Preferential flow as a potential mechanism for fire-induced increase in streamflow

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Abstract  After vegetation fires, discharge of streams and rivers is often higher than before. This is usually attributed to decreased canopy interception and evapotranspiration caused by vegetation removal, and to increased overland flow resulting from increased soil water repellency. In this paper we examine whether fire-induced changes in preferential flow can reinforce this postfire streamflow response. We studied five recently burned soils and adjacent unburned soils in Portugal and found that by reducing topsoil moisture and increasing soil moisture variability, fire increased the propensity for preferential flow. This was confirmed by 2-D soil moisture and repellency profiles that showed preferential paths in burned soil that were more distinct, wetter, and slightly narrower than in unburned soil. Since water infiltrating along preferential flow paths bypasses the dry soil matrix, we suggest that narrow flow paths promote deep infiltration—which effect size varies with soil depth, (effective) rainfall, and overland flow. We poset that the resulting increase in infiltration increases drainage and interflow because the excess water cannot stay in the soil, and incorporate fire-induced or –enhanced preferential flow into a conceptual model of flow routing that explains the commonly observed increase in streamflow postfire.

1. Introduction

Fires often lead to an immediate increase in streamflow, which can last from a few years to several decades [Robichaud et al., 2000]. As both peak- and dry season flows are increased [Kinoshita and Hogue, 2011; Loaiciga et al., 2001; Stoof et al., 2012], fires not only alter surface runoff but also interflow and baseflow generation. The size of this increase varies with fire impact and decreases with time [Shakesby and Doerr, 2006]; for a watershed in the same region in Portugal as the present study, 1 year postfire annual runoff ratios (streamflow divided by rainfall) were 1.7 to 2.5 fold higher than prefire values, while an unburned control watershed remained largely the same [Stoof et al., 2012]. This increased stream discharge is often attributed to decreased canopy interception and evapotranspiration caused by vegetation removal as well as increased overland flow resulting from the increased occurrence or dynamics of soil water repellency [Shakesby and Doerr, 2006; Stoof et al., 2012]. Here we introduce a new mechanism that reinforces the increase in streamflow after fire, namely that water infiltrating in burned soil follows narrower preferential paths, bypassing the dry soil matrix and providing additional water for interflow and baseflow.

Several studies have discussed the potential for and occurrence of preferential flow in burned soils [Granged et al., 2011; Zavala et al., 2009]. Preferential flow is, however, ubiquitous in fire-free environments [Parlange and Hill, 1976; Ritsema et al., 1996], and also unburned soils in fire-prone environments can develop preferential flow patterns because they are often dry and water repellent [e.g., Stoof et al., 2011]. A major unknown, therefore, is how fire alters preferential flow in soils. Our objective was to investigate how fire changes soil moisture and its variability, and explore whether these changes can lead to an increase in streamflow through enhanced preferential flow. Since drier soil typically carries narrower flow paths than moister soils [Liu et al., 1994a, 1994b] and hence increased development of preferential flow, we first tested the hypothesis that burning reduced topsoil moisture contents [Silva et al., 2006; Stoof et al., 2011] and increased soil moisture variation. We then quantified how this can lead to deeper infiltration of rainfall, increase soil drainage, and explain the increase in baseflow in burned watersheds using findings from the present study and from an experimentally burned watershed nearby.
2. Material and Methods

2.1. Study Area

The study area is the schist region in north-central Portugal (Figure S1), where average rainfall is 890 mm/yr and winters are wet and summers dry with high fire frequency. In Summer 2008, we selected five sites recently burned by wildfire and sampled recently burned plots (‘burned’) with adjacent unburned controls (‘unburned’, Table S1, Figures S2–S6) spaced ~10–50 m apart.

Selected sites had steep slopes (26–44%), with shallow soils (10–25 cm thin Leptosols) with high organic matter content (11–21%, Table S2). Prefire vegetation cover was representative for the region, with heaths and heathers (Ericaceae) at the Camelo and Friumes sites, and maritime pine (*Pinus pinaster*) with Ericaceae understory at Sobral, Pedras, and Colmeal. Further details are given in Tables S1 and S2.

