Runoff and Erosion from Wildfires and Roads: Effects and Mitigation

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1. Introduction

Forest disturbance can lead to land degradation, particularly in drier areas that are more sensitive to desertification. Both unpaved forest roads and high-severity forest fires can increase runoff and erosion rates by one or more orders of magnitude relative to undisturbed forested areas, and these can have long-term adverse effects on site productivity, water supplies, and other downstream resources. Forest managers commonly apply emergency rehabilitation treatments after wildfires to reduce runoff and erosion, but there are relatively few data rigorously testing the effectiveness of such treatments. Even fewer studies have compared long-term erosion and sediment delivery rates from roads and wildfires, yet such information is urgently needed to guide forest management.

Undisturbed forests typically have high infiltration rates (>50 mm h^{-1}) and very little bare soil (Robichaud 2000, Martin and Moody 2001, Libohova 2004). The high infiltration rates mean that nearly all of the precipitation and snowmelt infiltrates into the soil. Hence water flows to the drainage network primarily by subsurface pathways, resulting in low peak flows (Hewlett 1982, MacDonald and Stednick 2003), very low surface erosion rates and sediment yields (typically 0.005-0.5 Mg ha^{-1} yr^{-1}) (Patric et al. 1984, Shakesby and Doerr 2006), and runoff that is very high in quality and useful for municipal water supplies (Dissmeyer 2000).

Disturbances such as roads hinder infiltration and can serve as pathways for delivering water and sediment to streams, lakes, and wetlands (Trombulak and Frissell 2000). The low infiltration rates on unpaved road surfaces cause the dominant runoff process to shift from subsurface stormflow to infiltration-excess or Horton overland flow (HOF) (Robichaud et al. in press). The low infiltration rates and high overland flow velocities greatly increase the size of peak flows and surface erosion rates (Dunne and Leopold 1978). Furthermore, unless a road is outsloped, the runoff and sediment from unpaved road segments often is concentrated in rills or ditches and directly routed to the stream channel network (Robichaud et al. in press). In forested areas the human-induced increases in sediment loads are typically the pollutant of greatest concern (MacDonald 2000).

Wildfires are the other disturbance in forested environments that can greatly increase runoff and erosion rates. In many areas the risk of wildfires has increased as a result of human-induced changes in vegetation density, vegetation type, and the number of ignitions. Recent studies show that climate change also is increasing the risk of wildfires (Ryan 1991, Mouillot et al. 2002, Westerling et al. 2006). High-severity fires are of particular concern because they completely consume the surface organic layer (Neary et al. 2005a) and can induce a water repellent layer at or near the soil surface (DeBano 2000). Raindrop impact on the exposed mineral soil can detach soil particles and induce soil sealing, which reduces the infiltration rate. The resultant surface runoff greatly increases erosion rates by sheetwash, rill, and channel erosion (Shakesby and Doerr 2006). The change from subsurface to surface runoff and the loss of surface roughness greatly increases runoff velocities, and this further increases the size of peak flows and surface erosion rates. The risk of high runoff and erosion rates is substantially lower in areas burned at low or moderate severity because the fire does not consume all of the surface organic matter (Ice et al. 2004, DeBano et al. 2005).

Post-fire rehabilitation treatments--such as seeding and mulching--are commonly applied to severely-burned areas to reduce post-fire runoff and erosion. These treatments can be very costly, especially for large wildfires. For example, U.S. $72 million was spent on post-fire rehabilitation treatments after the 2000 Cerro Grande fire in New Mexico, and $17 million was spent after the 2002 Hayman fire in Colorado (Morton et al. 2003, Robichaud et al. 2003). The problem is that there are few data on the effectiveness of these treatments in reducing post-fire runoff and erosion (Robichaud et al. 2000, GAO 2003).

For the last six years we have been intensively studying how unpaved roads, wildfires, and post-fire rehabilitation treatments affect runoff and erosion rates in the Colorado Front Range, and the delivery of this sediment into and through the stream network. Much of this concerns stems from the fact that the South Platte River watershed provides 70% of the water for approximately two million people living in and around Denver, and both the quantity and the quality of this water is highly dependent on forest conditions and forest management activities. The specific objectives of this chapter are to: 1) summarize the effects of roads and fires on runoff and erosion in forested areas; 2) present our methods for measuring runoff and erosion so that they can be applied elsewhere; 3) review and explain the effectiveness of different post-fire rehabilitation treatments; and 4) compare the long-term erosion rates from unpaved forest roads and wildfires. By combining our detailed, process-based understanding with results from other areas, the information presented is much more broadly applicable. Both the methods and the results can provide useful insights and guidance to other researchers as well as land managers.

