FIRE-INDUCED WATER REPELLENCY IN SOILS: HYDROLOGIC IMPLICATIONS

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Water-repellent soils produced during fires in wildland ecosystems have attracted the attention of soil scientists and hydrologists throughout the world for more than 3 decades. The results of numerous studies have related fire-induced water repellency to specific hydrologic processes such as infiltration, runoff, and surface erosion (rill and sheet erosion). Relating fire-induced water repellency to overall watershed performance in terms of streamflow responses, however, has been more difficult. This paper reviews the formation of fire-induced water-repellent soils, the effect of soil water repellency on infiltration and runoff, erosional processes unique to water-repellent soils, and watershed and plot studies used to evaluate watershed responses to water repellency. Fire-induced water repellency has been reported in a wide range of wildland environments throughout the world, including United States, Turkey, Australia, New Zealand, Canada, and South Africa.

Water-repellent soils have an important effect on the infiltration of water into the soil and its subsequent movement and disposition throughout the soil profile. A brief description of wetting resistance to water drop penetration was presented in an earlier paper in this proceedings (DeBano 1999). The simplified contact-angle relationships of the water droplet test illustrated in this earlier paper become immensely more complicated when describing water movement through a porous media, such as a natural soil.

Fire-Induced Water Repellency

Laboratory tests of changes in water repellency resulting from different times and temperatures of heating have been 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. 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. 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 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. 1976). 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 the 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 of the burned area.

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Water Movement and Erosion

Fire affects the entry of water into a soil in two ways. First, the burned soil surface is unprotected from raindrop impact, which loosens and disperses fine soil and ash particles that can seal the soil surface. Second, soil heating during the fire produces a water-repellent layer at or near the soil surface, which impedes infiltration into the soil. If the water-repellent layer is on the soil surface, the hydrophobic particles are more susceptible to raindrop splash than if they were wettable (Terry and Shakesby 1993). The decreased infiltration produces a familiar rainfall-runoff-erosion scenario. Most important, the decreased infiltration rates increase surface runoff which initiates surface runoff and subsequent erosion. The increased surface runoff quickly entrains loose particles of soil and organic debris found on the soil surface following fire. Surface runoff may quickly concentrate into well-defined rills and increase surface erosion, particularly on steep slopes. The suspended material is then rapidly moved downslope to stream channels where it produces sediment-laden torrents that can eventually empty onto lower-lying flood plains. The effect of a water-repellent layer near, or at, the soil surface on infiltration and runoff has been easily conceptualized and has been validated in the laboratory and on small outdoor erosion plots. It has, however, been more difficult to validate on watershed-scale studies because of the large temporal and spatial variability of water repellency under field conditions. The following discussion first describes a conceptual framework of how different hydrologic processes are affected by water repellency, and then examines data collected during laboratory and field experiments.

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). The reason for the increased infiltration rates over time may be due to the dissolution of water-repellent substances over time and a more complete wetting of discontinuous wettable sites on the individual soil particles over time. 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. Water repellency has been expressed as "potential" if it is measured on air-dry soil and as "actual" if measured at field moisture content (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 the case 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 heterogeneity of soil water-repellency patterns and 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 in wildland soils, but under a more variable spatial environment.

Other Erosional Processes

Two important erosion processes usually occur following fire—dry ravel and rill formation. Dry ravel occurs during and immediately following the fire on steep slopes where gravity moves loose materials released during the fire downslope. Rill formation occurs when rainfall exceeds infiltration rates and causes surface runoff. Dry ravel is well illustrated in the southwestern United States where loose soil and rock material is held on steep slopes by shrubs during the interval between fires. High-severity wildfires burn the shrubs, releasing the stored material to move downslope by gravity. Dry ravel accumulates in channels at the base of steep slopes and remains there until increased streamflow moves it downstream (Wells 1987). The greatest mover of sediment, however, appears to be rill formation accompanied by sufficient sideslope runoff to move the debris stored in the channels. Two important processes that move soil from hillslopes during rain storms are raindrop splash and rill formation.

