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Fire Effects on Soils and Restoration Strategies

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Effects of Forest Fires and Post-Fire Rehabilitation: A Colorado, USA Case Study

Lee H. MacDonald[1]* and *Isaac J. Larsen*[1]

Abstract

Anthropogenic activities have increased the number of large, high-burn severity wildfires in the lower and mid-elevation coniferous forests in Colorado as well as much of the western US. Forests provide most of the water for cities and agriculture, and the increased runoff and erosion after wildfires is a major concern because of the potential adverse effects on flooding, water quality, and other aquatic resources. Areas burned at high severity are of primary concern because rainfall intensities of only 8 to 10 mm h^{-1} *can generate substantial amounts of runoff and surface erosion. Typical post-fire erosion rates from areas burned at high severity are 5 to 10 Mg* ha^{-1} yr^{-1} *for the first 2 to 3 yr after burning, and this is about 5 to 80 times the values measured from areas burned at moderate or low severity. Post-fire sediment yields are most closely associated with the amount of surface cover and rainfall erosivity. Three to five years are typically required before hillslope-scale sediment yields decline to near-background levels.*

Studies on multiple fires indicate that the most effective post-fire rehabilitation treatments are those that immediately provide surface cover, such as straw mulching. Seeding and seeding combined with scarification did not increase the rate of vegetative regrowth and therefore did not reduce post-fire sediment yields. Hydromulching varied in its effectiveness, and this was attributed to the differences in the mixtures applied to different sites. Contour-felled log erosion barriers were effective only for small and moderate-sized storms, and the effectiveness of this treatment is easily negated by poor installation. The application of a polyacrylamide also failed to significantly reduce post-fire sediment yields. Mulching is the most cost-effective treatment at US$50 to US$150 per megagram reduction in sediment yields.

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Post-fire sediment yields from Colorado are within the range of values reported from the western US and other countries. The results of this case study can provide useful guidance to land managers and researchers in other areas, as the basic principles and processes identified in this chapter are more broadly applicable.

INTRODUCTION

Over the last several decades there has been an increase in the number of large wildfires in the western US (Westerling et al. 2006). The increase in wildfires is a major concern for the public and resource managers because of the potentially large increases in runoff and erosion, and the resulting adverse effects on life, property, and aquatic resources. Flooding after the 1996 Buffalo Creek Fire southwest of Denver, Colorado caused two fatalities and repeatedly washed out a state highway, and the increased sediment load reduced the storage capacity in Strontia Springs Reservoir by approximately one-third (Agnew et al. 1997). Debris flows after the 2002 Coal Seam and Missionary Ridge Fires in western Colorado damaged homes, roads, and railways (Cannon et al. 2003). The high sediment and ash loads after high severity fires greatly increase water treatment costs and reduce macro-invertebrate and fish populations (Rinne 1996, Rieman and Clayton 1997, Minshall et al. 2001, Kershner et al. 2003).

The hydrologic and geomorphic effects of high severity wildfires are of particular concern in Colorado because most of the state's water supply is derived from forested areas and water-related resources are an important economic asset (MacDonald and Stednick 2003). There also has been a large increase in the number of people living in the wildland-urban interface, and this has increased the potential loss of life and property from high-severity wildfires and the subsequent flooding and erosion.

Land managers commonly apply rehabilitation treatments after high severity wildfires in order to reduce the potential increases in runoff and erosion. Mitigation treatments include seeding, scarification, mulching, hydromulching, and the application of soil binding agents such as polyacrylamides. The application of such treatments over large areas is quite costly, as evidenced by the US$25 million spent after the 2002 Hayman Fire by the U.S. Department of Agriculture, Forest Service (USFS) and the Denver Water Board (Robichaud et al. 2003, Wiley, personal communication 2005), and the approximately US$100 million spent after the Cerro Grande Fire in northern New Mexico (Morton et al. 2003). The problem is that there have been very few studies in the central Rocky Mountains on post-fire erosion rates or the effectiveness of mitigation treatments in reducing post-fire sediment yields. There also is an urgent need to better understand the underlying processes that cause the observed increases in post-fire runoff and erosion rates, as this is crucial to predicting post-fire effects and the application of cost-effective rehabilitation treatments.

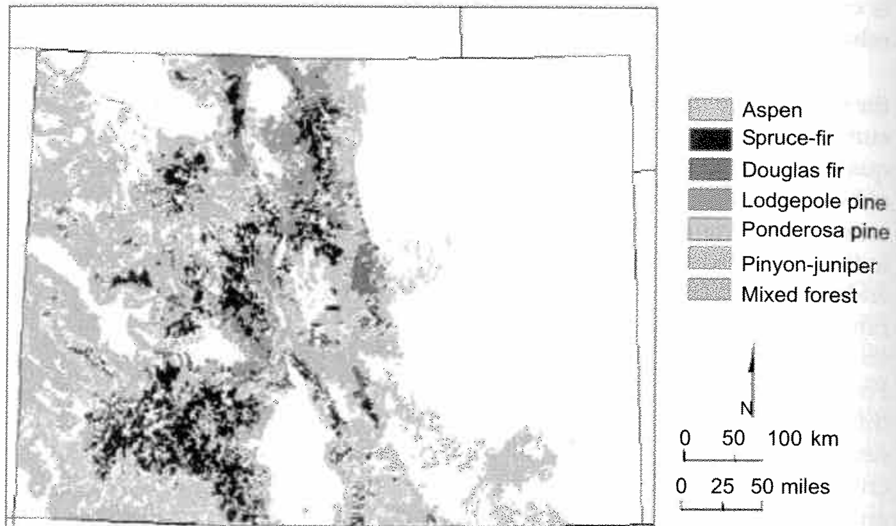
The objectives of this chapter are to: 1) provide a basic understanding of the historic fire frequency and severity in the major forest types in Colorado; 2) summarize our current understanding of post-fire erosion processes; 3) quantify the effects of wild and prescribed fires on soil and aquatic resources at both the hillslope and small catchment scales; and 4) summarize our data on the effectiveness of post-fire rehabilitation treatments. The data presented in this case study are derived from intensive, multi-year studies on how wild and prescribed fires affect soil properties, vegetative cover, runoff, and erosion rates. The fortuitous collection of hillslope and catchment-scale data prior to the Hayman Fire allows us to directly compare pre- and post-fire conditions. For three wildfires data also have been collected on the effectiveness of different post-fire rehabilitation treatments. The combined dataset includes nearly 600 plot-yr of data at the hillslope scale, and catchment-scale runoff, cross-section change, and sediment yield data from three wildfires (Moody and Martin 2001a, Eccleston and MacDonald 2006, Kunze and Stednick 2006, Eccelston 2008). Rainfall simulations and process-based studies provide more detailed insights into the causes of the observed increases in runoff and erosion after wild and prescribed fires, and help explain why different post-fire rehabilitation treatments vary in their effectiveness.

This combination of studies provides a unique, in-depth understanding of the effects of forest fires on runoff and erosion at different spatial scales, and the effectiveness of post-fire rehabilitation treatments. The resulting information should be of considerable use for researchers and land managers in other areas, as the underlying processes will vary in rates and magnitude but are generally applicable to other burned areas.

FOREST TYPES AND FIRE REGIMES

Colorado contains a variety of forest types (Fig. 1), and the type of forest is largely controlled by the amount of precipitation in relation to potential evapotranspiration (PET). In general, a rise in elevation increases precipitation while decreasing temperatures and PET. This moisture gradient means that higher-elevation forests provide most of the runoff for both municipal water supply and agriculture. Conversely, fire risk and fire frequency generally decline with increasing elevation. The moisture and temperature gradients largely control the presence of the different forest types in Colorado, and these can be broadly classified into the lower montane, montane, and subalpine zones. Each zone has a different moisture regime, species composition, fuel density, and historic fire regime (Romme et al. 2003a).

At the dry end of the moisture gradient is the lower montane zone (~1675 to 2000 m), and this is dominated by ponderosa pine (*Pinus ponderosa*) (Romme



Source: Colorado Gap Analysis

Fig. 1 Map of the major forest types in Colorado.

et al. 2003a). The natural fire regime is characterized by low-severity surface fires with a recurrence interval of 5 to 40 yr (Veblen 2000, Veblen et al. 2000, Grissino-Mayer et al. 2004). The frequent fires tended to maintain an open, park-like forest (Veblen 2000, Romme et al. 2003b).

