Sediment Production and Delivery from Wildfires: Processes and Mitigation

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Abstract. Few changes in forested areas can have as dramatic an effect on runoff and erosion rates as high-severity wildfires. The flooding, sedimentation, and degradation of water quality after high-severity wildfires is of increasing concern due to the increase in downstream property values, the growing demand for high-quality water, and the projected increases in burned area as a result of climate change.

Surface erosion is the predominant source of post-fire sediment, although debris flows and landslides can be locally important. Process-based studies indicate that the large increases in surface runoff after high-severity fires are due primarily to the loss of vegetative cover, loss of aggregate stability, and resultant soil sealing. The increased volume and velocity of surface runoff causes extensive rilling and a rapid expansion of the stream channel network. The sediment generated in headwater areas causes extensive sedimentation in lower-gradient, downstream reaches.

Since post-fire sediment production is most closely related to the amount of bare soil, it follows that the most effective treatments are those that immediately increase the amount of ground cover, such as mulching. In the absence of any treatment, vegetative regrowth causes hillslope runoff and erosion rates to return to near-background levels within 1-4 years. This decrease in runoff limits the ability of downstream channels to export the accumulated sediment, and in downstream areas post-fire recovery may require several decades or even centuries.

Regional comparisons show that post-fire sediment yields tend to be substantially lower in Mediterranean Europe relative to comparable areas in North America. This difference is attributed to the longer-term soil degradation as a result of repeated fires, forest clearing, and human cultivation. The large increases in erosion means that repeated wildfires can be a major cause of land degradation and desertification.

1. Introduction

High-severity wildfires in forests and shrublands can greatly increase runoff and erosion rates relative to most other land uses (e.g., MacDonald and Stednick, 2003). In most cases the increases in erosion are due to debris flows and mass movements, while in other cases the increases are due to a sequence of surface erosion processes (rainsplash, sheetwash, rilling, and channel incision/bank erosion). The observed increases in runoff and erosion can greatly affect site productivity and downstream resources. The purpose of this paper are to: (1) identify the key processes by which fires increase runoff and erosion rates; (2) compare the relative importance of landslides, debris flows, and surface erosion processes and the process domains where each is likely to dominate; and (3) use this information to assess the potential for different management techniques to mitigate the adverse on- and off-site impacts of high-severity wildfires.

In most undisturbed or minimally disturbed forests infiltration rates are greater than rainfall intensities. The high infiltration rate means that most or all of the precipitation infiltrates into the soil and is delivered to the stream network by relatively slow-moving subsurface stormflow (although some water may be forced to the surface in topographically convergent areas). Forests also have a protective litter layer on the soil surface, and this absorbs the raindrop impact and protects the underlying mineral soil against rainsplash and soil sealing. The predominance of subsurface flow—when combined with the presence of a protective litter layer—causes sediment yields from forest lands to be lower than other vegetation types and land uses.

High-severity fires are the disturbance of greatest concern in many forested areas because they can greatly increase surface runoff and erosion rates, and because relatively large areas can be affected (Figure 1). In Colorado USA, for example, the 2002 Hayman wildfire burned 550 km^2 of forest land. In the areas burned at high severity the infiltration rate decreased from more than 60 mm hr^{-1} prior to burning to only 7-10 mm hr^{-1} for the first couple of years after burning. This 10-fold decrease in infiltration increased the size of peak flows by two or more orders of magnitude, and similar increases have been observed in other areas. The increase in surface runoff caused hillslope-scale sediment yields to increase from almost nothing prior to burning to a mean of 10 Mg ha^{-1} yr^{-1} for the first three years after burning (Pietraszek, 2006). This means that larger fires can sharply increase the size of peak flows, surface erosion rates, and sediment yields at both the hillslope and large catchment scales. The resulting downstream effects include loss of human life and property, degradation of water quality and aquatic habitat, and large declines in reservoir storage capacity (e.g., Rinne, 1996; Agnew et al., 1997).

