Catena 142 (2016) 77–88

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Infiltration and interrill erosion rates after a wildfire in western Montana, USA

Peter R. Robichaud [a,*], Joseph W. Wagenbrenner [a,1], Fredrick B. Pierson [b], Kenneth E. Spaeth [c], Louise E. Ashmun [a], Corey A. Moffet [b,2]

[a] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1221 South Main Street, Moscow, ID 83843, USA
[b] U.S. Department of Agriculture, Agricultural Research Service, Northwest Watershed Research Center, 800 East Park Boulevard, Plaza IV Suite 105, Boise, ID 83712, USA
[c] U.S. Department of Agriculture, Natural Resources Conservation Service, Central National Technology Support Center, Fort Worth, TX 76115, USA

ARTICLE INFO

Article history:
Received 13 March 2015
Received in revised form 21 January 2016
Accepted 29 January 2016
Available online 1 March 2016

Keywords:
Ground cover
Post-fire recovery
Rainfall simulation
Sediment yield
Soil water repellency
Water drop penetration time

ABSTRACT

The 2000 Valley Complex wildfire burned in steep montane forests with ash cap soils in western Montana, USA. The effects of high soil burn severity on forest soil hydrologic function were examined using rainfall simulations (100 mm h^{-1} for 1 h) on 0.5-m^2 plots. Infiltration rates, sediment yields and sediment concentrations were compared among three treatments: control (unburned and undisturbed); bare (unburned with all surface vegetation, litter, and duff removed prior to each simulation); and burned. Rainfall simulations were done immediately after the fire and repeated in 2001, 2002, and 2005. Soil moisture, water repellency, and understory canopy and ground cover were measured and related to infiltration rates and sediment yields. The unburned forest soil was water repellent at the mineral surface. This surface repellency was no longer detected after it was burned at high severity, but a post-fire water repellent soil layer was observed at 1–2 cm below the surface. The control plots had high ground cover (90% overall), infiltration of 44–48 mm, and very low sediment concentrations (median values of 0.1–0.6 g L^{-1}) and sediment yields (6–54 g m^{-2}) for all years despite changes in soil moisture and strong water repellency. The bare and control plots had similar water repellency values, but the interrill erosion in the bare plots was high throughout the study (624–1277 g m^{-2}). In the year of the fire, the burned sites had high rates of soil water repellency (88%) and little ground cover (10%). This resulted in low infiltration rates (30 mm), high sediment concentrations (median value 21 g L^{-1}), and high sediment yields (1157 g m^{-2}). By 2005, the fire-altered water repellency decreased in occurrence (48%) and severity, and the ground cover increased (42%). This resulted in much greater infiltration (84 mm), lower sediment concentration (median value 0.5 g L^{-1}), and lower sediment yields (15 g m^{-2}) on the burned plots. The importance of ground cover for preventing interrill erosion was demonstrated by the very low sediment yields on the control plots as compared to the bare and burned plots. The strength and occurrence of water repellency in both the unburned and burned sites decreased as soil moisture increased; however, strong soil water repellency was detected at the soil surface whenever unburned soils were dry. Fire-altered soil water repellency influenced the infiltration capacity and increased runoff rates immediately after the fire; however, the loss of protective ground cover was a more significant factor for the increased sediment concentrations and sediment yields.

Published by Elsevier B.V.

1. Introduction

Post-fire increases in runoff, flooding, and erosion are generally attributed to the loss of vegetation and forest floor material which leaves the forest soil less protected and more vulnerable to the erosive effects of rainfall, overland flow, wind, and gravity. The direct effects of fire on forest soils, such as loss of organic matter and changes in soil water repellency, aggregate stability, and soil water retention, can change infiltration of water and runoff amounts and characteristics; thus contributing to post-fire erosion vulnerability as well (e.g., Bento-Gonçalves et al., 2012; Certini, 2005; DeBano et al., 1998; Inbar et al., 2014; Larsen et al., 2009; Leighton-Boyce et al., 2007; Shakesby and Doerr, 2006). Understanding fire effects on infiltration is vital for the prediction of post-fire flooding and erosion responses.