The predominant forest type in the montane zone (~2000 to 2600 m) is intermixed ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*), and in more mesic areas these grow in dense, closed-canopy stands (Romme et al. 2003a). The natural fire regime is mixed severity, with both frequent, low severity fires and infrequent, high severity fires (Brown et al. 1999, Ehle and Baker 2003, Romme et al. 2003a). Under the natural fire regime individual stands burned at intervals ranging from every 10 to 100 yr, and the larger, high severity fires tended to occur during severe droughts after a wetter period that allowed more fuels to accumulate. The larger fires could be up to thousands of hectares in size, but within the fire perimeter there would be a heterogeneous patchwork of high severity, low severity, and unburned areas (Romme et al. 2003a).

The forests in the subalpine zone (~2600 to 3400 m) are composed of relatively dense stands dominated by lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*) (Romme et al. 2003a). The cooler, moister environment and shorter summers means that most fires were naturally extinguished before they spread, but there were infrequent, high severity, crown fires (e.g., Romme et al. 2003a, Buechling and Baker 2004, Sibold et al. 2006). On average, individual stands burned only once every 100 to 500 yr because of the infrequent congruence of the drought conditions necessary for fire spread and a natural ignition source, such as lightning (Veblen 2000). In contrast to Engelmann spruce and subalpine fir, lodgepole pine is highly dependent on these infrequent, stand-replacing fires because it is not shade tolerant and requires bare mineral soil for establishment.

Native Americans used fire for hunting and manipulating vegetative cover, but they are not believed to have greatly affected the natural fire regime. European settlement in the second half of the 19th century had a much greater effect on fuel loads and the fire regime of Colorado forests. In many areas there was an initial reduction in forest density due to timber harvest, grazing, and clearing for pasture. Since the early 1900s there has been a decrease in fire frequency and an increase in forest density due to fire suppression, the cessation of widespread burning by settlers, and reductions in grazing and logging.

The changes in fuel loading and fire frequency have been most pronounced in the lower montane and montane forests (Romme et al. 2003a). In the lower montane forests there has been an estimated 2 to 14 fold decrease in fire frequency since about 1920 (Veblen 2000). The increased forest densities have increased the vulnerability of these forests to large, high severity fires during severe droughts (Keane et al. 2002, Romme et al. 2003b). Similarly, the montane forests have denser, even-aged stands following logging and fires in the 19th century and the relatively wet conditions early in the 20th century (Romme et al. 2003b). As in the lower montane zone, the increased density is believed to have increased the risk of large, high-severity fires (Romme et al. 2003b).

In the subalpine forests, European settlement has had a much smaller effect on the fire regime. Fire suppression has been in effect for less than 100 yr, while large portions of the spruce-fir forests have not been affected by fire for 400 yr. This means that the period of fire suppression is still too short to have greatly altered the natural fire regime (Buechling and Baker 2004, Sibold et al. 2006). Timber harvest, grazing, and other uses have altered the stand structure and species composition in some areas, but most stands are still within their natural range of variability in terms of forest density and fuel loadings (Romme et al. 2003b).

The number, size, and severity of wildfires since 1996 provides strong empirical evidence for an altered fire regime in the lower montane and montane zones in Colorado. Major fires in these zones include the 1996 Buffalo Creek fire, which burned 48 km^2 in the South Platte River Watershed southwest of Denver; the June 2000 High Meadows and Bobcat Fires, which each burned more than 40 km^2; and the record 2002 fire season, which included the 557 km^2 Hayman Fire southwest of Denver, the 295 km^2 Missionary Ridge Fire in southwestern Colorado, and the 49 km^2 Coal Seam Fire in western Colorado (Cannon et al. 2003, Graham 2003). The Hayman Fire was unprecedented in terms of both the size of the fire and homogeneity of high severity burns (Romme et al. 2003a). The resulting increases in runoff, flooding and erosion, together with the degradation of downstream aquatic resources, stimulated much of the research that is summarized in this case study.

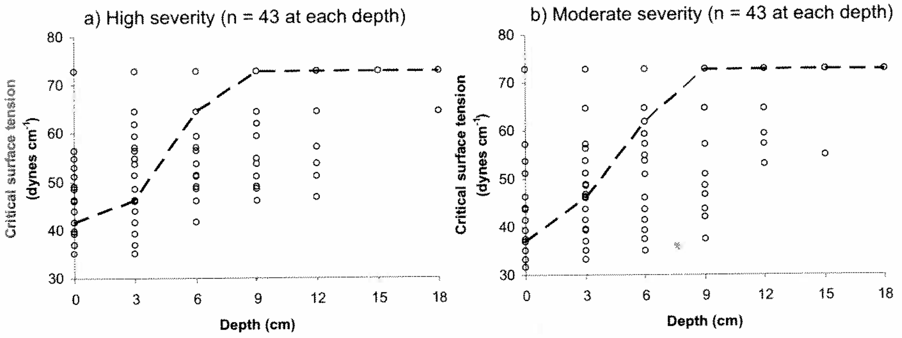
EFFECTS OF FIRES ON SURFACE COVER, SOIL WATER REPELLENCY, RUNOFF AND EROSION

Surface Cover and Soil Water Repellency

Under unburned conditions the lower montane and montane forests typically have greater than 85 percent surface cover (Libohova 2004) and infiltration rates in excess of 100 mm h^{-1} (Martin and Moody 2001). After a high-severity fire 85 to 95 percent of the surface is either bare mineral soil or bare soil covered with ash (Fig. 2) (Libohova 2004, Pietraszek 2006). In moderate severity fires the litter layer is completely consumed, but there is no alteration of the underlying mineral soil. Low severity fires are defined by the incomplete combustion of the surface litter (Wells et al. 1979). The consumption of the protective litter cover in high severity fires greatly increases the amount of rainsplash, propensity for overland flow, and wind erosion (e.g., Terry and Shakesby 1993, Prosser and Williams 1998, Whicker et al. 2006).

Burning also alters the strength, persistence, and depth of soil water repellency (see Chapter 7). In coniferous forests in Colorado, as in many other areas, the soil surface is often strongly water repellent under unburned conditions (Huffman et al. 2001). Burning at high and moderate severity vaporizes a variety of hydrophobic compounds in ponderosa and lodgepole pine forests, and the condensation of these compounds induces strong soil water repellency from the soil surface to a depth of approximately 6 cm (Fig. 3) (Huffman et al. 2001, Rough and MacDonald 2005). Data from several fires suggests that post-fire soil water repellency is slightly stronger and deeper after prescribed fires than wildfires, and this may be attributed to higher fuel loadings and greater heating due to the slower rate of fire spread (Huffman et al. 2001). Overall, the strength of soil water repellency rose with both increasing burn severity and sand content, and decreased with increasing soil moisture (Huffman et al., 2001). These trends are consistent with other studies (e.g., DeBano 1981, Chapter 7), but the high spatial and temporal variability means that these three variables explained only 30 to 41 percent of the observed variability (Huffman et al. 2001). The large spatial and temporal variability in soil water repellency within fires and severity classes appears to

Fig. 2 Photo from summer 2003 showing a pair of sediment fences, the piles of sediment excavated from the fences, and the relatively bare hillslopes one year after the June 2002 Hayman Fire.



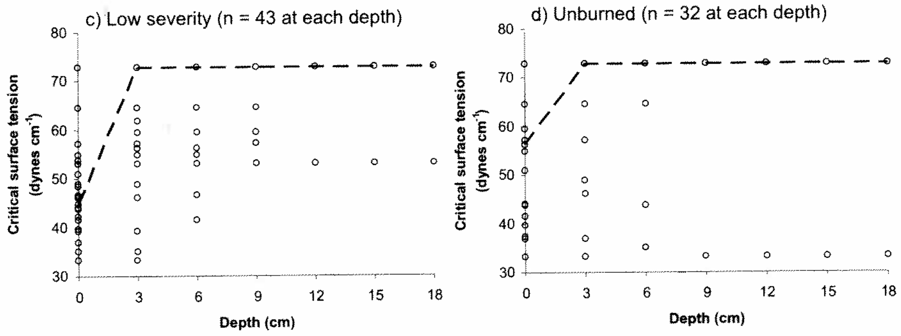


Fig. 3 Soil water repellency versus soil depth for: a) high burn severity, b) moderate burn severity, c) low burn severity, and d) unburned sites (from Huffman et al. 2001). The burned sites represent data from two wild and three prescribed fires the Colorado Front Range. Higher values indicate weaker water repellency and the dashed lines indicate the median values.

be characteristic of wildfires in Colorado and elsewhere (Hubbert et al. 2006, Woods et al. 2007).

