable soil begins to slide downslope (Fig. 2C). If the soil is coarse textured, initial failure causes a re-orientation of the soil particles in the failure zone and causes them to momentarily lose contact with each other. The loss of intergranular contact further reduces shear strength and extends the failure zone downslope. When most of the soil grains lose contact, a condition develops in which the shearing soil is almost fluid. This fluid condition produces a miniature debris flow in the upper wettable soil layer, which propagates downslope to the bottom of the slope or until it empties into a channel.

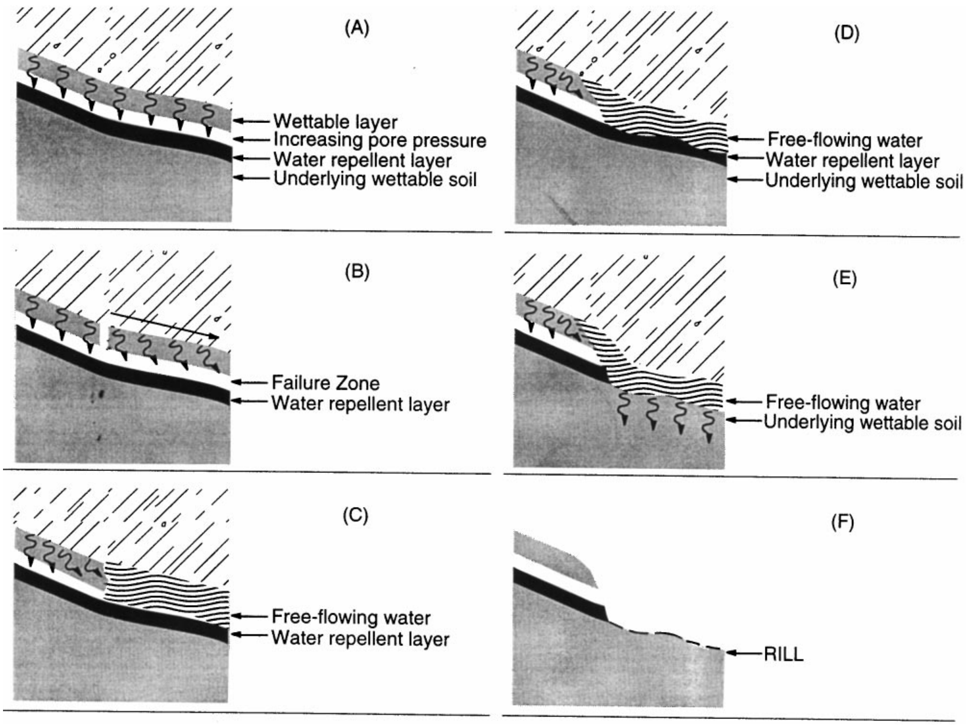

Fig. 2. Rill formation during rainstorms following fire involves: (A) saturation of the wettable soil surface; (B) a failure at the boundary between wettable and water repellent layers; (C) loss of the wettable surface layer, with the flow of water over the water repellent layer; (D) erosion of the water repellent layer; (E) erosion through the water repellent layer and infiltration into the underlying wettable soil; and (F) development of a well-defined rill (adapted from Wells, 1987).

Water in the wettable soil layer adjacent to the debris flow is no longer confined and can flow out into the rill formed by the debris flow and free-flowing water runs over and erodes into the water repellent layer (Fig. 2D). Flowing water confined to the rill still cannot infiltrate into the water repellent soil and, therefore, flows down the debris flow track as free water in an open channel (Wells, 1981). As the water flows down the track, turbulent flow develops, which erodes and entrains particles from the water repellent layer. The downward erosion of the water repellent rill occurs until eventually the flow cuts completely through the water repellent layer and begins infiltrating into the underlying wettable soil (Fig. 2E). Flow then diminishes, turbulence is reduced, and downcutting ceases. Finally the rill is stabilized immediately below the lower edge of the water repellent layer (Fig. 2F). The individual rills formed by the above process develop into a network that can extend the length of a small watershed. Observations of rills after the first rainstorms on recently burned watersheds confirm that the downcutting of rills stops at the bottom of the water repellent layer (Wells 1987).