Many factors control infiltration rates; vegetation is a dominant factor in forest environments (Castillo et al., 1997; Cerdà, 1999; Cerdà and Doerr, 2005; Cerdà and Robichaud, 2009; Faulkner, 1990). Vegetation

---

[*] Corresponding author.
E-mail addresses: probichaud@fs.fed.us (P.R. Robichaud), jwwagenb@mtu.edu (J.W. Wagenbrenner), fred.pierson@ars.usda.gov (F.B. Pierson), ken.spaeth@ftw.usda.gov (K.E. Spaeth), leashmun.work@gmail.com (L.E. Ashmun), corey.moffet@ars.usda.gov (C.A. Moffet).

[1] Present address: School of Forest Resources and Environmental Science, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, USA.

[2] Present address: U.S. Department of Agriculture, Agriculture Research Service, Southern Plains Range Research Station, 2000 18th Street, Woodward, OK 73801, USA.

http://dx.doi.org/10.1016/j.catena.2016.01.027
0341-8162/Published by Elsevier B.V.

increases infiltration rates by adding organic material to the soil, which improves soil structure and porosity, and by deepening the litter layer (Abrahams et al., 1995; Berndtsson and Larson, 1987; Jiménez et al., 2006; Wilcox et al., 1988). The macropores developed by plant roots provide preferential flow paths (Beven and Germann, 2013) and also increase the water holding capacity of the soil. The litter and duff layers can further enhance infiltration by absorbing and storing water and allowing more time for infiltration into the soil (Brock and DeBano, 1982; Lowdermilk, 1930). Both the vegetation and the forest floor protect the mineral soil from direct impact of the rain drops and the subsequent destruction of the soil aggregates, compaction, slaking, particle segregation, and the filling and clogging of pores by the wash-in of fine material, all of which can form structural seals at the soil surface and reduce infiltration capacity (Assouline, 2004; Liu et al., 2011; Mataix-Solera et al., 2011; Woods and Balfour, 2010).

Fire-altered water repellency forms when surface vegetation, litter, and near-surface soil organic matter are burned and a fraction of the vaporized hydrocarbons condense on soil particles in the cooler layers beneath the surface (DeBano, 1981; Doerr et al., 2000). The degree and depth of the fire-altered soil water repellent layer vary with the degree of soil heating over small spatial scales (Huffman et al., 2001), resulting in preferential flow paths through less water repellent areas and the formation of uneven wetting fronts (Dekker and Ritsema, 1994, 1995; Ritsema and Dekker, 1994, 2000). Macro-pores such as root channels that remain after roots burn can also serve as pathways for water to infiltrate through water repellent layers (Burch et al., 1989; Doerr et al., 2006a; Meeuwig, 1971; Shakesby et al., 2000). Because of the reduced infiltration rates, overlying layers of ash and/or soil may saturate, and this could lead to lateral surface or near-surface flow (Bodí et al., 2012; Doerr et al., 2006a; Ebel et al., 2012).

Soil water repellency has often served as a surrogate measurement of infiltration capacity in post-fire assessments (DeBano, 1981; Parsons et al., 2010; Robichaud et al., 2008). Although there is a clear association between fire-altered soil water repellency and enhanced post-fire hydrologic and erosion response, the effect of soil water repellency often has been oversimplified (Doerr et al., 2009a; Leighton-Boyce et al., 2007). The contribution of fire-altered soil water repellency on runoff and erosion is difficult to separate from other fire impacts such as loss of vegetation and forest floor material, decreased surface roughness, soil disaggregation, and soil sealing (Doerr and Moody, 2004; Larsen et al., 2009; Leighton-Boyce et al., 2007; Shakesby and Doerr, 2006).

Soil water repellency is not only caused by fire, but is an inherent soil characteristic found in many types of soils with a range of textures, organic contents, vegetation, land uses, and locations (Doerr et al., 2006b; Jordán et al., 2009, 2013; Mataix-Solera et al., 2007). Long unburned forest soils with inherent soil water repellency at or near the soil surface have been observed worldwide in certain forest types (Doerr et al., 2006b, 2009b). Although soil water repellency is classically associated with coarse-textured soils (Mataix-Solera et al., 2013; Moral García et al., 2005; Robichaud and Hungerford, 2000), the organic-rich surface layers of volcanic ash soils (Andisols) have highly aggregated soil structure that retain water and are often water repellent when dry (Kawamoto et al., 2007). Soil water repellency in fine-textured soils more consistently decreases with depth and has a greater impact on infiltration than soil water repellency in coarser soils (Fox et al., 2007; Mataix-Solera et al., 2013; Rodriguez-Alleres et al., 2007). In addition, inherent soil water repellency has been associated with vegetation that contains waxes, resins, or oils such as eucalyptus and pine trees and sagebrush and chaparral shrubs (DeBano, 1981; Lozano et al., 2013; Martínez-Zavala and Jordán-López, 2009; Mataix-Solera et al., 2007; Pierson et al., 2001).