2. Background

2.1 Effects of roads on runoff and erosion

In the absence of burning, unpaved roads are the dominant sediment source in forested areas (Megahan and King 2004). Infiltration rates for compacted road surfaces are typically 0.1 to 5 mm h^{-1}, and these low rates mean that rainstorms and snowmelt can generate overland flow on the road surface (Robichaud et al. in press). Roads that are cut into the sideslopes can intercept the downslope subsurface water flow, and the conversion of subsurface to surface flow further increases the amount of road runoff and the size of peak flows (e.g., Wigmosta and Perkins 2001, Wemple and Jones 2003). The lack of surface cover exposes the road surface to rainsplash erosion, and the high runoff rates subject the road surface to sheetwash and rill erosion. Road grading and vehicular traffic generally increase road erosion rates, as these increase the supply of easily erodible sediment (Reid and Dunne 1984, Luce and Black 2001, Ramos-Scharrón and MacDonald 2005).

The runoff and erosion from unpaved roads may have little effect if these materials are discharged in a diffuse manner onto undisturbed hillslopes where infiltration rates are high and the sediment is deposited or captured by litter, downed logs, and vegetation. On the other hand, road segments that cross perennial or ephemeral streams can deliver water and sediment directly to the stream. The amount of runoff and sediment that is delivered from the other road segments depends on the distance between the road and the stream, the hillslope gradient, the infiltration rate and surface roughness in the area between the road and the stream, the amount of runoff, and whether the road design disperses or concentrates road surface runoff (e.g., Megahan and Ketcheson 1996, Croke and Mockler 2001). A compilation of studies shows that the proportion of roads that are connected to the stream network is a linear function of the mean annual precipitation (Figure 1). In the absence of local data, the relationship shown in Figure 1 can be used to estimate the proportion of unpaved roads that are likely to be delivering runoff and sediment to the stream channel network.

2.2 Effects of forest fires on soils, runoff, and erosion

High-severity wildfires consume all of the surface organic matter and expose the underlying mineral soil (Neary et al. 2005a). In most coniferous forests and other vegetation types such as matorral, fynbos, and chaparral, the burning litter vaporizes water repellent compounds that are forced downwards by the heat of the fire. These compounds condense on the underlying, cooler soil particles, and they can induce a water repellent layer at or beneath the soil surface (Letey 2001). The depth of this water repellent layer increases with increased soil heating, and coarse-textured soils are more susceptible to the formation of a water-repellent layer than fine-textured soils because of their lower surface area (Huffman et al. 2001, DeBano et al. 2005). The water repellent layer is of concern because it can severely reduce infiltration rates and induce overland flow (Letey 2001, Benavides-Solorio and MacDonald 2001, 2002).

In moderate and high severity fires the loss of the protective litter layer exposes the mineral soil to rainsplash erosion. High severity fires also may burn the organic matter in the uppermost layer of the mineral soil, and the resulting loss of soil aggregates can greatly increase the soil erodibility (DeBano et al. 2005). The soil particles may clog the surface pores and induce surface sealing, which will further decrease infiltration rates (Neary et al. 1999). The loss of surface roughness by burning increases the velocity of surface runoff, and the combination of reduced infiltration and high overland flow velocities can increase the size of peak flows by one or two orders of magnitude (i.e., 10-100 times) (Scott 1993, Moody and Martin 2001a, Neary et al. 2005b).

In low severity fires not all of the surface organic material is burned. Because the soils do not become water repellent and the mineral soil is not directly exposed to rainsplash or soil sealing, low severity fires typically have little or no effect on infiltration and surface erosion rates (Robichaud 2000, Benavides-Solorio and MacDonald 2005).

The increase in erosion rates after high severity fires can be even greater than the increase in the size of peak flows because of the loss of soil aggregates and the exposure of the soil to rainsplash, sheetwash, and rill erosion (Neary et al. 1999, Moody et al. 2005). The lack of surface roughness results in high overland flow velocities, and this further increases the detachment and transport of soil particles. Rills and gullies readily form where the surface runoff becomes concentrated by topography, rocks, or logs. Rill and gully erosion (Fig. 2) can account for about 80% of the sediment generated from high-severity wildfires (Moody and Martin 2001a, Pietraszek 2006).