Other researchers have identified a soil moisture threshold, which is when soils shift from being water repellent to hydrophilic (e.g., Doerr and Thomas 2000). Data from the Bobcat Fire indicate that the soil moisture threshold increases with fire severity, as the soil moisture threshold was only 10 percent in unburned sites, 13 percent in sites burned at low severity, and at least 26 to 28 percent in sites burned at moderate and high severity (MacDonald and Huffman 2004). The presence of a soil moisture threshold probably helps explain why burning has little effect on winter runoff and erosion rates as discussed below.

Both repeated measurements on the same fire and comparisons from fires of different ages indicate that post-fire soil water repellency is relatively short-lived in the lower montane and montane forests in Colorado. At the Bobcat Fire, the soil water repellency was much weaker three months after burning and was statistically non-detectable 12 months after burning (MacDonald and Huffman 2004). At the Hayman Fire the post-fire soil water repellency broke down most rapidly at the soil surface, and was statistically undetectable at all depths within two years after burning (Fig. 4) (MacDonald et al. 2005). The more rapid decay at the soil surface was attributed to the preferential erosion of the finer-grained water repellent particles, chemical breakdown due to solar radiation, the physical disturbance induced by repeated freezing and thawing, and the greater biological activity at the soil surface. As discussed later, this rapid decay means that soil water repellency is unlikely to be the primary cause of the observed increases in runoff and surface erosion after burning (MacDonald et al. 2005).

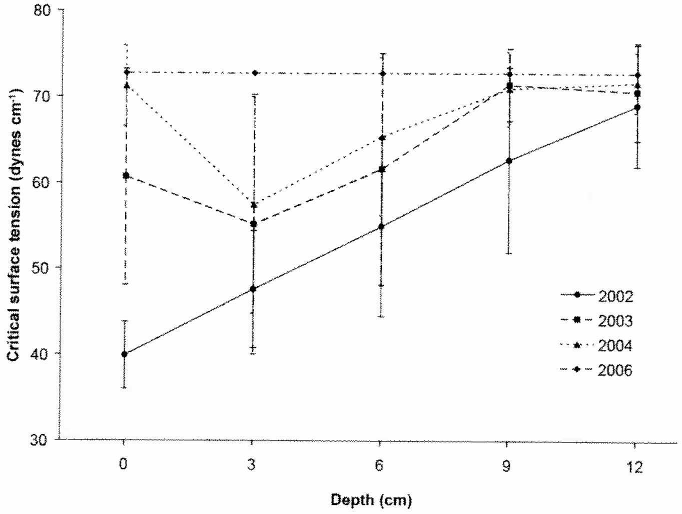


Fig. 4 Mean soil water repellency over time from the June 2002 Hayman Fire. Higher values indicate weaker soil water repellency and the bars indicate one standard deviation. There was no water repellency in 2006.

Runoff

In unburned forests infiltration rates typically are much greater than rainfall intensities, and this means that infiltration-excess (Horton) overland flow is very rare (MacDonald and Stednick 2003). In areas adjacent to the Hayman fire with coarse granitic soils, rainfall intensities of 60 to 65 mm h^{-1} did not induce any overland flow (Libohova, 2004). After a high-severity wildfire overland flow is much more prevalent, and data from wildfires in Colorado, New Mexico, and western South Dakota indicate that storms with a maximum 30 min (I_{30}) rainfall intensity of only 7 to 10 mm h^{-1} can induce Horton overland flow (Cannon et al. 2001a, Moody and Martin 2001b, Benavides-Solorio 2003, Pietraszek 2006, Kunze and Stednick 2006, Wagenbrenner et al. 2006). The dramatic change from subsurface to surface runoff can increase the size of peak flows by one to two orders of magnitude (Bolin and Ward 1987, Moody and Martin 2001a, Gottfried et al. 2003), and readily explains the observed flooding, scour in low-order channels, and increase in debris flows in steep, headwater basins (Cannon and Reneau 2000, Cannon et al. 2001b).

The problem is that we cannot yet quantify the relative importance of the various processes that are believed to contribute to the observed decrease in infiltration. In addition to the post-fire increase in soil water repellency, burning consumes the surface organic layer and this decreases interception. In high severity fires the consumption of the organic matter at the soil surface effectively disaggregates the soil particles (Giovannini and Lucchesi 1983), and this increases the potential for soil sealing (Neary et al. 1999). The loss of the protective litter cover reduces surface roughness and thereby increases overland flow velocities and the size of peak flows. The combined effect on runoff rates are well documented for different areas (e.g., Helvey 1980, Prosser and Williams 1998, Kunze and Stednick 2006), but more detailed, process-based experiments are needed to determine the role of each factor under different conditions.

Post-fire Sediment Yields in Lower Montane and Montane Forests

Post-fire erosion processes and sediment yields

The same set of processes that increase post-fire runoff rates play a major role in increasing post-fire erosion rates. The loss of surface cover decreases interception, increases rainsplash erosion, and increases runoff velocities. The disaggregation of soil particles increases soil erodibility (Moody et al. 2005) and the susceptibility to soil sealing. The increase in soil erodibility and surface runoff increases sheetwash, rilling, and channel erosion.

In the lower montane and montane forests in Colorado, a series of studies have shown that high severity wildfires increase hillslope- and catchment-scale sediment yields by several orders of magnitude (Morris and Moses 1987, Moody and Martin 2001a, Benavides-Solorio and MacDonald 2005, Pietraszek 2006). Plots established before the Hayman Fire generated no sediment or overland flow in the year prior to burning (Libohova 2004). After burning at high severity, individual storms with rainfall intensities of 8 to 40 mm hr^{-1} generated up to 15 Mg ha^{-1} of sediment from the same plots. On average, the plots burned at high severity in the Hayman Fire generated 7 to 11 Mg ha^{-1} of sediment during each of the first three years after burning (Fig. 2).

Controls on post-fire sediment yields

Data from six different fires in the Colorado Front Range show that over 90 percent of the post-fire sediment is generated by high intensity summer thunderstorms (Benavides-Solorio and MacDonald 2005). Little sediment is generated by snowmelt because the soils are not water repellent at higher soil moisture contents and snowmelt rates generally do not exceed the infiltration capacity. The spatial and temporal variability in summer thunderstorms causes a corresponding variability in post-fire sediment yields, and this limits our ability to deterministically predict post-fire sediment yields at different spatial scales (Larsen and MacDonald 2007).

In general, the areas burned at high severity are of greatest concern because in the first year after burning these areas produce about 5 to 40 times more sediment than the plots burned at moderate severity (Fig. 5; Benavides-Solorio and MacDonald 2005). The low burn severity plots generally produced only about half as much sediment as moderate burn severity plots (Fig. 5), but the validity of these relative values are constrained by the much smaller number of low and moderate burn severity plots (Benavides-Solorio and MacDonald 2005).

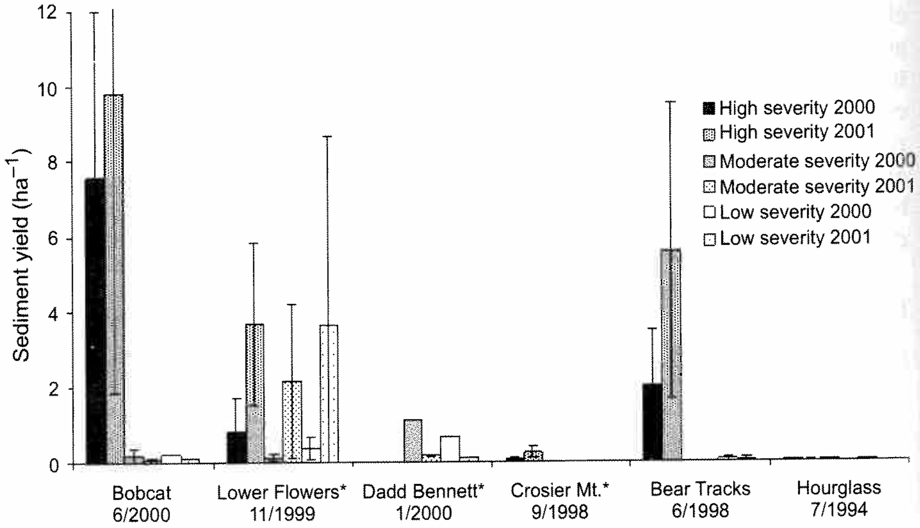


Fig. 5 Sediment yields by burn severity for six Colorado fires for June-October 2000 and June-October 2001. The bars indicate one standard deviation and an asterisk denotes a prescribed fire. Month and year of burning are listed under each fire. Not all severities were monitored in each fire.

