Nat Hazards (2012) 61:217–227
DOI 10.1007/s11069-011-9769-9

ORIGINAL PAPER

Wildfire impacts on the processes that generate debris flows in burned watersheds

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Received: 2 February 2010 / Accepted: 24 February 2011 / Published online: 17 March 2011

Abstract Every year, and in many countries worldwide, wildfires cause significant damage and economic losses due to both the direct effects of the fires and the subsequent accelerated runoff, erosion, and debris flow. Wildfires can have profound effects on the hydrologic response of watersheds by changing the infiltration characteristics and erodibility of the soil, which leads to decreased rainfall infiltration, significantly increased overland flow and runoff in channels, and movement of soil. Debris-flow activity is among the most destructive consequences of these changes, often causing extensive damage to human infrastructure. Data from the Mediterranean area and Western United States of America help identify the primary processes that result in debris flows in recently burned areas. Two primary processes for the initiation of fire-related debris flows have been so far identified: (1) runoff-dominated erosion by surface overland flow; and (2) infiltration-triggered failure and mobilization of a discrete landslide mass. The first process is frequently documented immediately post-fire and leads to the generation of debris flows through progressive bulking of storm runoff with sediment eroded from the hillslopes and channels. As sediment is incorporated into water, runoff can convert to debris flow. The conversion to debris flow may be observed at a position within a drainage network that appears to be controlled by threshold values of upslope contributing area and its gradient. At these locations, sufficient eroded material has been incorporated, relative to the volume of contributing surface runoff, to generate debris flows. Debris flows have also been generated from burned basins in response to increased runoff by water cascading over a steep, bedrock cliff, and incorporating material from readily erodible colluvium or channel bed. Post-fire debris flows have also been generated by infiltration-triggered landslide failures which then mobilize into debris flows. However, only 12% of documented cases

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exhibited this process. When they do occur, the landslide failures range in thickness from a few tens of centimeters to more than 6 m, and generally involve the soil and colluvium-mantled hillslopes. Surficial landslide failures in burned areas most frequently occur in response to prolonged periods of storm rainfall, or prolonged rainfall in combination with rapid snowmelt or rain-on-snow events.

Keywords Wildfire · Debris flows · Erosion · Hazards

1 Introduction

Debris flows originating in recently burned areas can greatly contribute to the overall damage and economic losses yearly produced by wildfires worldwide. The generation of debris flows from recently burned watersheds depends upon a number of factors, including the characteristics of the fire, the physical properties of the soil mantle, basin gradient and form, the availability of sediment in the channel, the type and presence of vegetation, and the triggering storm rainfall (Cannon et al. 2010). In order to appropriately mitigate the associated hazards, knowledge of the main processes that generate debris flows within the burned basins is crucial. In this article, we summarize information about the changes in hydrologic conditions in burned watersheds brought about by wildfire, and how these changes might lead to the production of debris flows.

2 Changes in watershed conditions caused by wildfires that affect hydrologic response

The primary effects of fire on the hydrologic response of a drainage basin include (1) the removal of soil-mantling vegetation and litter, (2) the deposition of ash, (3) altering the physical properties of both soil and rock, and (4) the enhancement, generation, or destruction of water-repellent soils.

2.1 Removal of soil-mantling vegetation and litter

Depending on both the type of fire and its severity, wildfire can remove some or all of the vegetation and litter cover, thereby altering key variables in the hydrologic cycle. Damage to, or consumption of, the tree canopy, shrubs, and herbaceous strata can temporarily reduce, or stop completely, both rainfall interception and soil-moisture transpiration (Loaiciga et al. 2001). For example, Hanshaw et al. (2009) found that rain gages located beneath a chaparral shrub canopy received an average of 42% less rainfall than did gages located in the adjacent burned area, and 1-h intensities were reduced by up to 67%. Consumption of soil-mantling litter and duff can also reduce rainfall interception and storage rates. With removal of litter and duff, water-storage capacities (measured for each centimeter thickness of litter) have been documented to decrease from pre-fire conditions by approximately 0.5 mm in pine forests and 3 mm in commercial eucalypt stands in Portugal (Shakesby and Doerr 2006). Exposure of the bare soil surface leaves it susceptible to raindrop impact and entrainment by overland flow and also results in changes in soil-moisture dynamics with increased solar heating (Shakesby and Doerr 2006).