The net effect is that high-severity fires can increase sediment yields by two or more orders of magnitude (Robichaud et al. 2000, DeBano et al. 2005, Shakesby and Doerr 2006). The delivery of this sediment to downstream areas leads to channel aggradation and adverse effects on aquatic habitat and reservoir storage (Moody and Martin 2001a, Rinne and Jacoby 2005). Water quality is severely degraded by the high concentrations of ash and fine sediment, and fires also can result in high concentrations of nutrients and heavy metals (Neary et al. 2005c).

Over time the fire-induced soil water repellency breaks down and plant regrowth provides a protective cover of vegetation and litter (e.g., Robichaud and Brown 1999, MacDonald and Huffman 2004; Benavides-Solorio and MacDonald 2005). Runoff and erosion rates usually return to background levels after several years, but post-fire recovery can occur within three months or require up to 14 years (Shakesby and Doerr 2006). Recovery is more rapid as fire severity decreases (Pietraszek 2006).

2.3 Rehabilitation treatments

The adverse effects of high-severity fires on runoff and erosion rates often compel land managers to apply emergency rehabilitation treatments. These emergency rehabilitation treatments are designed to either increase revegetation rates and surface cover (e.g., seeding, mulching), or provide physical barriers for trapping runoff and sediment at the hillslope or watershed scale (e.g., contour log erosion barriers, check dams).

The most common post-fire rehabilitation treatments are grass seeding, mulching, and the placement of contour-felled logs (Robichaud et al. 2000, Raftoyannis and Spanos 2005). Grass seeding has been the most widely used technique because it is relatively inexpensive and can be done over large areas with aircraft. Straw mulch immediately increases the amount of surface cover, but it is more difficult and costly to apply. The application of straw mulch also raises concerns about the possible introduction of weeds or other non-native species (Kruse et al. 2004, Keeley et al. 2006).

Contour-felled logs, or contour log erosion barriers, are burned trees that are cut down, de-limbed, and staked parallel to the contour on burned hillslopes (Figure 3). They are designed to trap the runoff and sediment coming from upslope areas. To be effective, a small trench needs to be dug upslope of the log and the excavated material has to be packed underneath the log to prevent underflow. The trench may temporarily enhance infiltration by cutting through the water repellent layer, and the trench also can slightly increase the water storage capacity on the hillslope (Wagenbrenner et al. 2006). Straw wattles and straw bales also are used to trap runoff and sediment from burned hillslopes (Robichaud 2005).

3. Monitoring methods

Monitoring the effects of fires and roads on soils, runoff, and erosion can be done at different spatial scales for different purposes. At the point or very small plot scale infiltration rates can be measured by minidisk (Lewis et al. 2006) or ring infiltrometers (Martin and Moody 2001), but it is difficult to extrapolate these small-scale data to hillslopes or small catchments.

Soil water repellency can only be measured at the point scale, and this is most commonly done by measuring the Water Drop Penetration Time (WDPT). In this test one or more drops of water are placed on the soil surface and the time required for the water to penetrate the soil is recorded (Letey 1969). An alternative method is the Critical Surface Tension (CST), and this uses varying concentrations of ethanol in water. Higher ethanol concentrations lower the surface tension of water, and the CST is the surface tension of the drops that infiltrate the soil within 5 seconds (Watson and Letey 1970). Longer WDPT penetration times and lower CST values denote stronger water repellency. Though WDPT is more widely used than the CST, the CST procedure is faster, has less spatial variability, and has shown better correlations with predictive variables (Scott 2000, Huffman et al. 2001).

Changes in soil structure, cohesion, and erodibility can be assessed by measuring aggregate stability and critical shear stress (e.g., Badìa and Martì 2003, Mataix-Solera and Doerr 2004, Moody et al. 2005). The infiltration rates and soil conditions on unpaved roads can be readily compared to values from adjacent undisturbed sites, and this allows one to estimate the local effects of unpaved roads. Pre-burn data are almost never available for wildfires, and in larger fires there may be no immediately adjacent unburned sites to serve as reference conditions. These limitations make it more difficult to rigorously evaluate the effects of burning on soil properties as compared the effects of unpaved roads.