For plots burned at high severity, the hillslope-scale sediment yields from wildfires were substantially greater than the sediment yields from prescribed fires. The lower sediment yields from prescribed fires can be attributed to more needlefall, the patchier distribution of burn severity, and the resultant potential for downslope areas to capture some of runoff and sediment coming from the more severely burned areas (Benavides-Solorio and MacDonald 2005).

Data from the Bobcat fire show that convergent hillslopes produced 3 to 4 times more sediment per unit area than planar hillslopes, and this difference is attributed to the rilling observed in the convergent hillslopes (Benavides-Solorio and MacDonald 2005). Subsequent measurements have shown that rill incision in convergent hillslopes accounts for about 60 to 80 percent of the hillslope-scale sediment yields from the Hayman and Schoonover Fires (Pietraszek 2006). Hillslope erosion and channel incision measurements after the 1996 Buffalo Creek Fire also indicate that channel incision generated about 80 percent of the estimated sediment yield from a 27 km^2 basin (Moody and Martin 2001a). Our current conceptual model is that most of the surface runoff is being generated from the hillslopes, but most of the sediment is being generated by concentrated flow and incision in the convergent rills and lower order channels. In the most extreme storms we posit that the more planar sideslopes generate and deliver a greater proportion of the sediment through the development of a dense rill network.

Both univariate and multivariate analyses show that percent surface cover is the predominant control on post-fire sediment yields, as this explains approximately 61 percent of the variability in post-fire sediment yields (Fig. 6; Benavides-Solorio and MacDonald 2005, Pietraszek 2006). If cover is held constant, rainfall erosivity becomes the most important control on post-fire sediment yields (Benavides-Solorio and MacDonald 2005, Pietraszek 2006). A plot of the annual sediment yields from 72 hillslopes that burned at high severity in nine different fires shows that median sediment yields are highest in the second year after burning (Fig. 7), and this is due to the greater summer rainfall and slow rate of regrowth. By the fourth summer after burning the median sediment yield drops from nearly 10 Mg ha^{-1} to only 0.1 Mg ha^{-1}, but there is tremendous variability due to the variations in summer rainfall and rate of vegetative regrowth (Fig. 7). Sediment yields drop to near background levels once the percent bare soil drops below 30 percent (Fig. 6), and this typically requires about four years for plots burned at high severity, two years for plots burned at moderate severity, and less than one year for plots burned at low severity. Plots with coarser soils generally have slower regrowth rates due to their poorer water holding capacity (Benavides-Solorio and MacDonald

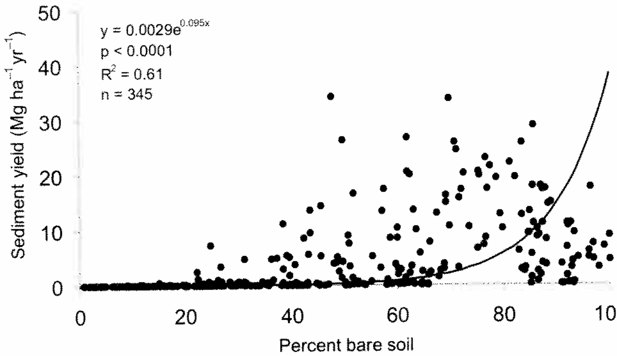


Fig. 6 Relationship between percent bare soil and annual sediment yield. Data were collected from seven wildfires and three prescribed fires in the Colorado Front Range.

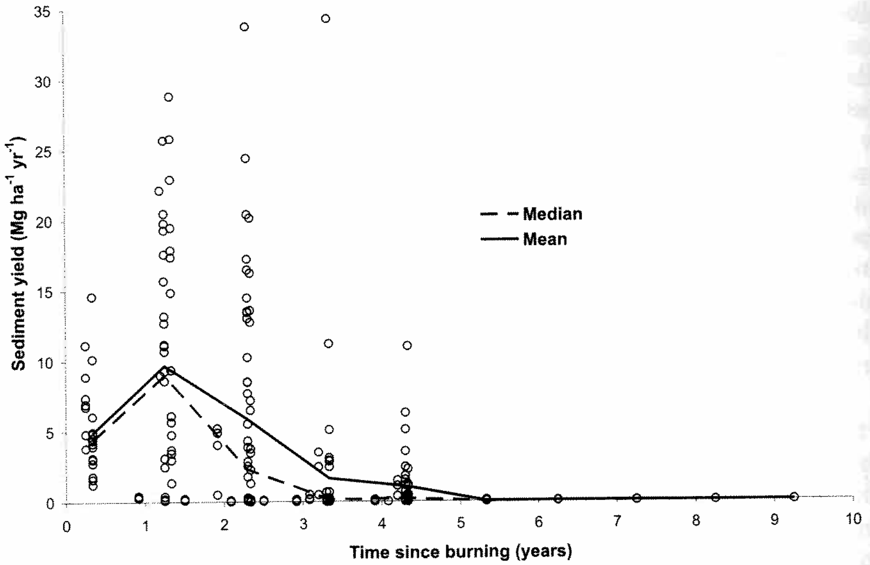


Fig. 7 Annual sediment yields versus time since burning for plots burned at high burn severity in six wildfires and three prescribed fires in the Colorado Front Range.

2005). In the case of the Hayman Fire, which has very coarse-textured soils, sediment yields were still elevated in the summer of 2006, which is four full years after burning.

Comparison of post-fire sediment yields from Colorado against other regions

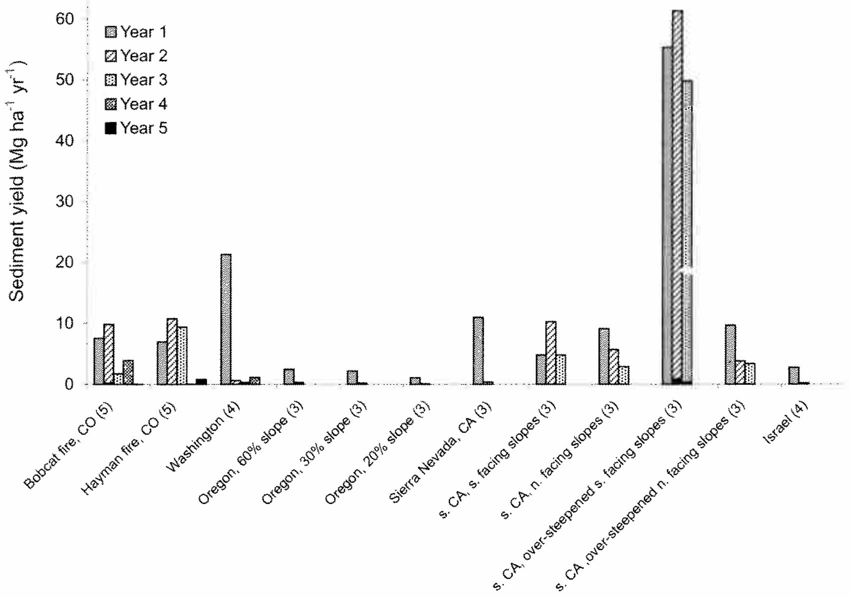


Fig. 8 Annual post-fire sediment yields over time for different locations. Year 1 refers to the year burned, and the number of years of data for each location is in parentheses. The sediment yield data are taken from Robichaud et al. (2006) for Washington, Robichaud and Brown (1999) for Oregon, MacDonald et al. (2004) and Chase (2006) for the Sierra Nevada, Krammes (1965) for southern California (all in USA), and Inbar et al. (1997) for Israel. South and north are abbreviated by s. and n. respectively.

