Fire–Induced Water Repellency: An Erosional Factor in Wildland Environments

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Abstract.—Watershed managers and scientists throughout the world have been aware of fire-induced water-repellent soils for over three decades. Water repellency affects many hydrologic processes, including infiltration, overland flow, and surface erosion (rill and sheet erosion). This paper describes; 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 the results of watershed and plot studies used to evaluate watershed-level responses to water repellency.

Introduction

Hard-to-wet soils are commonly found on freshly burned watersheds, particularly on those covered with chaparral brush. Hydrophobic organic compounds found in plant litter are vaporized during wildfires and condense at or near the mineral soils surface where they produce a water-repellent layer. This layer reduces infiltration of rain water into soil surface, causing overland flow and extensive surface erosion. This paper provides a theory for the formation of a water-repellent layer during a fire and describes the effects of fire-induced water repellency on postfire infiltration and erosion.

Fire-Induced Water Repellency

A hypothesis describing how a water-repellent layer is formed beneath the soil surface during a fire has been developed (DeBano et al., 1998). According to this hypothesis, organic matter accumulates on the soil surface under vegetation canopies during the intervals between fires. During fire-free intervals, some water repellency can be found in the organic-rich surface layers, particularly when they contain prolific fungal mycelia.

The combination of fuel combustion and heat transfer during wildfires produces steep temperature gradients in the surface layers of the mineral soil. Heat produced during combustion of litter and above-ground fuels vaporizes organic substances which are moved downward into the underlying mineral soil where they condense in the cooler underlying soil layers, forming a distinct water-repellent layer below and parallel to the soil surface.

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Water Movement and Erosion

Fire affects water entering the 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. Secondly, soil heating during a fire produces a water-repellent layer at or near the soil surface that impedes infiltration into the soil. This severity of the water repellency in the surface soil layer, however, decreases over time as it is exposed to moisture; so that, in many cases, it does substantially affect infiltration beyond the first year following fire.

Raindrop Splash

When the water-repellent layer is formed at the soil surface, the hydrophobic particles are more sensitive to raindrop splash than a wettable soil surface when both soils are were exposed to different rainfall intensities, durations and soil surface inclinations (Terry and Shakesby, 1993). Synchronized measurements by video cameras have shown that raindrop impact on hydrophobic soils produced fewer, slower-moving ejection droplets, which carry more sediment a shorter distance than a wettable soil. The soil surfaces having an affinity for water (wettable soil) become sealed and compacted during a rainfall event which makes them increasingly resistant to splash detachment. Conversely, the hydrophobic soil remains dry, noncohesive and are easily displaced by splash when the raindrop breaks the surrounding water film.

Rill Formation

A reduction in infiltration caused by a water-repellent layer quickly causes a highly visible rainfall-runoff-erosion pattern to develop on burned watersheds. 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. As a result, extensive rill networks develop when rainfall exceeds infiltration rates during the first postfire rainstorms (Wells 1987).

The sequence of rill formation has been found to follow several well-defined stages. First, the wettable soil surface layer, if present, is saturated during initial infiltration. Water infiltrates into the wettable surface until it encounters a water-repellent layer (Wells 1987). This process occurs uniformly over the landscape so that when the wetting front reaches the water-repellent layer, it can neither drain downward or laterally. As rainfall continues, water fills all available pore space until the wettable soil layer becomes saturated. Because pores cannot drain, positive 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 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 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 the 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, it flows down the debris flow track as free water in an open channel. 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 flow eventually 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.

Hillslope and Watershed Responses

Studies on the effects of fire-induced hillslope runoff and erosion from natural watersheds are much more difficult to establish than those dealing with the occurrence of specific erosional processes (e.g. raindrop splash, rill erosion). This is because wide spatial and temporal variation occurs in natural ecosystems. Two general techniques have been used to study the hydrologic responses to water repellency in outdoor environments. One uses small plots and the other focuses on entire watersheds.

Hillslope Responses

Small plots are a popular technique for studying water repellency under field conditions and have been used extensively for studying hillslope runoff and erosion. Rainfall can occur naturally or be applied with a rainfall simulator. For example, it was found on small hillside plots under an eucalyptus forest in Australia, that fire-induced water repellency produced localized runoff and sediment movement only on hillslopes, but did not appreciably affect watershed performance (Prosser and Williams, 1998). Plot studies 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. A study of overland flow from small burned and unburned plots in Portugal identified two mechanisms that were 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 re-established, leading to increased runoff generation and soil loss (Terry, 1994). Water repellency in soil increases upon drying because additional, and more stable, organic coatings responsible for water repellency are formed (Dekker et al., 1998).

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 extrapolating these relationships to a watershed scale often fails to recognize 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 for several years before and following a treatment (in this case, prescribed fire or wildfire).

The best documented studies reporting simultaneous measurements on fire-induced water repellency, runoff and erosion from small plots, and total watershed response have been done in South Africa. Although several studies were conducted, the most comprehensive study measured streamflow, stormflow, and sediment yields on four catchments following a fire (Scott 1993). Two catchments (Swartboskloof and Langrivier) were covered with over-mature scrub vegetation (fynbos) prior to burning, a third catchment (Ntabamhlope) was covered with eucalypt forest (*Eucalyptus fastigata*), and a fourth catchment (Bosboukloof) with pine (*Pinus radiata*). One of the fynbos catchments (Swartboskloof) was burned by a prescribed burn and all other watersheds were burned during 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 (Bosboukloof and Swartboskloof) to assess the effect of fire on soil wettability. On the remaining catchments, only brief qualitative field surveys were carried out after the fires to determine the extent of water repellency in soils. In addition, overland flow plots (3 X 22 meters) were established after the fires on two of the catchments (Bosboukloof and Swartboskloof). On the other two watersheds plots were established but only total sediment yield was measured. The differences in burning conditions (prescribed fire versus wildfires) 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 which lead to the development of hydrophobic soils (i.e., eucalyptus and pine) produced sharp hydrological responses which 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 cause the 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 by numerous well-designed laboratory experiments and studies involving small hillslope plots that water repellency can be intensified by soil heating during a fire and that the resulting water repellency developing in soils impedes infiltration into the soil, leading to extensive surface erosion. However, extrapolating information gained from these laboratory and small plot studies to entire catchments is complex because of the spatial and temporal variability of fire-induced water-repellency patterns. The identification of specific effects of water repellency on catchment performance requires knowing how fire reduces vegetative cover, destroys surface litter, degrades soil structure, and changes a host of other parameters which also can affect the overall hydrologic performance of a catchment. Very few studies have evaluated on-site water repellency, hillslope hydrology, and watershed response simultaneously. Research to date, however, indicates that fire-induced water repellency can have a substantial effect on watershed responses, particularly during the first year following fire.

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