Runoff and sediment yields can be measured at the plot scale (≤~300 m^2) by capturing the overland flow produced by natural storms in containers. Rainfall simulations provide a more controlled means for assessing the effect of site characteristics and rainfall rates on runoff and erosion (e.g., Benavides-Solorio and MacDonald 2001 and 2002, Cerdà and Doerr 2005). Practical considerations usually limit rainfall simulations to plots that are 1 m^2 or smaller, although some studies have used plots of 10-300 m^2 (e.g., Wilson 1999, Johansen et al. 2001, Rulli et al. 2006).

At the hillslope and road segment scale, sediment production rates can be readily measured with sediment fences (Figure 4). These are inexpensive and relatively simple to construct (Robichaud and Brown 2002; http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm). Sediment fences need to be regularly checked and manually emptied in order to obtain valid data. Runoff can be measured at the hillslope scale by installing small flumes or weirs with water-level recorders, but these are much more costly than sediment fences.

Runoff and sediment yields are much more difficult and costly to measure at the watershed scale than at the plot or hillslope scale (Shakesby and Doerr 2006). Runoff can be most accurately measured by installing a flume or weir. The use of a standard design, such as a 90^{o} V-notch weir or a Parshall flume, is advantageous because there is a known relationship between water height and discharge. Measuring discharge in natural channels is more difficult because one must make the necessary field measurements to establish the relationship between water level and streamflow, and these are less accurate and difficult to obtain at high flows (e.g., Kunze and Stednick 2006). Sediment yields can be measured at the watershed scale by constructing sediment rating curves from simultaneous measurements of streamflow and suspended sediment and/or bedload, or by trapping the eroded sediment behind debris dams (e.g., Rice et al. 1965, Moody and Martin 2001a). Measuring runoff after high-severity fires is extremely difficult because the high sediment yields tend to clog up flumes, fill the ponded area behind weirs, and alter the stage-discharge relationship by altering the channel cross-section through aggradation and/or incision (Fig. 5). It also is much more difficult to replicate or compare sites at the watershed scale.

In summary, small-scale measurements are cheaper, more easily replicated, and can be used to isolate the effects of specific site conditions. Larger-scale measurements integrate much of the smaller-scale spatial variability and they are closer to the scale of interest to land managers. The disadvantages of larger-scale measurements include their higher cost, the difficulty of replication, the difficulty of characterizing larger and more diverse areas, and the associated difficulty of making process-based interpretations of the data collected at larger scales.

4. New insights from the Colorado Front Range

4.1 Road erosion

In the Colorado Front Range we have been measuring road erosion rates and assessing the connectivity between roads and streams since summer 2001. The most complete erosion data are for five years from 11 unpaved road segments along the Spring Creek road in the Pike National Forest approximately 65 km southwest of Denver. From 2002 to 2006 the mean annual sediment production rate was 42 Mg per hectare of road surface. The importance of longer-term measurements is shown by the 10-fold variation in annual sediment production (Fig. 6). The high interannual variability is attributed primarily to the differences in rainfall erosivity, although the higher sediment yields in 2005 also may be due to an increase in traffic as a result of forest thinning operations.

Since unpaved roads occupy about 0.003% of the South Platte watershed, unpaved roads produce about 0.13 Mg ha^{-1} of sediment per year. Detailed surveys of 13.5 km of unpaved roads indicate that about 2.4 km or 18% of the roads drain directly to perennial or ephemeral streams via stream crossings, rills, or sediment plumes (Libohova 2004). This value is consistent with the relationship shown in Figure 1.

4.2. Surface cover, soil water repellency, runoff, and sediment yields for undisturbed vs. severely-burned hillslopes

Undisturbed ponderosa pine forests in Colorado typically have at least 85% surface cover and infiltration rates in excess of 100 mm h^{-1} (Martin and Moody 2001, Libohova 2004). These characteristics mean that overland flow is rare and surface erosion rates are very low (Morris and Moses 1987, Libohova 2004). We have collected over 100 hillslope-years of data from 34 undisturbed sites, and only one site with an unusually low amount of surface cover (<55%) has generated measurable amounts of sediment. No sediment was generated from any of the other sites, even though some sites with slopes of up to 55% have been subjected to rainfall intensities of more than 60 mm hr^{-1}. Similarly, no sediment has been produced from any of the hillslopes where over half of the trees were mechanically chipped to reduce wildfire risk (Libohova 2004).