Post-fire sediment yields for the Colorado Front Range are within the range of values reported in the western US and other countries (Fig. 8). First-year sediment yields from Colorado are generally similar to values from southern California (Krammes 1965) and the Sierra Nevada (MacDonald et al. 2004, Chase 2006), but are only about 15 percent of the values from burned south-facing, over-steepened hillslopes in southern California and about 35 percent of the values from north-central Washington (Krammes 1965, Robichaud et al. 2006; Fig. 8). First-year sediment yields in Colorado are about three to seven times greater than values from Oregon and Israel (Inbar et al. 1997, Robichaud and Brown 1999).

The time needed for post-fire erosion rates to return to near-background levels can be longer for Colorado than most other areas (Fig. 8). In relatively wet areas, such as Washington, Oregon and California's Sierra Nevada, post-fire erosion rates decline to near-background levels by the third year after burning. In the Colorado Front Range the median sediment yield from sites burned at high severity is only 0.13 Mg ha^{-1} for the fourth summer after burning, but the mean value is 1.6 Mg ha^{-1} because the maximum value was 34 Mg ha^{-1} (Fig. 7). The slower recovery rates in Colorado can be attributed to the dry, cold climate and relatively poor soils, and the longest recovery rates are usually in areas with particularly coarse-textured soils because these have the poorest growing conditions and slowest rates of vegetative regrowth.

Effects fires on channels

The predominance of rill and channel erosion means that much of the sediment generated after fires is delivered to streams. On hillslopes and in the steeper headwater channels the predominant post-fire response is rill and channel incision, but further downstream the predominant post-fire response is aggradation (Fig. 9). The shift from incision to aggradation is attributed to the lower transport capacity associated with decrease in channel gradient, and the decrease in runoff with increasing catchment size due to the small size of the convective thunderstorms that generate most of the surface runoff and erosion (Eccleston 2008).

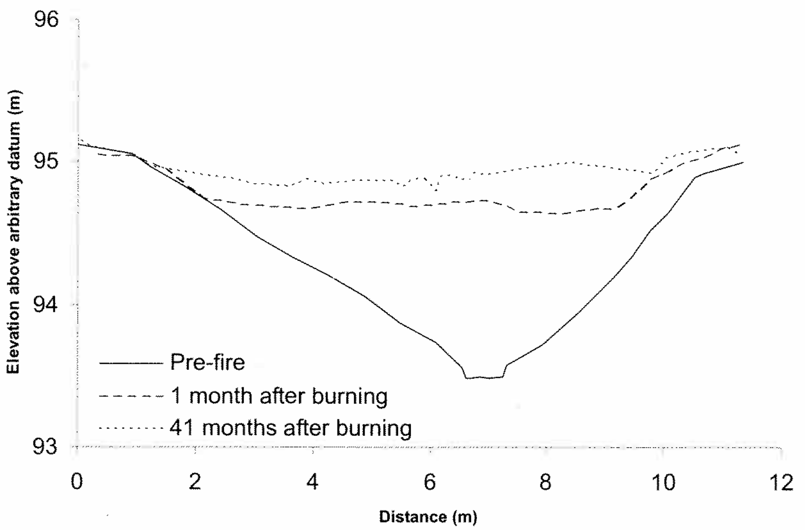


Fig. 9 Channel cross-section in a 3.4 km^2 watershed that was burned by the Hayman Fire. The cross-section was surveyed in the year before the fire, shortly after the second post-fire runoff event, and 41 months after burning.

Measurements of channel cross-sections and sediment transport rates indicate that the recovery rate for downstream, aggraded channels is likely to be at least an order of magnitude slower than the recovery rate for hillslope erosion. In most cases the median hillslope erosion rate is close to zero by the third summer after burning, and by the fifth year after burning all of our hillslope study sites produce little or no sediment (Fig. 7). The drop in sediment production indicates that infiltration and surface runoff rates also have recovered to near-background levels. The reduction in surface runoff will decrease downstream runoff and sediment transport capacities, and the decline in high flows will limit the rate at which the downstream channels can export the accumulated sediment (Fig. 9; Eccleston 2008). The estimated residence time of the post-fire sediment stored in channels after the Buffalo Creek Fire is 300 yr (Moody and Martin 2001a), and an even longer residence time is expected for the channel in Fig. 9 because all of the discharge is currently subsurface (i.e., within the coarse aggraded material). In the absence of surface runoff, the aggraded sediment will not be transported to the channels further downstream that have perennial flow and a greater capacity to transport sediment. The implication is that the altered fire regime in the lower montane and montane forests could have long-term effects on channel morphology and other aquatic resources.

Fire Effects in Subalpine Forests

Few post-fire runoff and sediment yield data are available for the subalpine zone, but these areas are of lesser concern for several reasons. First, wildfires are much less frequent and humans have not yet greatly altered the natural fire regime. Second, the lower population density means a lower risk for life and property. Third, model simulations using Disturbed WEPP (Elliot 2004) indicate that subalpine forests have a much lower risk for post-fire flooding and erosion than the lower montane and montane forests Simulations were done for 14 different climate stations assuming a 100 m-long hillslope with a 30 percent slope that had burned at high severity. The mean predicted sediment yields for the sites above 2400 m was 4.3 Mg ha^{-1} yr^{-1}, or just 31 percent of the mean value for the seven sites below 2400 m.

To the best of our knowledge, only one study has documented the effects of a wildfire on runoff and erosion rates in the subalpine zone. The 1967 Comanche Fire burned 190 ha of lodgepole pine and spruce-fir forest, and field measurements indicated higher infiltration rates in the burned areas than unburned areas and no evidence of soil water repellency (Striffler and Mogren, 1971). Soil tracer studies indicated that the maximum particle displacement on a 62 percent slope was only about 8 m. The limited erosion can be at least partly attributed to the lack of intense rainfall, as the post-fire rainstorms had maximum 30 min intensities of only 5 to 10 mm h^{-1} (Striffler and Mogren 1971). The limited data from this study are consistent with the Disturbed WEPP simulations and help confirm that post-fire erosion risks are substantially lower in the subalpine zone.

EFFECTIVENESS OF POST-FIRE REHABILITATION TREATMENTS

Bobcat Fire

Rehabilitation treatments are commonly applied after forest fires in order to minimize the increases in runoff and erosion, but very few studies have documented the effectiveness of these treatments (Robichaud et al. 2000). In Colorado treatment effectiveness has been evaluated by comparisons of hillslope-scale sediment production rates on three different wildfires – the June 2000 Bobcat Fire near Fort Collins and the 2002 Hayman and Schoonover Fires southwest of Denver.

At the Bobcat Fire three sets of replicated plots were set up to compare the mean surface cover and annual sediment yields for three treatments – seeding, straw mulching, and contour-felling – against the mean values from untreated control plots (Wagenbrenner et al. 2006). All of the treatments were applied to hillslopes burned at high severity by the USFS or following USFS protocols. The seeding treatment included slender wheatgrass (*Elymus trachycaulus*), mountain brome (*Bromus marginatus*), and a commercial mix of sterile grass seed applied at a target rate of 34 kg ha^{-1} or 430 seeds m^{-2}; two plots were seeded by air and two plots were seeded by hand. In the mulch treatment wheat straw was applied to three plots at a rate of 2.2 Mg ha^{-1}. In the contour-felled log erosion barrier (LEB) treatment the burned trees were cut down, delimbed, and placed on the contour to act as sediment traps. Earthen berms were constructed on the uphill side of each log to prevent underflow, and the target density was 300 to 450 m of logs per ha. Log density, sediment storage capacity, and log failure rates were assessed on two sites in the Bobcat Fire and two sites in each of two other fires (Wagenbrenner et al. 2006). For each treated and control plot vegetative recovery was assessed by classifying the surface cover at a minimum of 100 points in late spring and early fall, and hillslope-scale sediment yields were monitored with sediment fences (Fig. 2) (Robichaud and Brown 2002, http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm).