2.2 Ash deposition

Loss of surface cover can also allow for translocation of mineral or ash particles into soil pores, resulting in sealing that can enhance post-fire sediment yields (e.g., Durgin 1977; Larsen et al. 2009).

Ash accumulations on hillslopes can create a water-storage reservoir that temporarily reduces the potential for the generation of runoff. From rainfall simulation experiments, Woods and Balfour (2008) found that a 1–3.5–cm-thick ash layer at a burned site in Montana resulted in increased rainfall storage capacities and infiltration rates, increased time to ponding and runoff, and reduced runoff rates. In contrast, data from rainfall-runoff simulations on ash overlying a sandy mineral soil at a burned site in Colorado by Kinner and Moody (2010) indicated that infiltration rates were limited by coarser underlying mineral soil, rather than by the ash.

2.3 Altering the physical properties of soil and rock

Consumption of organic matter within the top few centimeters of soil, including fine roots, soil microbes, and fungal mycorrhizae, can result in a loss or degradation of aggregate stability and associated increases in the ease of detachment-driven erosion (Neary et al. 1999; Shakesby and Doerr 2006); many researchers maintain that the passage of a fire results in a more friable, less cohesive, and more erodible soil (DeBano et al. 1998; Scott et al. 1998; Neary et al. 1999), with the changes to the soil depending on soil type and the temperatures reached during burning (Guerrero et al. 2001). Cannon and Reneau (2000) noted the relation between areas of fibrous root mat consumption and increased surface erosion. Soil microbial and fungal activity are thought to contribute to aggregate stability through the secretion of cohesive compounds and the production of stabilizing fungal hyphae (Shakesby and Doerr 2006).

Physical properties of soils, including the particle-size distribution, soil-aggregate stability, bulk density, plasticity, and elasticity can also change during burning. Hubbert et al. (2002) excavated pits into coarse, loamy soils following a prescribed burn in Southern California and, by comparing burned areas to unburned areas, found that the average clay content decreased from 5.4 to 3.4%. Exposure to temperatures associated with wildfires has also been shown to result in decreases in both clay- and silt-size fractions, and a corresponding increase in the sand-size range (Dyrness and Youngberg 1957). High temperatures are thought to fuse soil particles, creating coarser, but less cohesive soil aggregates that are vulnerable to erosion and raveling (DeBano et al. 1998; Neary et al. 1999; Wondzell and King 2003). Heating to above 460°C drives off hydroxyl (OH) groups from clays, resulting in a structure loss that is also thought to increase erodibility and promote raveling (Durgin 1985; DeBano et al. 1998; Mills and Fey 2004). This loss also corresponds to losses in soil plasticity and elasticity (Giovannini et al. 1987). Soil-aggregate stability has also been reported to decrease due to the presence of ash; in a series of lab experiments, Durgin (1985) demonstrated that ash, when mixed with water, creates a high pH solution that facilitates dispersion of soil aggregates.

Wildfire can change strength properties of shallow soils through destruction of the root network and consequent decreases in the cohesive strength provided by roots. Removal of the fine root network can lead to an increase in raveling of loose materials from shallow soils that have been severely burned (Fig. 1), an effect which can be quite pronounced either during or immediately after fires. Over longer time frames, the larger diameter and deeper root networks of vegetation burned during the fire will decay, so that instability

Fig. 1 Dry ravel off hillslopes burned by the 2009 Station fire in the San Gabriel Mountains, southern California, USA. LA Times photograph

effects may appear months or years after the fire (Meyer et al. 2001; May and Gresswell 2003).