As in many coniferous forests, the soils in the undisturbed ponderosa pine forests are water repellent at the soil surface at depths of 0-3 cm. Below 6 cm the soils in our study areas exhibit little soil water repellency (Libohova 2004). Burning at high and moderate severity strengthens the soil water repellency at 0 and 3 cm, and induces moderate to strong soil water repellency at a depth of 6 cm (Huffman et al. 2001). Multivariate analyses show that soil water repellency strengthens with increasing burn severity and sand content, and decreases with increasing soil moisture content (Huffman et al. 2001). When measuring soil water repellency, we prefer the CST procedure over the more widely-used WDPT because the CST procedure is faster, has less spatial variability, and was more strongly correlated with the different predictive variables (Huffman et al. 2001). In general, however, soil water repellency is high variable in time and space (Doerr et al. in press), and we found that the three predictive variables of burn severity, sand content, and soil moisture could only explain 30-41% of the variability in soil water repellency measured on two wild and three prescribed fires (Huffman et al. 2001).

Measurements over time indicate that the fire-enhanced soil water repellency in the Colorado Front Range is relatively short-lived. In the case of the Bobcat fire there was a significant decline in soil water repellency within three months, and the effect of burning on soil water repellency was not statistically detectable within 12 months (MacDonald and Huffman 2004). Similarly, the soil water repellency was strongest at the soil surface and decreased with depth after the 2002 Hayman wildfire, but by the second year after burning this water repellency was not statistically significant compared to unburned sites (Figure 7) (MacDonald et al. 2005). The greater persistence of soil water repellency at a depth of 3 cm relative to the soil surface may be due to the preferential erosion of water repellent particles and the faster chemical and physical breakup of the water repellent layer at the soil surface by solar radiation, biological activity, and freeze-thaw processes. Most other studies also have shown a relatively rapid decay of fire-induced soil water repellency (e.g., Hubbert et al. 2006; Doerr et al. in press).

As soils wet up they no longer are water repellent (Leighton-Boyce et al. 2003, Hubbert and Oriol 2005). The soil moisture threshold for the shift from water repellent to hydrophilic appears to increase with increasing burn severity (MacDonald and Huffman 2004). For unburned sites adjacent to the Bobcat fire in Colorado there was no evidence of soil water repellency once the soil moisture content exceeded 10%. For burned sites the soil moisture threshold was 13% for sites burned at low severity, while sites burned at high severity could still be water repellent when the soil water content was 26% (MacDonald and Huffman 2004). In a California chaparral watershed the proportion of the surface with high or moderate water-repellency dropped from 49% to 4% when once the soil moisture content reached 12% (Hubbert and Oriol 2005). These results and other studies indicate that post-fire soil water repellency is unlikely to increase runoff rates once the soils have wetted up, but soil water repellency can be re-established once the soils dry out (Leighton-Boyce et al. 2003).

Measurements at the small catchment scale in Colorado indicate that overland flow is initiated from severely burned areas when the maximum 30-minute rainfall intensity (I_{30}) exceeds about 8-10 mm h^{-1} (Moody and Martin 2001b, Kunze and Stednick 2006). Peak flows increase exponentially as I_{30} exceeds 10 mm h^{-1} (Moody and Martin 2001b), and the maximum peak flows of 4 to 24 m^3 s^{-1} km^{-2} from the Front Range of Colorado are comparable to the range of values (3.2-50 m^3 s^{-1} km^{-2}) measured from severely-burned areas in the western U.S. (Moody and Martin 2001a, b, Kunze and Stednick 2006). In the ponderosa pine zone in Colorado the post-fire increases in the size of peak flows and surface erosion rates persist for 2-5 years after a high-severity wildfire (Moody and Martin 2001a, Benavides-Solorio and MacDonald 2005, Kunze and Stednick 2006). Since the decrease in post-fire soil water repellency is much more rapid than the decrease in post-fire runoff and erosion rates, there must be some other process, such as soil sealing, that is contributing to the observed, longer-term increases in post-fire runoff and erosion.

4.3 Effects of fires on hillslope-scale sediment yields

Hillslope-scale sediment yield data have been analyzed from six Colorado fires (Benavides-Solorio and MacDonald 2005). Over 90% of the sediment was generated by high intensity summer thunderstorms. Very little sediment was generated by snowmelt because the soils were not repellent due to the wet conditions and snowmelt rates are much lower than the rainfall intensities for the larger summer thunderstorms.