In the case of the Bobcat Fire, a storm with an I_{30} of 48 mm h^{-1} and an estimated recurrence interval of 5 to 10 years occurred 2 months after burning (Wagenbrenner et al. 2006). The sediment generated by this storm caused all of the sediment fences to fill and overtop except for three of the mulched plots and one of the LEB plots. This meant that the measured sediment yields were primarily a function of the total storage capacity, and none of the treatments had significantly lower sediment yields than the controls for the first year after burning (Wagenbrenner et al. 2006). Following this storm, three new mulched plots and seven new LEB plots were established.

Seed densities in the seeded plots were 25 to 50 percent lower than the target density, and field observations indicated that much of the seed was washed downslope during the first rainstorm. Seeding did not significantly increase the amount of surface cover in either the aerial- or hand-seeded plots at any point during the study, and in the absence of any difference in surface cover there were no significant differences in sediment yields (Fig. 10; Wagenbrenner et al. 2006).

After mulching there was only 26 percent bare soil as compared to the mean value of 67 percent on the control plots, and this difference was highly significant. Vegetative regrowth was significantly higher on the three old mulched plots than the control plots, and the combination of mulching and vegetative regrowth resulted in significantly more surface cover on the old and new mulched plots than the control plots for each of the first three years after burning. In the second to fourth years after burning the mean sediment yields from the mulched plots were only about 5 percent of the mean value from the corresponding control plots (Fig. 10; Wagenbrenner et al. 2006).

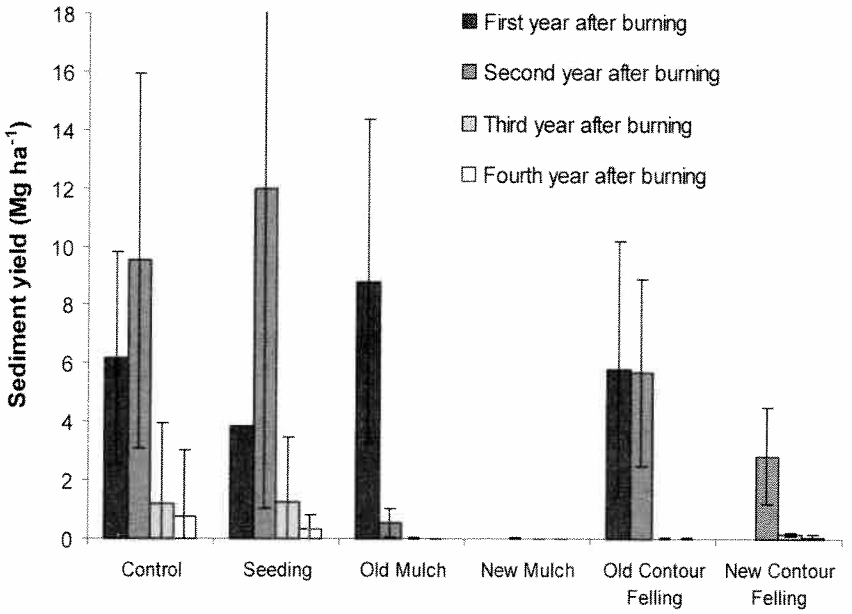


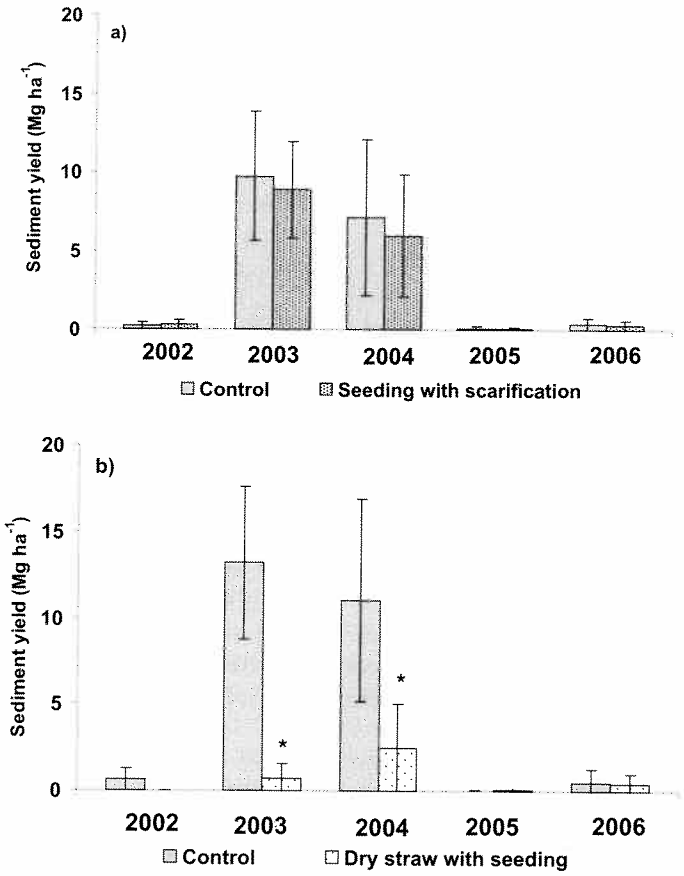
Fig. 10 Mean annual sediment yields by year since burning from the control plots and the different rehabilitation treatments at the Bobcat Fire. The old mulch and old contour-felled log erosion barrier treatments were applied before the very large storm that occurred two months after the fire. The new mulch and new contour-felled log treatments were applied after this storm. The bars indicate one standard deviation.

The sediment storage capacity in the first set of LEB plots was completely filled as a result of the large storm in August 2000, and there was no difference in sediment yields between these plots and the corresponding controls because all but one of the sediment fences had overtopped (Fig. 10). After this storm 7 new LEB plots were established and sediment yields in the new LEB plots were reduced by 71 to 90 percent relative to the controls (Fig. 10), but the high variability within treatments meant that this difference was only significant for the second year after burning (i.e., the summer after installation) (Wagenbrenner et al. 2006). As might be expected, the LEB treatment had no significant effect on the total amount of surface cover or the rate of revegetation. The survey of 210 contour felled logs at 6 sites showed that 32 percent of the logs were ineffective in trapping sediment because they were installed off-contour, had poor ground contact, or both (Wagenbrenner et al. 2006). The mean sediment storage capacity was 16 m^3 ha^{-1}, but both the failure rate and the estimated sediment storage capacity varied widely among the 6 sites.

Hayman and Schoonover Fires

At the Hayman and Schoonover Fires a similar approach was used to evaluate the effectiveness of five different post-fire rehabilitation treatments – seeding combined with scarification, straw mulch with grass seeding, hydromulch applied by ground spraying, hydromulch applied by helicopter, and a polyacrylamide applied in both a wet and a dry formulation (Rough et al. 2004). Since most of the treatments were applied relatively late in the summer and there were only 1 to 3 small storm events after these treatments had been installed, treatment effectiveness is only evaluated for the second through fifth years after burning.

The scarification treatment was done by hand using a heavy metal rake with long tines (McLeod), and the subsequent seeding used a barley (*Hordeum vulgare*) and triticale (*Triticosecale rimpaui*) mixture with a target density of 80 kg ha^{-1} or 280 seeds m^{-2}. The mean scarification depth was only 1.6 cm, which was too shallow to break up the observed water repellent soil layer (Fig. 3). Similar to the Bobcat Fire, the scarification and seeding treatment did not significantly increase the amount of surface cover, nor did it have any significant effect on sediment yields (Fig. 11a). The data suggest that the scarification treatment increased sediment yields in the first few storms after treatment by disturbing the soil surface and increasing the soil erodibility, but the 45 percent increase was not statistically significant relative to the controls.