2.4 The generation and enhancement of water-repellent soils

Among the hydrologic properties that change significantly in response to wildfire the most frequently cited is the development or enhancement of soil water repellency. Soil water repellency refers to the inability of water to wet or infiltrate a dry soil, a phenomenon that has been documented in a wide range of vegetation types and climates, including both unburned and burned terrains (Doerr et al. 2000, 2009). The intensity and persistence of soil water repellency will vary with fire temperature and duration, vegetation type, soil moisture and texture, and time since burning (Huffman et al. 2001). Vegetation type affects the amount and type of hydrophobic compounds available for translocation in a soil, and thus the degree of water repellency (DeBano 2000).

Fire-induced rock weathering produces development of fractures that are generally parallel to the rock surface, and spalling and cracking of rocks of all sizes, including boulders, caused by high temperatures are often observed in burned areas (Blackwelder 1927; Ollier and Ash 1983; Allison and Bristow 1999). This physical weathering may combine with chemical weathering processes to produce a greater amount of materials available to be transported during rainstorms than would be available otherwise (Garfi' et al. 2007; Ollier et al. 2007).

3 Increases in erosion rates due to fire

Erosion yields or rates, measured as a transport or delivery rate of sediment in terms of mass per unit area per unit time (for example: tons/ha/year), have been documented to increase dramatically following wildfire (e.g., Meyer et al. 2001; Moody and Martin 2001, 2009), generally due to the combined effects of loss of protective vegetative cover, decreases in soil infiltration rates and increases in the availability of readily eroded sediment (Wondzell and King 2003). Summarizing data from burned hillsides in different continents, Moody and Martin (2001) found that erosion rates increased after fires between 50 and 870 times, with a median increase of 160 times. From a compilation of the total amount of erosion for 83 hillslope sediment yield rates measured within 2 years of fires in the western United States, Moody and Martin (2009) report an average value of 82 tons/ha. It is important to note that reported values vary considerably with measurement method. Typical annual sedimentation rates reported for burned areas range between 500 and 10,000 g/m^2, while typical rates for unburned, low severity burned, or recovered areas are between 1 and 50 g/m^2 (Benavides-Solario and MacDonald 2005; Roering and Gerber 2005; Campo et al. 2006; Shakesby and Doerr 2006).

A recent database produced for evaluating the effects of wildfires on erosion and debris-flow generation in Mediterranean climatic areas (Parise and Cannon 2008) indicate similar results for reported sediment yields following wildfire. However, reports of post-fire debris flows are scarce in Mediterranean ecosystems, in contrast to the abundance reported, for example, in southern California. The authors suggest that the paucity of reported debris flows might be due to occurrence of less severe fires in the Mediterranean basin, varying rainfall conditions, or possible differences in watershed morphology, but also indicate that additional data are necessary to definitely evaluate the issue (Parise and Cannon 2008).

Increased erosion following wildfire can result in immediate channel aggradation, particularly for lower order channels in the higher reaches of drainage basins. Channel deposits are typically bedload materials, as the sediment supply exceeds the stream carrying capacity (Santi et al. 2008). Suspended sediments are carried much farther, and streams draining burned areas can be muddy throughout the window of disturbance time frame. Over time, stream flow removes bedload channel deposits and redeposits some of them at locations where the stream gradient drops, creating terraces and alluvial fans (Meyer and Wells 1997).

4 Processes that generate debris flows from burned watersheds

Two primary processes for the initiation of fire-related debris flows have been identified in the literature: (1) erosion and entrainment of material by surface runoff and (2) infiltration-triggered failure and mobilization of a discrete, shallow landslide mass. The runoff-dominated process for generating debris flows is the most frequently reported immediately post-fire (Gartner et al. 2005).