2.2. Sampling and Analyses

The five wildfire sites were sampled 2–11 days after fire and before any significant postfire rainfall, using intensive transect sampling to allow visualization of small-scale variability of soil moisture. This sampling was done in July/August 2008 (Table S3) and composed of taking three transects on each plot using 50 cm$^3$ cores (eight samples wide × three samples deep) that were analyzed for soil water repellency (Water Drop Penetration Time, WDPT) and soil moisture. For details on site selection and methods, see Text S1.

To capture the longevity of fire effects, three sites (Camelo, Sobral, and Colmeal) were revisited four times after the initial sampling. In October/November 2008, December 2008 and October 2009, fire effects on top-soil moisture content were determined at 10 random points within each burned and unburned plot using TDR, and in February 2009, transect sampling was again performed to visualize soil moisture and water repellency variation with depth. Mixed models were used to assess fire effects on soil properties, with details given in Text S1. Fire effects on topsoil moisture (0–5 cm) were analyzed for each of the sampling dates. The transect data was furthermore used to assess fire effects on soil water repellency, bulk density, and soil organic matter content as a function of depth. They were also used to quantitatively assess fire effects on the submeter-scale variability of soil moisture, an indication of preferential flow [Ritsema and Dekker, 1995]. For this, the submeter-scale variability of soil moisture was quantified with the coefficient of variation (CV) of soil moisture in each transect layer.

3. Results and Discussion

3.1. Fire Effects on Soil Moisture and Water Repellency

In line with our hypothesis, burned topsoils were drier than their unburned counterparts (Figures 1 and 2): the top 5 cm of burned soil was consistently drier than that of unburned soil throughout the monitoring period (Figure 1). This effect increased with time until December 2009 and was significant at the $p < 0.05$ level at all but the wettest sampling date (February 2009), when the fire effect was slightly weaker...
Drier topsoils after fire are common [e.g., Silva et al., 2006; Stoof et al., 2011] and can be explained by the increased albedo and lack of shading on the exposed burned (and initially blackened) soil, leading to higher postfire soil temperatures (Figure S7) and increased soil evaporation. Two-dimensional images of the soil moisture profile indicate that the drying effects of fire were often restricted to the top 5 cm, with the 6–8.5 cm depth generally being as moist or even moister in burned soil as in unburned soil (Figure 2, Text S2). This can likely be explained by the higher soil evaporation in burned soil being balanced out by increased infiltration due to increased flow instability [Ritsema and Dekker, 1995] (section 3.4) and lower evapotranspiration with depth in burned soil [Silva et al., 2006].

Soil water repellency was prevalent in both burned and unburned soil, and even occurred after ~500 mm of winter rainfall (Figure 1) before sampling in February 2009 (Figures 2 and S8). Interestingly, fire had no significant effect on soil water repellency in August 2008, nor in February 2009, for any of the layers (Figure S8). This lack of fire-induced soil water repellency may be surprising to some, but is in fact not uncommon for soils that have “natural background” or “prefire” soil water repellency [Dutt et al., 2009; Rodríguez-Alleres et al., 2012; Stoof et al., 2011].

As for the other soil properties assessed, organic matter content remained unchanged and increased bulk density was limited to the top 2.5 cm (Figure S9).