Fig. 1. View over a portion of the 2002 Hayman wildfire in Colorado, which burned 550 km^2.

The effects of high-severity wildfires on runoff and erosion rates are of increasing concern for two main reasons. First, the rapid population growth in downstream areas is greatly increasing the values at risk. This includes the direct risk to human life as well as the increased risk to property and the increasing demand for high-quality water. Second, the frequency, extent, and severity of wildfires are projected to sharply increase as a result of global warming. This warming will increase the length and severity of the summer dry season and hence the likelihood of large, high-severity wildfires. In parts of the northwestern U.S. peak snowmelt is already occurring up to three weeks earlier, and this effectively increases the length of the summer dry season and has been correlated with an increase in the area burned by wildfires (Westerling et al., 2006). Other areas, such as the southwestern U.S., are expected to become drier as a result of global climate change.

In general, global climate change will increase the likelihood of large wildfires in historically fire-prone areas such as Australia and the Mediterranean, and also increase the likelihood of severe forest fires in areas that historically have not been subjected to frequent wildfires, such as eastern Europe. This means that post-fire runoff and erosion are an increasing concern for both the public and resource managers (NRC, 2008)

2. Processes by Which Fires Increase Runoff and Erosion

An understanding of the mechanisms by which wildfires increase runoff and erosion is essential for predicting the likely effects of current and future fires, and for developing effective post-fire mitigation techniques. The large increases in runoff and sediment yields after burning have been attributed to three types of erosion, and these are: (1) surface erosion (i.e., rainsplash, sheetwash, rilling, and gullying); (2) debris flows; and (3) landslides.

Each of these mechanisms varies in its spatial frequency, temporal extent, and the proportion of a watershed that is likely to be affected, and this in turn controls the likely magnitude of downstream effects. The importance of each mechanism also will vary according to the specific landscape conditions, and any efforts to mitigate these changes has to be based on an understanding of the underlying processes plus the relative likelihood of each of these three types of erosion. Hence the following sections discuss each mechanism in more detail, their relative importance, and the potential for mitigating the adverse effects.

2.1. Surface erosion

The increases in surface erosion after high-severity wildfires are generally due to the decrease in infiltration and loss of surface cover. More specifically, the observed decrease in infiltration and corresponding increase in surface runoff have been attributed to different processes, including: the development of a fire-induced water repellent layer at or near the soil surface; the loss of surface cover; the loss of aggregate stability; a decrease in surface roughness; and soil sealing.

The role of soil water repellency has historically been emphasized, as this is relatively easy to document after a fire, and it provides a logical explanation for the observed increases in runoff. However, recent studies have emphasized the rapid decay of fire-induced soil water repellency, the large spatial and temporal variability in post-fire soil water repellency, and the presence of soil water repellency in unburned areas (particularly coniferous forests and certain types of shrublands) (Doerr et al., 2008). The implication of is that some other process besides soil water repellency must be helping to cause the observed increases in runoff and surface erosion after high-severity fires.

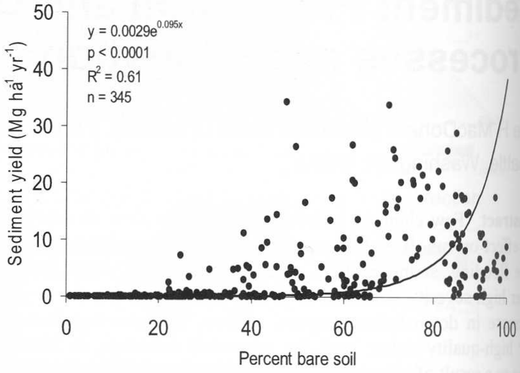

Fig. 2 Relationship between percent bare soil and sediment production for seven wild and three prescribed fires in the Colorado Front Range, USA.