It has been reported that raindrop splash losses for hydrophobic soils were greater than for similar wettable sandy loam soils when both were exposed to various rainfall intensities, durations, and soil surface inclinations (Terry and Shakesby 1993). Information gained through the use of synchronized videocameras has revealed that 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 for two reasons. First, soil surfaces having an affinity for water become sealed and compacted during a rainfall event, which makes them increasingly resistant to splash detachment. Conversely, the hydrophobic soil remains dry, non-cohesive, and easily displaced by splash when the raindrop breaks the surrounding water film. Second, the splash resulting from raindrop impact differs substantially between the hydrophobic and wettable soil surfaces, as described above.

A striking feature on freshly burned watersheds during the first postfire rainstorms is the formation of an extensive rill network, which has been directly 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. 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 drain neither 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. 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. If the soil is coarse textured, initial failure causes a reorientation of the soil particles in the failure zone and they 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 down to the bottom of the slope or until it empties into a channel.

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. 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. Flow then diminishes, turbulence is reduced, and downcutting ceases. Finally the rill is stabilized immediately below the lower edge of the water-repellent layer. 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).

Hillslope Plot Studies of Erosion and Runoff

Using small plots has been a popular technique for studying water repellency under field conditions. These plots have been particularly useful for studying hillslope runoff and erosion. In a study on small hillside plots under a eucalyptus forest in Australia, it was concluded that fire-induced water repellency produced localized runoff and sediment movement only on hillslopes; it 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 eight times greater on plots burned at high intensities than on unburned controls (Soto and Diaz-Fierros 1998). Plots have also been used to study the spatial variability of water repellency (Doerr et al. 1998) and the relationship between the spatial distribution of water repellency and the erosion potential produced during prescribed burning (Robichaud 1996).

The results of several plot studies suggest that the hydrologic responses to fire-induced water repellency depend upon soil dryness. During evaluation of the hillslope module for the Water Erosion Prediction Project (WEPP), higher runoff coefficients were consistently measured during dry periods compared to the remainder of the year (Soto and Diaz-Fierros 1998). The increased runoff was attributed to an increase in the severity of water repellency at lower soil water contents during the dry season. While studying the effect of litter applications on overland flow from small burned and unburned plots in Portugal, two mechanisms were identified as being responsible for runoff. After long dry periods, overland flow was Hortonian and was linked closely to the presence of hydrophobic soils (Walsh et al. 1994). During wet periods, however, soils lost their hydrophobicity and overland flow resulted from a perched water table developing in shallow soils. A study on small plots in Portugal also concluded that during extended dry periods, latent soil hydrophobicity appeared to become reestablished, leading to increased runoff generation and soil loss (Terry 1994).

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 extrapolation of the relationships to a watershed scale often misses the increased variability found in 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 other for several years before and following a treatment (in this case, prescribed fire or wildfire). Reports of several studies in South Africa are used here to illustrate how watershed-level studies can be designed and the responses evaluated when studying watershed responses to fire-induced water repellency (Scott 1993, 1997; Scott and Van Wyk 1990). All of these studies involved coordinated measurements of streamflow response, sideslope erosion, and soil water repellency.

In one study, paired watersheds were used to compare streamflow and sediment responses to fire, with supplemental data on water repellency and soil loss collected on hillslopes in the calibrated watersheds. Streamflow and suspended sediment were measured on both watersheds before and after fire at permanent stream gauging stations. Soil losses were measured using 18 x 3 m plots on hillslope study sites following the fire. Water-repellency tests were taken throughout the watershed at four soil depths. The watershed sideslopes had been reforested with *Pinus radiata* to replace an indigenous cover of sclerophyllous scrubs (fynbos). The channels of both watersheds supported native riparian forests. In 1986 an intense wildfire burned about 80 percent of one watershed. During the first year following the fire, the weekly streamflow total increased 12 percent, stormflow increased 62 percent, quick flow volumes increased 201 percent, peak flow rates increased 290 percent, and the watershed response ratio increased 242 percent as a result of the fire (Scott and Van Wyk 1990). The second-year responses were somewhat less, with stormflow volume increased 20 percent, quick flow volumes increased 47 percent, peak discharges increased 108 percent, and watershed response increased 88 percent over that for the unburned watershed (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 fourfold following the fire. Wettability of the soils was decreased significantly and the most severe water repellency was found deeper in the soil.