4.1 Erosion and entrainment of material by surface runoff

Debris-flow initiation in recently burned areas is generally attributed to significantly increased rates of rainfall runoff. Although these data are generally lacking or difficult to obtain, sediment availability has been identified as a primary factor controlling post-fire sediment yields (Moody and Martin 2009). A common observation following fires and subsequent rainstorms are the development of a series of rills on the steeper hillslopes. Rill formation is considered one of the strongest differences between pre-fire and post-fire sediment delivery. Rills (Fig. 2) often form within minutes of even very small rainstorms after wildfire (Wells 1987; Cerda 1988): they are typically between 1 and 2 cm deep, and between 5 and 15 cm wide (Cannon et al. 2001a, b; Moody and Martin 2001; Gabet 2003).

Fig. 2 Levee-lined rill erosion in the 2009 Station Fire in the San Gabriel Mountains of southern California, USA. *Photo* by Dennis Staley, USGS

In contrast, Atkinson (1984) reports post-fire rills in southeastern Australia up to 60 cm deep. In some cases, the rills can be lined with levees consisting of poorly sorted, unstratified, matrix-supported materials typical of debris flows. Because these hillslope-generated debris flows can be diluted by additional water from overland and stream flow, they do not always persist or evolve into more destructive debris flows once they travel into channels (Cannon et al. 2001a).

Johnson (1984), Meyer and Wells (1997), and Cannon et al. (2001b, 2003) each traced debris-flow deposits upslope through small gullies and into a series of rills, and noted the lack of a discreet landslide mass of a significant size at the head of the flow. These workers observed evidence of convergence and concentration of runoff within hollows and in low-order channels, as well as erosion and entrainment of significant amounts of surficial material. Erosion was often to bedrock, with both runoff and sediment transported through the channel network (Fig. 3). Water-transported deposits were observed within low-order (0–2) channel reaches, and deposits characteristic of debris flows were observed farther down within the drainage network (Fig. 4). Based on these observations, Meyer and Wells (1997) and Cannon et al. (2003) conceptualized a process wherein surface runoff from a rainfall event erodes sediments from hillslope and channels until a position within the drainage network where sufficient material has been entrained, relative to runoff volume, for a debris flow to be generated.

Debris flows have also been generated from burned basins in response to increased runoff by water cascading over a steep, bedrock cliff, and incorporating material from readily erodible colluvium or channel bed. Johnson (1984) described this process in unburned terrain as the “firehose” effect. In Mediterranean settings, this process was observed during the 1998 generation of mudflows in the Campania region of southern Italy, where water and debris flows cascading over both natural (carbonate scarp) and man-made (mountain pathways) breaks in slope increased the overall volume and the destructive power of the flows by eroding and entraining channel material (Calcaterra et al. 2000).

Fig. 3 Incision produced by debris flow following a wildfire near Sula, Montana, USA

Fig. 4 Debris flow deposits in Dunsmore Canyon, Station fire, San Gabriel Mountains, USA. *Photo* by Jason Kean

Runoff-initiated debris flows have been produced in response to storms that occur within 2–3 years of the fire, with the largest of triggered by the initial significant rainstorms (Cannon et al. 2008). Debris flows have occurred in response to both short-duration, high-intensity convective thunderstorms as well as to longer-duration, lower-intensity frontal systems. Approximately 2-year recurrence interval storms of either type are often sufficient to generate debris flows from recently burned basins (Cannon et al. 2008). Rainfall intensity-duration thresholds that can be used to identify the conditions under which runoff-initiated debris flows can be expected, have been defined for some areas (e.g., Cannon et al. 2008). These thresholds vary with local rock, soil and vegetation types, basin shapes and gradients, and burn severity distributions.

Rainfall conditions that trigger fire-related debris flows are attained at durations at least an order of magnitude less that those described for the generation of debris flows in unburned settings, and at significantly lower intensities (e.g., Caine 1980; Larson and Simon 1993). This difference can likely be attributed to the extremely rapid, runoff-dominated processes acting in burned areas compared with longer-term, infiltration-dominated processes on unburned hillslopes (Martin and Moody 2001). In contrast to the rainfall conditions necessary to initiate shallow landslides and debris flows from unburned slopes where antecedent rainfall is a critical element, it is not uncommon for debris flows to be generated from recently burned hillslopes in response to the first rainstorm to impact an area, when antecedent soil moisture would be minimal (Cannon et al. 2008).