Several studies have found a strong empirical relationship between the amount of exposed mineral soil and post-fire erosion rates (Figure 2) (Benavides-Solorio and MacDonald, 2005), and similar results have been reported from agricultural studies. Rainfall simulations on bare soils and soils with litter or other ground cover suggest that the development of a structural soil seal may be the primary cause of the observed decrease in infiltration after a high-severity fire (Larsen et al., in press). A field experiment in the Colorado Front Range also showed no significant differences in surface erosion between hillslopes burned by a high-severity wildfire and three unburned hillslopes where the litter was removed to expose the mineral soil (Larsen et al., in press). All of these studies indicate that percent ground cover is the primary control on surface runoff, and that post-fire soil water repellency plays a much smaller role than is commonly assumed.

The loss of the litter layer by burning is further exacerbated by the loss of soil organic matter, disaggregation of the soil aggregates, and resulting increase in soil erodibility. Burning the surface litter and vegetation also decreases the surface roughness, which increases the overland flow velocity. The surface sealing, increase in soil erodibility, and decrease in surface roughness all combine to greatly increase the amount and velocity of overland flow. These same factors cause a tremendous increase in rainsplash detachment, sheetwash, and rilling, resulting in a rapid upslope expansion of the stream channel network (Figure 3).

In the Colorado Front Range, for example, storms with only 10-15 mm of rainfall caused extensive rilling in formerly unchannelled swales, and these rills extended to within 5 or 10 m of the ridgetops (Figure 3). Detailed volumetric measurements of the newly-formed rills over successive storms indicated that about 80% of the measured hillslope sediment yield is due to rill incision rather than rainsplash and sheetwash (Pietraszek, 2006). Channel incision extended downslope until the channel gradient decreased to around 10%, at which point some of the post-fire sediment was deposited (Figure 4) with the remainder being transported further downstream. The downstream delivery of ash and sediment can cause severe aggradation and degrade water quality.

Regional comparisons show that post-fire surface erosion

Figure 3. Rill erosion in a formerly unchanneled swale.

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rates tend to be substantially lower in Mediterranean Europe relative to comparable areas in North America. The lower erosion rates in countries such as Portugal and Spain are attributed to the long-term soil degradation as a result of repeated forest clearing, human cultivation, and fires. The observed differences in post-fire erosion rates suggest that frequent wildfires are a major cause of land degradation and desertification.

2.2. Debris Flows

In some areas debris flows can be an important mechanism for post-fire erosion. The underlying processes that cause the initial increase in runoff should be identical to the processes discussed in the previous section on surface erosion, but the main difference is the extent to which the concentrated runoff scours channels and transforms into debris flows. Post-fire debris flows occur when 30-minute rainfall intensities exceed 10-15 mm h^{-1}, which is similar to or slightly greater than the 8-10 mm h^{-1} needed to initiate surface runoff and erosion (Cannon et al., 2008). Empirical models indicate that debris flows only occur when channel gradients exceed 15-30% and the upslope contributing areas are greater than 0.1-1 ha (Gabet and Bookter, 2008; Gartner et al., 2008). Although they typically occupy a much smaller proportion of the drainage basin than the rainsplash, sheetwash, rilling and gullying discussed in section 2.1, debris flows can deliver comparable volumes of sediment to downstream channels and alluvial fans.

Fig. 4. After a high-severity fire there is extensive channel incision in the steeper upslope areas, and deposition occurs when the channel gradient drops from around 16% to 10%

2.3. Landslides

High-severity wildfires consume or kill the vegetation. This will decrease transpiration and interception, thereby increasing soil moisture levels and the likelihood of shallow landslides by increasing pore pressures. In steep forest and shrubland areas the post-fire loss of root strength is often a more important concern, as root cohesion is often a primary contributor to slope stability (Montgomery and Dietrich, 1994). However, post-fire landsliding has generally been reported only after extreme storms (e.g., Meyer et al., 2001). Relative to surface erosion and debris flows, landslides are much less frequently cited as a primary source of post-fire sediment, and there are at least four main reasons for this.