### 3.2. Submeter-Scale Variability

All 2-D images of the soil moisture and water repellency profiles of the five study sites showed a high degree of submeter-scale variability (Text S2), indicating the susceptibility of these soils to preferential flow: in dry and in wet conditions and in burned and unburned soil. This increased variability with fire is confirmed by the moisture variability (CV) being significantly higher in burned than in unburned soil (18 ± 10 versus 14 ± 5%, p = 0.011). Figure 2 shows that compared to unburned soil, burned soil in summer had more distinct and wetter preferential paths, while the surrounding soil matrix was considerably drier. These preferential paths are not only visible in the soil moisture profile but also in the water repellency profile, since similar to other studies [e.g., MacDonald and Huffman, 2004; Stoof et al., 2011] soil water repellency and soil moisture were highly related. In the burned soil, the width of path 1 increases with depth from...
ing the soil surface for our shrub vegetation. Copy interception is lacking in a postfire environment, resulting in nearly double the amount of rainfall reaching the soil (black arrows in Figures 3a–3c). This increased infiltration is further enhanced by the fact that concentration but also soil drainage and interflow or subsurface flow, as the excess infiltration will not remain in moist soil with a finger width of 20 cm (Figures 3a versus 3b). As a result, finger flow not only promotes infiltration but also increases the risk of soil erosion and preferential flow. This explains why the net effect of finger flow can lead to drier soils despite increased infiltration. The increased variability in soil moisture indicates the greater propensity of burned soil for flow instability and preferential flow. The drier burned topsoil (Figures 1 and 2) adds to this, given that finger flow is greatly affected by a soil’s initial moisture content, with dry soils developing narrower fingers than moist soils [Liu et al., 1994a, 1994b]. This increased propensity for finger flow is further enhanced by the fact that before the first postfire rains, potential preferential paths were already distinct in the burned soil (Figures 2 and S2, summer). As fingers in not-completely dried out soil have a strong tendency to recurrently follow existing zones of (even slightly) higher moisture content [Liu et al., 1994a], it is very likely that the wetter preferential paths in Figures 2 and S2 developed into fingers during the first postfire rains. The consistently drier soil in the burned areas throughout the monitoring period (Figure 1) moreover suggests that the increased propensity for finger flow is not limited to the first postfire rains but may last as long as it takes for the vegetation to regenerate to the point that exposure and drying out of the topsoil ends. In the wildfires assessed here, this will have taken longer than 14 months, because in October 2009, before the onset of autumn rains, vegetation cover was only 10–40% (50–60% short of the unburned cover; see also Shakesby et al. [2014] for data on the Camelo site) and burned soil was still significantly drier than unburned soil (0.8 ± 0.9 versus 3.5 ± 2.1 cm$^3$ cm$^{-3}$ soil moisture content, $p = 0.000$, 0–5 cm depth average of all sites).

3.3. Potential for Preferential Flow

The increased variability in soil moisture indicates the greater propensity of burned soil for flow instability and preferential flow. The drier burned topsoil (Figures 1 and 2) adds to this, given that finger flow is greatly affected by a soil’s initial moisture content, with dry soils developing narrower fingers than moist soils [Liu et al., 1994a, 1994b]. This increased propensity for finger flow is further enhanced by the fact that before the first postfire rains, potential preferential paths were already distinct in the burned soil (Figures 2 and S2, summer). As fingers in not-completely dried out soil have a strong tendency to recurrently follow existing zones of (even slightly) higher moisture content [Liu et al., 1994a], it is very likely that the wetter preferential paths in Figures 2 and S2 developed into fingers during the first postfire rains. The consistently drier soil in the burned areas throughout the monitoring period (Figure 1) moreover suggests that the increased propensity for finger flow is not limited to the first postfire rains but may last as long as it takes for the vegetation to regenerate to the point that exposure and drying out of the topsoil ends. In the wildfires assessed here, this will have taken longer than 14 months, because in October 2009, before the onset of autumn rains, vegetation cover was only 10–40% (50–60% short of the unburned cover; see also Shakesby et al. [2014] for data on the Camelo site) and burned soil was still significantly drier than unburned soil (0.8 ± 0.9 versus 3.5 ± 2.1 cm$^3$ cm$^{-3}$ soil moisture content, $p = 0.000$, 0–5 cm depth average of all sites).

3.4. Potential Effects on Routing of Flow in a Watershed

Since fingers can rapidly funnel rain water down the soil profile due to increased hydraulic conductivity in the wetter flow paths [Ritsema and Dekker, 1995], its increased occurrence can have considerable impacts on the hydrology of burned areas. Narrower fingers have greater finger front velocities [Liu et al., 1994a], therefore, water moves more quickly down existing flow paths. Because it then bypasses a larger part of the soil matrix, less water is used to wet the soil, leading to more water being conserved for deeper infiltration and interflow. This explains why the net effect of finger flow can lead to drier soils despite increased infiltration. The effects of finger flow on infiltration are illustrated in Figure 3, where we show that for the same rain event, water infiltrates roughly five times as deep in a dry soil with a finger width of 10 cm than in a moist soil with a finger width of 20 cm (Figures 3a versus 3b). As a result, finger flow not only promotes infiltration but also soil drainage and interflow or subsurface flow, as the excess infiltration will not remain in the soil (black arrows in Figures 3a–3c). This increased infiltration is further enhanced by the fact that canopy interception is lacking in a postfire environment, resulting in nearly double the amount of rainfall reaching the soil surface for our shrub vegetation [Stoof et al., 2012]. To quantify the effect of fingerling, taking into account this increase in effective rainfall, we calculated deeper infiltration or interflow ($Q_i$) in a conceptual model following Text S3. As input parameters, we used data from the wildfire sites (e.g., soil depth, finger widths) as well as from an experimentally burned watershed 8 km from Camelo [Stoof et al., 2010; Stoof et al., 2011; Stoof et al., 2012]. Results show that 20 mm rainfall on a dry postfire soil (without vegetation)