The range of sediment production rates after fires as measured by sediment traps is from 0 to 70 Mg ha^{-1} yr^{-1}. The mean annual sediment production for high severity sites in the Bobcat fire was 8.7 Mg ha^{-1} for the first two years after burning, while the mean value for sites burned at moderate and low severity was less than 0.3 Mg ha^{-1} yr^{-1} (Figure 8) (Benavides-Solorio and MacDonald 2005). The high severity sites in prescribed fires produced only about 10% as much sediment as the high severity sites in the Bobcat wildfire (Figure 8), and this is attributed to the more patchy nature of the prescribed fires and greater surface cover in the prescribed fires due to litterfall and more rapid vegetative regrowth (Benavides-Solorio and MacDonald 2005).

Multivariate analysis showed that the amount of bare soil was the dominant control on post-fire sediment yields, as this explained nearly two-thirds of the variability in annual sediment yields (Figure 9). The lower sediment production rates in 2000, which was the year of burning, are due to the lack of large storm events. In summer 2001 there were more large storm events, and annual sediment yields were consistently high when there was more than about 35% bare soil (i.e., less than 65% surface cover). The same general trends were shown for a much larger data set by Pietraszek (2006), and studies in other areas also have documented the importance of surface cover in reducing runoff and erosion from forests and shrublands (e.g., Lowdermilk

1930, Brock and DeBano 1982, Robichaud and Brown 1999). The implication is that the progressive decline in post-fire sediment yields over time largely depends on the regeneration of surface cover.

After the amount of surface cover, the most important factors for predicting post-fire sediment yields in the Colorado Front Range were rainfall erosivity, soil texture, and fire severity. Rainfall erosivity was the most important of these additional factors, and its influence is greatest in recently-burned areas with little surface cover. Coarser soils tended to have lower sediment yields, and this can be attributed to the greater difficulty in detaching and transporting larger particles. Fire severity was a significant variable primarily because the amount of surface cover decreases with increasing severity. A multivariate model using percent bare soil, rainfall erosivity, soil texture, and fire severity explained 77% of the variability in post-fire sediment yields in the Colorado Front Range (Benavides-Solorio and MacDonald 2005).

The 2002 Hayman wildfire provided a unique opportunity to evaluate the effects of high-severity wildfires because it burned 20 study sites that had been established in the previous summer to evaluate the effects of a proposed forest thinning project. Prior to burning the mean amount of surface cover on each of these convergent hillslopes was about 85%, there were no channels or visual evidence of overland flow, and there were no measurable amounts of sediment in any of the sediment fences. After burning the mean amount of surface cover dropped to less than 5%, and the first rainstorm of only 11 mm caused rills to form in areas with convergent flow and a mean sediment yield of 6.2 Mg ha^{-1} (Libohova 2004). These rills rapidly extended to within 10-20 m of the ridgetops, and they continued to incise during each major rainstorm for the first three years after burning (Pietraszek 2006). From 2002 to 2004 the mean sediment yield was 7, 11, and 9 Mg ha^{-1}, respectively.

The importance of topography, concentrated overland flow, and rilling can be shown by the observed differences between planar and convergent hillslopes, respectively. Planar hillslopes on the Bobcat and Hayman fires developed much smaller rills that showed little net incision over time relative to the convergent hillslopes, and unit area sediment yields were three times higher for the convergent hillslopes with central rills than for planar hillslopes (Benavides-Solorio and MacDonald 2005, Pietraszek 2006). Successive measurements of rill cross-sections from the convergent hillslopes showed that rill erosion could account for 60-80% of the sediment collected from the sediment fences (Pietraszek 2006).

Within our study sites there was no evidence of sediment deposition, and this was also true for the steep headwater channels below our sediment fences. This means that nearly all of the sediment generated at the hillslope scale is being delivered to the newly-formed channel network (Pietraszek 2006). Cross-section measurements after the nearby 1996 Buffalo Creek wildfire also showed that channel incision accounted for about 80% of the estimated sediment yield from small catchments (Moody and Martin 2001a). Together these results indicate that rill and channel incision are the dominant sources of post-fire sediment.

Continued monitoring of these and other study sites shows that the median sediment yield from areas burned at high severity decreases by an order of magnitude between the second and third years after burning (Figure 10), and we attribute this decline to the increase in surface cover as a result of vegetative regrowth. Sediment yields generally return to near-undisturbed levels in 3-5 years in the Colorado Front Range (Figure 10) (Pietraszek 2006). A similar recovery period was noted in a seven-year study in a dryland area in Spain, as this showed that catchment-scale runoff and sediment yields were highest in the third year after burning but were very low after five years (Mayor et al. 2007). The long recovery period was attributed to below average rainfall and the correspondingly slow revegetation rate (Mayor et al. 2007). In Colorado we have observed slower vegetative regrowth in areas with coarser soils because of the poorer growing conditions (Pietraszek 2006). The Hayman fire is one area with particularly coarse-textured soils, and after five years the mean amount of surface cover has nearly stabilized at about 65-70%, which means that some sites are still generating some sediment during the larger storm events (MacDonald et al. 2007).