First, high-severity fires will kill the dominant vegetation, but it generally takes 3-15 years before root decay reduces root cohesion and slope stability to a minimum (Sidle and Ochiai, 2006). Second, as the time since burning increases vegetative regrowth will progressively restore on-site water use and reduced the likelihood of excess pore pressures. Third, there usually is a rapid decline in the frequency and intensity of post-fire measurements, and this means that post-fire landsliding is less likely to be documented relative to the surface erosion and debris flows that occur in the first 1-3 years after burning. Fourth, the basic physical processes mean that most landslides occur on steep hillslopes with convergent topography, but in many burned areas the slopes are not steep enough and the geologic conditions are not conducive to shallow landslides.

This means that post-fire landsliding will only be important in selected geographic terranes, while post-fire surface erosion can occur on almost any sloping surface. The relatively widespread occurrence of surface erosion processes is supported by the much greater number of studies devoted to post-fire surface erosion relative to landslides.

3. Post-fire Treatments

The differences in these three erosion mechanisms have important implications for the design of treatments to minimize post-fire erosion. With respect to surface erosion, the critical change is the decrease in infiltration and the most critical variable is the amount of surface cover. This means that the most effective treatments are those that immediately increase the amount of ground cover and thereby reduce soil sealing. Studies in different areas consistently show that mulching with straw, wood chips, or wood fiber products can reduce post-fire sediment yields by around 90% for the first couple of years after burning (Bautista et al., 1996; Wagenbrenner et al., 2006). Other types of mulch treatments, such as hydromulch, have had mixed success, and this may be due to the variations in matching the specific hydromulch formulation to local site conditions (Rough, 2007).

In contrast to mulching, seeding is rarely effective in reducing post-fire erosion, as this generally does not increase ground cover relative to untreated plots (e.g., Wagenbrenner et al., 2006). Similarly, efforts to physically break up the water repellent layer ("scarification") have not been successful in reducing post-fire erosion. The effectiveness of a surface binding agent (i.e., a polyacrylamide) also has not been proven, as this also will require a careful matching of the polyacrylamide to the specific site conditions (Rough, 2007).

The same principles for reducing post-fire surface erosion should also apply to debris flows, as these also result from the post-fire decrease in infiltration. The problem is that few studies have evaluated post-fire debris flow mitigation treatments, but in southwestern Colorado a combination of watershed-scale hillslope and channel treatments reduced debris flow volumes by several orders of magnitude relative to untreated watersheds (deWolfe et al., 2008).

The potential treatments to minimize post-fire landslides are very different because of the differences in the causal processes. Since a primary cause of post-fire landslides is the increase in soil wetness and pore water pressures after burning, the primary objective is to reduce rather than increase infiltration. Maintaining a high percent bare soil would be the most effective means for reducing infiltration, but this has the obvious trade-off of increasing surface runoff and erosion with the resulting adverse effects on water quality and downstream resources. The installation of subsurface drains could prevent the development of high pore pressures, but this is very expensive and could only be done on a few high-risk hillslopes that are a direct threat to life and property. A more effective procedure would probably be to maximize the regrowth of deep-rooted species, as this would both increase transpiration and quickly restore root strength. Given the uncertainty over which slopes will fail and the magnitude of future storm events, managers generally have very limited possibilities for substantially reducing post-fire landsliding.

4. Conclusions

High-severity fires can increase runoff and erosion rates in forested areas by several orders of magnitude. These large increases can be attributed to the sharp decrease in infiltration as a result of soil sealing and other processes. High-severity fires also remove the protective litter layer, increase soil erodibility by consuming soil organic matter, and decrease surface roughness. The increase in the amount and velocity of overland flow induces severe rilling and gullying. Because these surface erosion processes can occur over large portions of a watershed, fires can have larger-scale effects on flooding, water quality, and aquatic habitat than most other disturbances in forested areas.