In a different experiment in South Africa, four treated and three control watersheds were used to evaluate the effect of prescribed fires and wildfires on watersheds with different vegetative covers (Scott 1993). Two of the treated watersheds were covered with indigenous native fynbos—one with *Pinus radiata* forest and one with *Eucalyptus fastigata* forest. One of the two fynbos watersheds was prescribe-burned and the second was burned by a wildfire during the wet season. Both of the forested watersheds were burned by an intense wildfire during the dry season. Data from runoff plots and on water repellency were collected on treated watersheds. The two forested watersheds burned by the intense wildfires experienced significant increases in stormflows and soil loss. After fire, the storm hydrographs were higher and steeper, though their duration was little changed. The first-year increases were 190 and 1110 percent for peak discharge, 210 and 92 percent for quickflow volume, and 242 and 319 percent for the pine and eucalyptus watersheds, respectively. Neither of the fynbos watersheds showed a change in stormflow although annual flow increased 16 percent because of reductions in transpiration and interception. Water-repellency measurements suggested that the stormflow 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 stormflow and hillside erosion of a high-intensity wildfire that burned a eucalyptus forest. The fire markedly increased stormflows 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 gauging stations because a healthy riparian area acted as an effective buffer, trapping large amounts of eroded soil and ash.

The most complete studies describing the linkage have been reported by David Scott in South Africa. In one study (Scott 1993) the streamflow, stormflow, and sediment yield were measured on four catchments in South Africa following a fire. Two of the catchments were covered with overmature scrub vegetation (fynbos) prior to burning, a third with eucalypt forest (*Eucalyptus fastigata*), and a fourth with pine (*Pinus radiata*). One of the fynbos catchments was prescribe-burned and all other watersheds were burned by wildfires. The catchments were instrumented to determine changes in total streamflow volume, some stormflow characteristics, and the sediment yields of each catchment in terms of suspended sediment and bedload. Soils were sampled for water repellency at 12 to 15 locations in each major vegetation type on two catchments to assess the effect of fire on soil wettability. On the remaining catchments, only brief field surveys were carried out after the fires to determine the extent of water repellency in soils; they produced only a qualitative assessment. In addition, overland flow plots (3 x 22 m) were established after the fires on two of the watersheds. On the other two watersheds plots were established but only total sediment yield was measured. The differences in burning conditions (prescribed fire versus wildfire) and the vegetation cover (scrub and forest trees) produced several measurable differences. Under severe fires, produced when heavy, dry fuel loads were consumed, postfire erodibility was increased. Prescribed burns, particularly after rains, did not completely consume fuel materials. Vegetation types that lead to the development of hydrophobic soils (eucalyptus and pine) produced sharp hydrological responses that played a part in generating surface runoff following fire. Neither of the two fynbos watersheds produced substantial increases in stormflow or total flow increases. In contrast, on the two timbered catchments, substantial increases in stormflow and soil losses occurred. The effects of fire were considered to be due to changes in stormflow generation consistent with an increased delivery of overland flow (surface runoff) to the stream channel. This was caused, in part, by the reduced infiltration resulting from water repellency in the soils of the burned catchments. Overall, the hydrological responses to fire were related to numerous interactive factors, including the degree of soil heating, the vegetation type, and the soil properties.

Summary

It has been well established that water repellency can be intensified by soil heating during a fire. It is easy to relate the effect of water repellency in soils to water movement in the laboratory or on small hillslope plots, and these responses have been confirmed by numerous well-designed experiments. Extrapolating information gained during laboratory studies and small plots, however, to entire catchments is complex because of the spatial and temporal variability of fire-induced water-repellency patterns found in the soil. Further complicating the isolation of the effects of water repellency on catchment performance is the knowledge that fire also reduces vegetative cover, destroys surface litter, degrades soil structure, and changes a host of other parameters that can affect the overall hydrologic performance of a catchment. Very few experiments have evaluated on-site water repellency, hillslope hydrology, and watershed response simultaneously.

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