\[ Q_{\text{i}} = \frac{P}{W} \times (1 - \text{Repellency}) \times \text{Finger Width} \]

\[ Q_{\text{s}} = \frac{P}{W} \times \text{Finger Width} \times \text{Initial Moisture Content} \]

\[ Q_{\text{total}} = Q_{\text{i}} + Q_{\text{s}} \]

\[ \text{Finger Velocity} = \frac{Q_{\text{i}}}{\text{Finger Width}} \]

where $P$ is the rainfall, $W$ is the finger width, \text{Repellency} is the soil repellency, and \text{Initial Moisture Content} is the soil moisture content.
generates up to 0.9 mm interflow per unit rainfall more than a moister prefire soil (with vegetation), depending on soil depth and overland flow (Figures 3d and 3e). While finger flow effects on interflow are smaller than the effect of increased effective rainfall, its impact also varies with rainfall (Figure 3f). This clearly demonstrates that a fire-induced increase in finger flow can increase interflow, which may reinforce the increase in streamflow resulting from greater effective rainfall and reduced evapotranspiration. This mechanism provides a new view on flow routing in burned areas. While our wildfire sites did not allow for detailed validation of this mechanism in the field, our findings can be used to design studies to assess the effect of fire on streamflow partitioning, quantify the potential contribution of finger flow to the postfire increase in streamflow in situ (e.g., using tracer experiments combined with hydrograph separation analysis), and compare the hydrological effects of finger flow to the effects of fire-induced changes that may occur, such as changes in soil texture, water retention, and infiltration capacity [Shakesby and Doerr, 2006; Stoof et al., 2010].

Soil water repellency was not significantly altered by the wildfires assessed in the present study, but because of fire effects on soil moisture and flow paths, preferential flow is an important factor to be considered in areas where fires occur. This effect will be even more severe where fires do lead to an increase in water repellent conditions [e.g., MacDonald and Huffman, 2004]. Because soil water repellency can induce or intensify finger development [Bauters et al., 1998] by enhancing saturation overshoot conditions [DiCarlo, 2014], it likely magnifies the hydrological impact of flow instability discussed above. Direct runoff (streamflow) from repellent soil is therefore not automatically the result of increased overland flow, as assumed by Stoof et al. [2012] (see Text S3); it can also be caused by an increase in preferential flow and resulting increased interflow.

4. Conclusions and Implications

Five soils burned by wildfire in the Portuguese schist region had significantly and consistently drier topsoils and higher submeter-scale moisture variability than adjacent (on-site) unburned soils. This confirms our
hypothesis that fire can increase the propensity for finger flow development. Since increased finger flow enhances deep infiltration of rain and causes more rapid groundwater recharge [Ritsema and Dekker, 1995], it can contribute to the common increase in streamflow after fire by increasing interflow and/or baseflow volume. This suggests that in addition to the known contribution of decreased canopy interception and plant uptake to fire hydrology, increased preferential flow is a potential mechanism that reinforces the increase in postfire streamflow. These findings give rise to questions as to whether this effect is cyclical or cumulative, as well as to the interactions between uneven moisture distribution and the rate and patterns of plant regeneration. As preferential flow bypasses the soils’ natural capability of filtering out chemicals, its impacts are furthermore also relevant from a water quality perspective, particularly in areas where (toxic) fire retardants are used to suppress wildfires. Because fire frequency is expected to increase in many parts of the world [Carvalho et al., 2010], understanding the hydrology of burned soils and watersheds will become increasingly relevant.

References


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