Recent work indicates that the accumulation of sediment in downstream channels may persist for a much longer period than the 3-5 years needed for hillslope erosion rates to recover to pre-fire levels. As noted above, nearly all of the sediment eroded from the convergent hillslopes is delivered to the channel network, but this sediment tends to accumulate in lower-gradient, downstream channels because of the lower transport capacity. In the case of the Hayman wildfire, the first couple of storms caused over 1.2 m of aggradation in some downstream reaches in the 3.4 km^2 Saloon Gulch watershed, and this sediment completely buried an 0.75 m H-flume that had been installed to measure runoff. Another 0.2 m of aggradation occurred in this channel over the next four years.

We project that much of the sediment deposited after fires becomes long-term storage, as the combination of vegetative regrowth and the decline in soil water repellency means that hillslope- and catchment-scale runoff rates approach pre-fire values within 3-5 years (e.g., Moody and Martin 2001a, Kunze and Stednick 2006). The decline in runoff means a corresponding decline in sediment transport capacity, and this severely limits the amount of post-fire sediment that can be entrained and transported further downstream. In the nearby Buffalo Creek fire the residence time of fire-related sediment has been estimated to be about 300 years (Moody and Martin 2001a). In other cases, such as the Saloon Gulch watershed, the residence time is likely to be even longer, as in severely aggraded channels most of the runoff flows subsurface. In watersheds with less aggradation and perennial surface flow, the channels can more readily return to pre-fire conditions because the streams can slowly excavate the accumulated sediment. In these cases the channels might recover in decades rather than centuries.

4.4 The effectiveness of post-fire rehabilitation treatments

After the Bobcat fire large areas were treated by aerial seeding, while some of the more sensitive areas that burned at high severity were treated with straw mulch at 2.2 Mg ha^{-1} or by contour felling. A 5-10 year storm event that occurred two months after the Bobcat fire caused three-quarters of the sediment fences to fill with sediment and overflow. Although the sediment fences on the mulched plots were not overtopped, the high erosion rates and high spatial variability meant that in the first summer after burning none of the treatments had significantly lower sediment yields than the controls (Fig. 11) (Wagenbrenner et al. 2006).

In each of the next three years the hillslopes treated with straw much had significantly lower sediment yields than the untreated controls (Fig. 11). The effectiveness of mulching in reducing post-fire sediment yields is attributed to the increase in mean surface cover from 33% to 75% (Wagenbrenner et al. 2006). In contrast, neither aerial nor hand seeding had any detectable effect on the amount of vegetative regrowth or on hillslope-scale sediment yields (Fig. 11).

The plots treated with contour log erosion barriers prior to the large storm did not significantly reduce sediment yields because the amount of sediment generated by this storm greatly exceeded the sediment storage capacity (Fig. 11). After this storm seven more plots were treated with contour log erosion barriers, and this second contour-felling treatment reduced sediment yields by 71% in the second year after burning ($p<0.05$). In the third and fourth years after burning the sediment yields from these contour-felled plots were 83-91% less than the sediment yields from the adjacent control plots, but this difference was not significant due to high between-plot variability in sediment yields (Wagenbrenner et al. 2006). Detailed surveys of contour log treatments on three fires showed that 32% of the contour-felled logs were completely or partially ineffective in trapping runoff and sediment because they were installed off-contour or had incomplete ground contact (Wagenbrenner et al. 2006). These results indicate that contour felling treatments in the Colorado Front Range are only effective for small- to moderate-sized storms because of the limited storage capacity, and proper installation can be a major problem.

Our studies on the Hayman wildfire generally have confirmed the results from the Bobcat fire. Mulching plus seeding was able to significantly reduce sediment yields relative to the control plots. Seeding plus scarification had no significant effect on the amount of ground cover or sediment yields in any of the first three years after burning (Fig. 12). Subsequent monitoring has confirmed that seeding and scarification has had no significant effect on either the amount of ground cover or post-fire sediment yields.