Generally, both inherent and fire-altered soil water repellency are lost during long wet periods and are re-established upon drying, causing short-term or seasonal variations (de Jonge et al., 1999; Dekker and Ritsema, 1996; Dekker et al., 2001; MacDonald and Huffman, 2004; Robichaud and Hungerford, 2000). The change in soil water repellency may occur over a range of soil moistures, or a “transition zone,” such that both water repellent and wettable soils may exist within the transition zone but only water repellent conditions exist when soil moisture is below the lower boundary and only wettable conditions exist above the upper boundary (Dekker and Ritsema, 1994; Dekker et al., 2001; Regalado and Ritter, 2005).

The influence of forest floor material on infiltration rates into inherently water repellent soils is not easily determined. If the organic material that overlays the mineral soil helps maintain soil moisture above the threshold for wettability, it enhances infiltration (Feng et al., 2001; Letey, 2001; Wang et al., 2000). However, short rainfall simulations may not capture this process. Leighton-Boyce et al. (2007) found that inherent soil water repellency in mature eucalyptus plantation sites persisted through a 30-min high intensity (107 mm h^{-1}) rainfall simulation and that the majority of rainfall which did not become overland flow was stored within the litter layer rather than infiltrating into the soil.

Several others have used rainfall simulation to evaluate the impact of fires in coniferous forests (Table 1; see review by Vieira et al., 2015). However, the small plot rainfall simulations, such as those used in our study, may not accurately represent infiltration and erosion processes at larger scales. The short lengths of the rainfall simulation plots restrict erosion to rain splash and sheetwash (interrill) processes (Bryan, 2000; Huang et al., 2001). At larger scales, however, hillslope processes include differential flow patterns, detention and storage of runoff and sediment, and rill erosion. Generally, small plots have greater per-unit-area runoff rates than larger scales where the existence of preferential flow paths may create scattered “sink” areas across a hillside that allows water to infiltrate (Imeson et al., 1992; Nyman et al., 2010; Prosser and Williams, 1998; Stoof et al., 2012). Yet these studies can provide insight to fire effects especially when unburned plots are used for comparison (Table 1).

Given the large, and occasionally extreme runoff events that occur post-fire and the associated flooding and erosion, the need to understand and accurately predict post-fire hydrologic and geomorphic responses continues to drive research (Moody et al., 2013). We measured the immediate and short-term effects (5 years) of high severity wildfire on infiltration rates, interrill erosion rates, and other related variables. Specifically, the objectives of the study were to use small-plot rainfall simulations to compare infiltration rates, sediment concentrations, and sediment yields among three treatments—unburned with no recent disturbance (control), unburned with surface litter, duff, and vegetation removed (bare), and burned at high soil burn severity (burned). Soil water repellency, canopy cover and ground cover were also compared. Rainfall simulations and other measurements were done immediately after the fire and repeated in post-fire years one, two, and five to measure temporal effects.

2. Materials and methods

2.1. Site description

We measured the runoff and sediment concentrations from simulated rainfall on seven forested sites within the 144,000 ha burn perimeter of the 2000 Valley Complex Fire in the Bitterroot Valley, Montana (Fig. 1). About a third of this area burned at high soil burn severity (USDA Forest Service, 2000), our study site was in the high soil burn severity portion of the burned area and adjacent unburned area. Three unburned sites (U5–U7) and four high soil burn severity sites (B1–B4) (approximately 3 km south) were selected based on similarity of slopes (37–50%), elevations (1880–2050 m), aspects (200–285°, with the exception of U5 with an aspect of 150°), and road access. For all seven sites, the vegetation or pre-fire vegetation was sub-alpine fir (*Abies lasiocarpa*) and fool's huckleberry (*Menziesia ferruginea*). Soils were