6.2.2. Raindrop splash

Larger amounts of soil are moved by raindrop splash on hydrophobic soils compared to similar wettable sandy loam soils when they are exposed to different rainfall intensities, durations, and soil surface inclinations (Terry and Shakesby, 1993). Raindrop impact on hydrophobic soils produces fewer, slower-moving ejection droplets that carry more sediment to a shorter range than a wettable soil. Hydrologically, raindrop detachment is more effective on hydrophobic soils compared to wettable soils because soil surfaces having an affinity for water becomes sealed and compacted during a rainfall event which makes them increasingly resistant to splash detachment. Conversely, hydrophobic soils remain dry, non-cohesive and easily displaced by splash when the raindrop breaks the surrounding water film.

7. Longevity of fire-induced water repellency

The longevity of fire-induced water repellency depends on some of the same factors that affect its formation. Water repellency produced by low-to-moderate severity fires is usually of shorter duration than that produced by high severity fires. For example, water repellency produced by a low severity burn in late spring in the forests of southwestern Oregon began to allow infiltration at a nearly normal rate after the rains began to fall (McNabb et al., 1989). Dyrness (1976) found that wettability of soil on areas that burned at low severity recovered more rapidly than that of soils in severely burned areas. Wettability of soils on sites burned at either low or high severity approached that of an unburned soil by the sixth year after fire. Conversely, three years after passage of a fire on an experimental plot in Sardinia, subsurface layers (in which translocated hydrophobic matter had accumulated) showed these hydrophobic substances to be unaltered, but they were more strongly cemented because the translocated hydrophobic organic matter complexed with polyvalent ions (Giovannini et al., 1987).

8. Ameliorating fire-induced water repellency

Tests on small plots that treated water repellency chemically with wetting agents appeared encouraging during the earlier studies on fire-induced water repellency that began in the early 1960s (Osborn et al., 1964a). Although the benefit–cost ratio of these early wetting agent treatments was favorable (Osborn et al., 1964b), the rapid increase in the prices of chemicals (particularly during the energy crisis in the 1970s) probably would have limited their use for wide-scale applications. Also, for unknown reasons, the treatment of entire watersheds on an operational scale was found to be unsuccessful (Rice and Osborn, 1970). Mechanical techniques used to break up the water repellent layer, such as discing or using a "sheepsfoot" roller, are generally impractical when treating large steep landscapes that are burned during wildfires.

The only practical solution to manage fire-induced water repellency on wildland areas appears to be the regular use of prescribed fire as part of a comprehensive fuels management program. To prevent hydrophobic conditions during prescribed burning, it is recommended that prescribed burning programs be implemented on a regular basis to minimize soil heating (Robichaud, 1996). Frequent burning would reduce the dead fuel loading on areas, allowing fire managers to conduct low severity prescribed burns that would produce less opportunity for creating heat-induced water repellency. The regular reduction of fuel loading would further reduce the risk of high severity wildfires occurring. Also, the prescribed burning could be scheduled when the moisture in the lower layers in the duff is high enough so that the fire does not consume the lower duff layers, which insulate the soil from surface heating.

9. Summary

Much has been learned during the past three decades about a unique water repellent soil condition that is formed by wildfires. The severity of the water repellency depends on the combined interactions of soil properties and the soil heating regime developing during a fire. A hypothesis involving the volatilization and condensation of hydrophobic substances during soil heating has been developed by combining the results of laboratory experiments, field observations and controlled plot and watershed studies under field conditions. The precise chemical composition of the hydrophobic substances producing water repellency in soils has not been determined, perhaps due to the large number of organic compounds that can be altered by soil heating during a fire. The effect of the water repellent layer is manifested in several hydrologic processes, involving raindrop splash, rill formation and total watershed responses. The increased erosion by raindrop splash and rill formation has been well verified by controlled experiments. Watershed responses to water repellency are less clearly defined, but seem typically to include increases in quick flow and peak flow, larger watershed response ratios, and greater erosion and sedimentation rates. The longevity of the water repellent condition, if any, following cooler burning prescribed fires is less than a year, but water repellency can extend over several years if produced by a severe wildfire burning through large fuel accumulations during the dry season. Treatment of the postfire water repellency with wetting agents has not been successful on a watershed scale, although small plot and laboratory studies have shown better infiltration and reduced runoff following treatment with non-ionic surfactants. The best overall management strategy to ameliorate this "hard-to-wet" soil condition seems to be an effective fuels management program which reduces fuel buildups and thereby minimizes the occurrence of severe wildfires, particularly during the dry seasons.

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