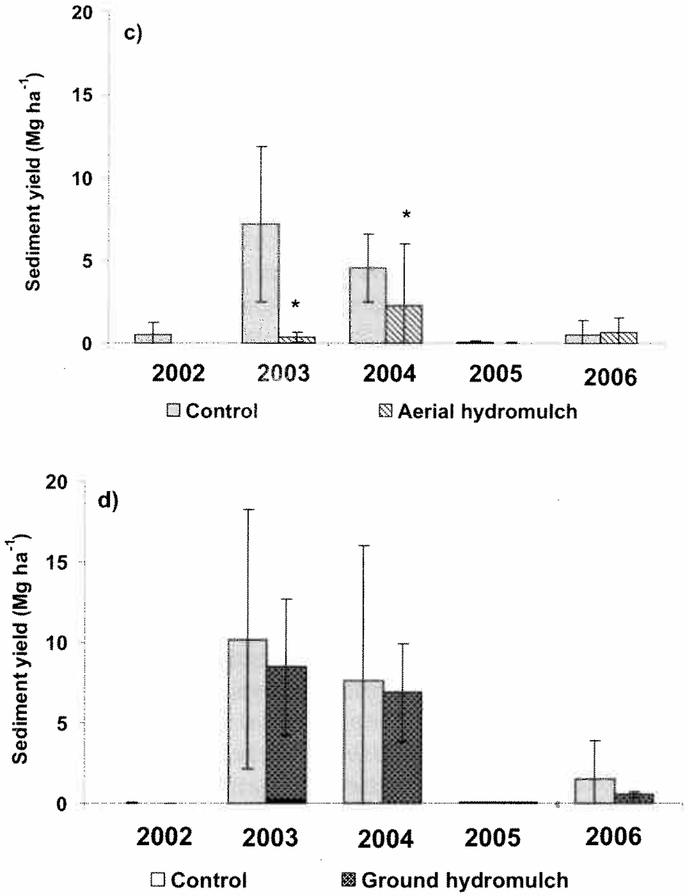


Fig. 11 Mean annual sediment yields from replicated control and treated plots in the Hayman Fire from 2002 to 2006. The treatments include: a) seeding with scarification; b) dry mulch with seeding; c) aerially-applied hydromulch; and d) ground-applied hydromulch. Bars represent one standard deviation. The Hayman Fire burned in June 2002, and the summers in 2002 and 2005 were exceptionally dry. An asterisk indicates a significant treatment effect ($p = 0.05$).

The straw mulch and seeding treatment significantly increased the amount of surface cover relative to the controls for the first 2 yr after burning. In the second year after burning mean sediment yields for the mulched plots were only 5 percent of the mean value for the control plots, and in the third year after burning the mean sediment yield for the mulched plots was still only 23 percent of the mean value from the controls (Rough and MacDonald 2005). Both of these differences in sediment yields were significant (Fig. 11b). In the fourth and fifth years after burning the mulch and seeding treatment ceased to be effective in reducing sediment yields relative to the untreated controls, and this is attributed to the progressive increase in ground cover on the untreated controls.

The results for the hydromulch treatments were mixed. Both the aerially- and ground-applied hydromulch treatments had about 65 percent surface cover in the second year after burning, and this was significantly higher than the mean value from the corresponding control plots. The aerially-applied hydromulch reduced sediment yields by more than 90 percent in the second year after burning, and by about 50 percent in the third year after burning, and these differences were significant. The ground-applied hydromulch did not significantly reduce sediment yields relative to the controls (Fig. 11d) despite providing a similar amount of surface cover as the aerially-applied hydromulch, and the lack of a significant effect is attributed primarily to the differences in the formulation of the aerial- and ground-applied hydromulch mixtures (Rough, 2007). Neither of the hydromulch treatments significantly reduced sediment yields in the fourth and fifth year after burning (Fig. 11c).

The polyacrylamide (PAM) applied in a wet formulation appeared to significantly reduce sediment yields in the first year after application while the dry formulation had no significant effect. The wet formulation was then applied to the 3 plots that had been treated with the dry PAM, but in contrast to the first year results, the new wet PAM treatment had no significant effect on sediment yields. Subsequent laboratory tests showed that the PAM tended to bind with the residual ash, and the potential for PAM treatments to reduce post-fire erosion is not clear due to the complications of soil type, amount of ash present on the soil surface, the application rate, the high variability among sites, and the limited number of experimental plots studied to date (n = 3 for each treatment in our study; Rough 2007).

DISCUSSION OF REHABILITATION EFFECTIVENESS IN COLORADO

Factors Contributing to Treatment Effectiveness

The data from the untreated plots and the different post-fire rehabilitation treatments indicate that percent surface cover is the most important control on sediment yields. Very similar results have been obtained from a series of small (~5 ha) treated and untreated catchments set up after the 2002 Hayman Fire (P.R. Robichaud, personal communication 2006). The resulting principle is that any treatment that immediately increases the amount of surface cover is most likely to reduce post-fire sediment yields. The straw mulch and aerially-applied hydromulch were the most effective treatments because they protected the soil from raindrop impact and soil sealing, and this helped sustain high infiltration rates. The straw mulch was more effective than the hydromulch in terms of increasing the surface roughness, and the increased roughness will help slow overland flow, increase infiltration, and reduce particle entrainment. Studies from other types of disturbed areas also indicate that straw mulch increases seed germination and plant growth by increasing soil moisture and reducing surface temperatures (Goldman et al. 1986), but our data generally do not show significantly more live vegetation in the mulched plots than untreated control plots (Wagenbrenner et al. 2006, Rough 2007). The disadvantage of straw mulch is that it is more susceptible to redistribution by wind and overland flow than a well-formulated hydromulch, and it can contribute to the introduction of noxious weeds.

The ground-applied hydromulch was ineffective despite immediately increasing surface cover. The ground- and aerially-applied hydromulch used different mixtures, and the binding agent in the aerially-applied hydromulch was specifically selected for the coarse-grained soils at the Hayman Fire (P.R. Robichaud, personal communication 2006). Field observations indicate that the ground-applied hydromulch did not bind to the soil surface and was readily broken up or displaced by overland flow (P.R. Robichaud, personal communication 2006, Rough 2007). The results suggest that the exact formulation of the hydromulch can greatly affect its ability to bind with the soil and its effectiveness in reducing post-fire erosion.

Seeding treatments, including scarification and seeding, were not effective because they had no significant effect on the amount of surface cover, rate of vegetative regrowth, or hillslope-scale sediment yields (Wagenbrenner et al. 2006, Rough 2007). The failure of post-fire seeding to significantly reduce sediment yields is consistent with most other studies, and the lack of effectiveness is attributed to the fact that much of the erosion occurs before a dense plant cover can be established (Robichaud et al. 2000). Seeding should be most effective when a fire is followed by a well spaced series of gentle storms, but this sequence would facilitate natural regrowth and rarely occurs. In Colorado the effectiveness of seeding also is limited by the tendency for the seeds to be washed downslope in small- or moderate-sized storms and the relatively poor growing conditions (e.g., limited summer precipitation, coarse-textured soils, and low fertility).

The effectiveness of LEB treatments depends primarily on the sediment storage capacity relative to the post-fire erosion rates. The estimated mean sediment storage capacity of 16 m^3 ha^{-1} is about equal to the total mass of sediment captured in the control plots, and this would suggest that the contour-felled logs should, on average, be able to capture most of the sediment generated by a high-severity wildfire. The LEB plots installed after the large storm were on planar hillslopes (Wagenbrenner et al. 2006), but post-fire sediment is derived primarily from convergent rills and channel incision. The problem is that contour-felled logs are designed to trap sediment on planar hillslopes, and they cannot be easily placed to reduce erosion or trap the sediment from central rills in convergent topography or small headwater channels.

Some proponents have claimed that LEB treatments can reduce the amount of surface runoff and hence the amount of rill and channel erosion by enhancing infiltration and trapping overland flow. Infiltration tests after the Bobcat Fire did show a significantly higher permeability in the trenches upslope of the logs relative to the hillslopes (Wagenbrenner et al. 2006). The potential reduction in surface runoff was calculated from the increase in infiltration and the potential runoff storage capacity. The results showed that the amount of runoff from a 10 mm storm would be reduced by about 26 percent, but this value would be progressively smaller for larger storms (Wagenbrenner et al. 2006). Subsequent measurements indicated that the potential for LEB treatments to reduce runoff would rapidly diminish as the deposition of fine sediment reduced the infiltration rates in the trenches, infiltration rates increased on the untreated hillslopes, and the capacity for storing overland flow was reduced by the accumulation of sediment behind the logs (Wagenbrenner et al. 2006). We conclude that LEB treatments can reduce the amount of runoff only from the first and smaller storms after installation; potentially reduce sediment yields primarily through the storage of sediment rather than runoff; and will be more effective on planar rather than convergent hillslopes.