Debris flows and landslides also can occur after high-severity fires, but these are more dependent on extreme storm events and generally occur in specific, limited locations. Hence these two types of post-fire erosion are less common and are not as important as the more ubiquitous changes in surface erosion.

Mitigation techniques that immediately restore the ground cover, such as mulching, are most effective in reducing surface erosion. In contrast, there is relatively little potential for mitigating or reducing post-fire landslides. Repeated fires can lead to severe degradation and desertification, and the effects of fires are an increasing concern as a result of global climate change and the increasing value of the resources at risk.

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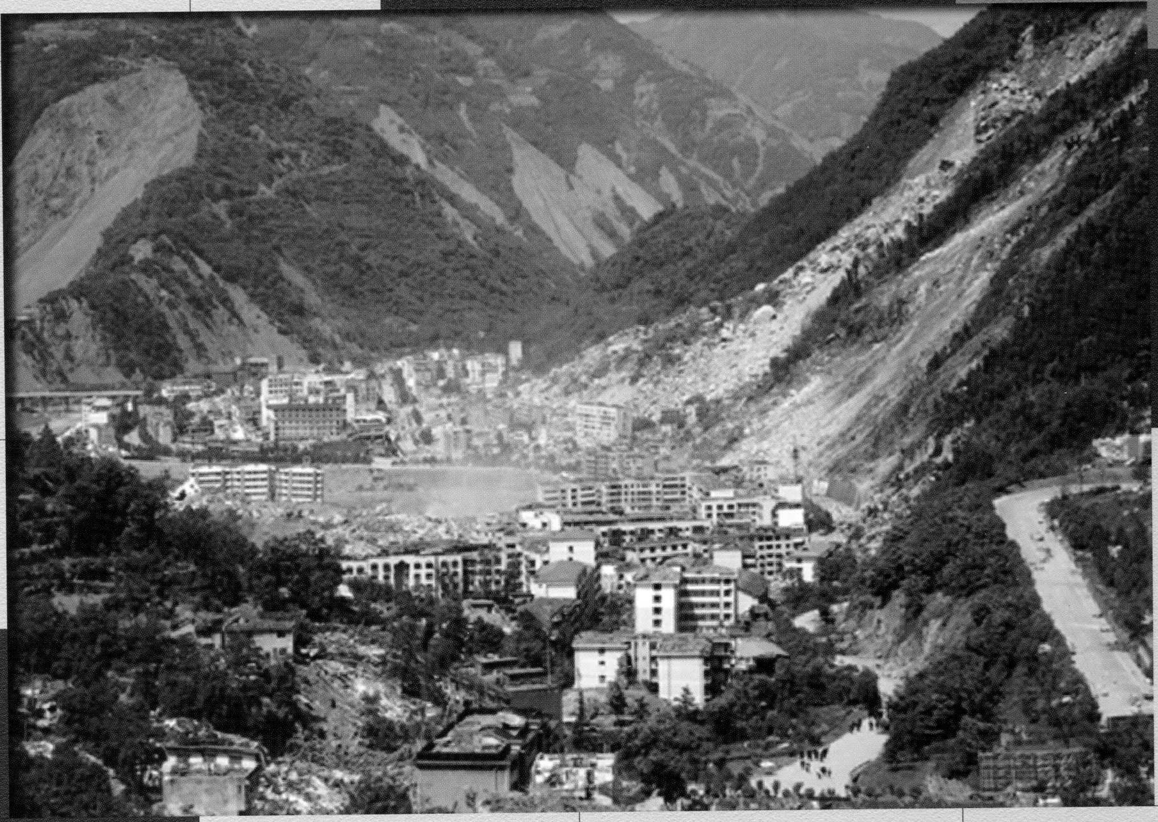

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