4.2 Infiltration-triggered failure and mobilization of a discrete, shallow landslide mass

Failure of shallow discrete landslide masses has also been documented in wildfire-affected watersheds (Meyer et al. 2001; Cannon and Gartner 2005), with failures ranging in thickness from a few tens of centimeters up to 6 m, generally involving soil- and colluvium-mantled hillslopes (Fig. 5). There is always uncertainty in attributing shallow landslides in burned areas to the real effects of fires: to do this, it would be necessary to consider the effective changes imparted by the fire, but there is little well-controlled data available on this subject. Nevertheless, three possible wildfire-related landslide-triggering effects have been proposed so far in the literature. Increases in soil moisture after fires, due to the loss of vegetative interception and transpiration, have been measured by Megahan (1983) and Cannon et al. (2001a), but further research is necessary to determine whether such increase might be sufficient to produce shallow landslide failures. Second, wildfire-induced tree mortality can lead to the decay of regolith-anchoring roots, which, in turn, could result in decreased soil cohesion and increased probability of landsliding, as proposed by Swanson (1981). In addition, Wondzell and King (2003) suggest that increased peak flows occurring after fire can contribute to accelerated bank erosion, with a concurrent increase in rate of bank-side failure.

Surficial landslide failures in burned areas most frequently occur in response to prolonged periods of storm rainfall (a week or more in duration), or prolonged rainfall in

Fig. 5 Shallow landslide on hillslope burned the previous summer (Durango, Colorado, USA)

combination with rapid snowmelt or rain-on-snow events (Meyer et al. 2001; Cannon and Gartner 2005). Landslides have been documented as occurring during the first rainy season immediately after the fire (e.g., Morton 1989; Cannon and Gartner 2005), 1–2 years after the fire (Meyer et al. 2001), and up to 10 years or even 30 years (May and Gresswell 2003) after the fire. It would be important to establish whether the landslide can indeed be attributed to fire, and not simply to extreme meteorological events which would have triggered it even without the effect of the fire, especially for those failures that occur after significant time periods. Of the 203 basins included in Gartner et al. (2005), only 24 (12%) were characterized by observations of debris flows originating exclusively from shallow landslide failures.

5 Conclusions

Wildfire is a widespread phenomenon that is expected to increase in spatial extent and severity in the future as fuel accumulations, shifting land management practices, and possible climate change influences on the landscape balance. Primary effects of fire include the removal of soil-mantling vegetation and litter, the deposition of ash, the creation of water-repellent soils, and the effects of temperature extremes on soil and rock. The post-wildfire changes in geomorphic processes have long-term implications for landscape development and more immediate societal implications (De Graff et al. 2007). Flooding, sedimentation, and debris flows can threaten the lives, homes, and economic well-being of people living near a burned area. Most of these threats are particularly acute during the first rainy season following the wildfire event. Debris flows are among the most hazardous consequences of rainfall on recently burned hillslopes, and pose a hazard distinct from other sediment-laden flows because of their unique destructive power (Cannon and Gartner 2005; Cannon et al. 2010).

Although studies are currently underway to develop methods for characterizing post-fire debris flow hazards in varying geologic settings and determine the rainfall intensity-duration thresholds that control post-fire debris-flow generation (e.g., Cannon et al. 2010), additional studies are necessary to gain a better understanding of the processes working in burned watersheds and to relate these processes to the geologic and morphologic conditions within watersheds and the rainfall characteristics of debris-flow triggering events. The spectrum of possibilities for the occurrence of different types of events is, in fact, very complex, from short-term responses that follow a single fire, to long-term effects of multiple fire-flood cycles over geologic time.

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