Treatment Effectiveness in Relation to Storm Size and Time Since Burning

The sediment yield data from the different storms on the Bobcat Fire suggest that treatment effectiveness declines with increasing storm size. None of the treatments was effective in reducing sediment yields when subjected to a 5 to 10 yr storm event, but both the old and new mulch treatments and the new LEB treatment significantly reduced sediment yields in the following summer when the storm events were less severe. For the Hayman and Schoonover Fires there is no evidence of a decrease in effectiveness with increasing storm size, but there were no storm events with a recurrence interval greater than 2 yr.

The effectiveness of each of the rehabilitation treatments will decline over time, and there are several reasons for this. Both straw mulch and hydromulch break down over time, but the data presented here indicate that these treatments were effective in reducing sediment yields for as long as the third summer after burning (Figs. 10 and 11). In the case of contour-felled log erosion barriers, the effectiveness will decline as the sediment storage capacity fills up. Installation of the logs off contour or leaks beneath the logs will tend to concentrate flow and initiate rill erosion, and these problems are likely to increase over time. The absolute effectiveness of any treatment also will decline over time because of the natural decline in sediment production rates from untreated hillslopes (Figs. 10 and 11). It also should be recognized that our ability to detect treatment effectiveness is limited by the high variability in sediment production rates within replicated treatments as well as the spatial variability in rainfall.

Treatment Cost-effectiveness

As noted earlier, large amounts of public and occasionally private funds are spent on post-fire rehabilitation treatments. Seeding has long been the most commonly-applied treatment in forested areas because it costs only US$45 per hectare and is easily applied by airplanes over rough, unroaded terrain. Scarification requires much more labor and this increases the cost per hectare by a factor of about 13 (Robichaud et al. 2003). Straw mulching costs about US$1000 to US$1600 per hectare for ground application by machine and US$1850 to 3000 for hand application (http://www.fs.fed.us/r5/baer/index.html). For logistical reasons straw mulching has been limited to areas with road access, but after the Hayman Fire straw mulch was successfully applied by helicopters with bales of hay in cargo nets suspended beneath the helicopter. The cost of mulching from air is roughly US$1800 per hectare, which is similar to the cost of ground mulching because the reduced labor costs compensate for the high cost of helicopter time. Hydromulching is generally the most expensive treatment as ground-applied hydromulch after the Hayman Fire cost US$2350 per hectare (Robichaud et al. 2003). Aerial hydromulching is about three times the cost of ground-based hydromulching (Robichaud et al. 2003).

These cost data can be combined with our measured reductions in sediment yields to estimate the cost effectiveness of the different treatments (Table 1). The results show that ground-applied dry mulch is the most cost-effective at approximately US$50 to US$150 per megagram reduction in sediment yields. Hydromulching is roughly 5 to 15 times as expensive as mulching, and there was not a large difference between ground- and aerially-applied hydromulching because the ground-based hydromulch treatment was less expensive and less effective in reducing sediment yields. Ground-based hydromulching could be more cost-effective than aerial hydromulching if one assumes a similar hydromulch formulation and a similar effectiveness, but hydromulching is still much more expensive than straw mulching. The cost-effectiveness of seeding with scarification was calculated for Table 1, but this calculation assumes that the statistically insignificant reduction in sediment yield is a real value.

Both the public and land managers need to recognize that the sheer size of the 2002 wildfires in Colorado far exceeded the resources available for post-fire rehabilitation treatments. Table 1 clearly indicates which treatments are most cost-effective at the hillslope scale, but there are no data to indicate these treatments would be effective if they were applied across catchments larger than a few hectares. Since treatment effectiveness also declines with increasing storm size, both financial and physical constraints will limit our ability to reduce larger-scale runoff and sediment yields after large, high severity wildfires.

Table 1 The cost of post-fire rehabilitation treatments applied after the 2002 Hayman Fire, the mean reduction in sediment yields, and the calculated treatment cost per Mg reduction in sediment yields at the hillslope scale. All treatment costs except ground-based dry mulching are from Robichaud et al. (2003). Ground-based dry mulch costs are from the U.S. Department of Agriculture, Forest Service Region 5 Burned Area Emergency Response website (http://www.fs.fed.us/r5/baer/index.html). The cost-effectiveness of machine and aerially-applied dry mulch assumes that both treatments are as effective in reducing sediment yields as mulch applied by hand. The cost-effectiveness of the seeding with scarification and the ground-applied hydromulch assume that the statistically insignificant reductions in sediment yield are real.

Treatment	Cost	Mean sediment yield reduction from 2002–2006	Cost per unit sediment yield reduction
	US$ ha^{-1}	Mg ha^{-1}	US$ Mg^{-1}
Seeding with scarification	640	2.1	305
Ground-applied dry mulch (machine application)	990–1600	21.0	47-76
Ground-applied dry mulch (hand application)	1830-2970	21.0	86
Aerially-applied dry mulch	1800	21.0	86
Ground-applied hydromulch	2350	3.5	673
Aerially-applied hydromulch	7410	8.9	828

CONCLUSIONS

Approximately one-third of Colorado is covered by forests, and the changes in precipitation and temperature with increasing elevation allow the forested areas to be classified into three distinct zones with widely varying forest densities, fuel loadings, and natural fire regimes. The lower montane and montane forests are of greatest concern because: 1) the drier conditions result in more frequent fires; 2) human activities have increased the risk of large, high-severity fires; 3) these forests have higher potential post-fire runoff and erosion rates; and 4) there are a large number of human and natural resources at risk.

Detailed studies on a series of wildfire and prescribed fires have resulted in an extensive and unique dataset for assessing the effects of wildfires, the effectiveness of different post-fire rehabilitation treatments, and post-fire recovery rates. Areas burned at high severity are of greatest concern because runoff and sediment yields increase by several orders of magnitude, and summer rainfall intensities of 8 to 10 mm h^{-1} can generate substantial amounts of overland flow and surface erosion. Percent surface cover and rainfall erosivity are the most important controls on post-fire sediment yields; three to five years are generally required for hillslope sediment yields to decline to near-background levels. The persistence of elevated sediment yields is longer than in most other areas, and this is attributed to the relatively poor conditions for post-fire regrowth.

The most effective post-fire rehabilitation treatments are those that immediately provide surface cover, such as straw mulching or hydromulching. Seeding, or seeding combined with scarification, did not significantly affect vegetative regrowth or sediment yields. Contour-felled log erosion barriers were only effective for small and moderate-sized storms because of the limited sediment storage capacity, and the effectiveness of this treatment can be negated by poor installation. The application of a polyacrylamide did not consistently reduce sediment yields. Mulching is by far the most cost-effective post-fire rehabilitation treatment at US$50 to US$150 per megagram reduction in sediment yields.

Climate projections indicate an increased likelihood of extreme fire weather and high-severity wildfires in the Rocky Mountains (Baker 2003), and this translates to a greater need for predicting the effects of future fires and post-fire rehabilitation treatments. The results presented here can provide useful guidance to land managers and researchers in other areas, as the basic principles and processes identified in this chapter are more broadly applicable.

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Fire Landscapes in Canada: How to Restore or Prevent Them

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Abstract

Canada contains a wide range of fire landscapes, with the steeper and considerably higher mountainous areas of British Columbia and Alberta, in the west, representing the greatest risks for post-wildfire erosion. The full potential of this problem was recently recognized following the 2003 wildfire season. Traditionally, 'rehabilitation' following wildfire has focused primarily on the access structures (firelines, etc.) constructed to fight the fire, along with some broadcast seeding or reforestation. Opportunities exist to capitalize on ecosystem restoration which attempt to restore a 'natural disturbance regime' to forests, particularly in urban interface areas where wildfire risks are of serious concern. This is because reducing the risk of severe wildfires will also reduce the risk of subsequent soil erosion. In recognition of the greater potential for soil erosion after wildfires, we are planning for increasing problems as variable climate, due to global change, impacts Canadian forests. This climate variation has already created increased areas of dead timber (fuels) due to pests like mountain pine beetle, and increased potential for more severe wildfires. Policy revision is ongoing in some provinces, with risk assessment procedures being drafted and tested, and provisions being developed for targeted hillslope restoration of burned slopes, which may become standard practice.

INTRODUCTION TO THE CANADIAN FOREST ENVIRONMENT

Canada is comprised of a wide variety of forest landscapes, and a correspondingly wide range of fire regimes. Forest regions (or landscapes) of

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