Studies in other areas confirm the relative effectiveness of mulching and the general ineffectiveness of seeding in reducing post-fire sediment yields. At the Cerro Grande Fire in New Mexico, the application of straw mulch plus grass seed reduced sediment yields by 70% in the first year after burning and 95% in the second year after burning (Dean 2001). Mulching also reduced sediment yields by an order of magnitude following a wildfire in Spain (Bautista et al. 1996). In contrast, only one of eight studies showed that seeding reduced post-fire erosion (Robichaud et al. 2000). More recently, a four-year study in north-central Washington (USA) showed that neither seeding nor seeding plus fertilization reduced post-fire sediment yields (Robichaud et al. 2006). However, seeding increased surface cover and reduced sediment yields by 550% after an experimental prescribed fire in scrub vegetation in northwest Spain (Pinaya et al. 2000), but it is not clear why seeding was more successful in this instance.

4.5. Comparison of the effects of fires and roads

The sediment production and delivery data from unpaved forest roads and fires allows us to compare the effects of these two disturbances over different time scales at both the hilllslope and watershed scale. Over a five-year period the mean sediment production rate from unpaved roads was 42 Mg ha^{-1}, but unpaved roads only occupy about 0.003% of the Upper South Platte River watershed. When the road area is multiplied by the road sediment production rate, the unit area value drops to 0.13 Mg ha^{-1} per year. This converts to 130 Mg ha^{-1} over a 1000-year time span, but the actual sediment production rate over this long time scale would probably be substantially higher because the largest storm events generate a disproportionate amount of sediment (Larson et al. 1997), and the largest rainstorm over the 5-year monitoring period had a recurrence interval of about 6 years. The road connectivity surveys indicate that about 18% of the unpaved roads are connected to the stream network. If all of the sediment from 18% of the roads is assumed to be delivered to the stream network, the watershed-scale sediment yield from unpaved roads over a 1000-year period would be about 23 Mg ha^{-1}. In reality, not all of the sediment from the connected segments would be expected to reach the stream network and be delivered to the South Platte River, but this overestimate is extremely difficult to quantify and might compensate for the likely underestimate of the long-term sediment production rate.

The hillslopes burned at high severity by the Hayman wildfire produced about 10-50 Mg ha^{-1} of sediment before the sediment production rates declined to near-background levels (Pietraszek 2006). The dating of charcoal-rich horizons in alluvial fans at the nearby Buffalo Creek fire indicate that the recurrence interval of large-scale fire and sedimentation events is close to 1000 years (Elliot and Parker 2001). If the erosion rates that we measured after the Hayman fire are assumed to represent one of these millennial scale events, the long-term sediment production from fires is 10-50 Mg ha^{-1} per 1000 years. This value is only about 10-40% of the estimated long-term sediment production rate from roads, but our field observations indicate that nearly all of the sediment from a high-severity fire is delivered to the stream network. If we assume a 100% delivery rate, the long-term sediment yield from fires is 10-50 Mg of sediment per 1000 years. This value is very similar to the estimated sediment delivery rate of 23 Mg ha^{-1} per 1000 years for unpaved forest roads. Again, not all of the sediment will necessarily be delivered to the South Platte River, but nearly all of the stored sediment is potentially accessible for fluvial transport.

The key point is that roads and fires can be expected to deliver a similar amount of sediment to streams over a 1000-yr period. However, the physical and biological effects of these two sediment sources may be quite different, as the fire-related sediment is being delivered in a large pulse, while the sediment inpts from roads are more continuous. Both fire- and road-derived sediment can degrade aquatic habitat and water quality, and adversely affect algal, macroinvertebrate, and fish populations (Waters 1995). However, native species are generally adapted to the disturbance induced by fires and can quickly recolonize burned areas (Gresswell 1999). The chronic inputs of road sediment do not provide the same opportunities for habitat recovery (Forman and Alexander 1998, Trombulak and Frissell 2000). The implication is that the long-term effects of road erosion on water quality and aquatic ecosystems are at least comparable to, and may be worse than the effects of large, high-severity fires. From a management perspective, the production and delivery of sediment from roads can often be greatly reduced with Best Management Practices, while it is much more difficult to apply mitigation treatments and reduce sediment yields after large, high-severity wildfires. Given the potentially significant effect of road sediment delivery on steams and water quality, it follows that forest resource managers should be devoting more effort to minimizing the chronic inputs from unpaved roads rather than trying to reduce the flooding and sedimentation after infrequent, high-severity wildfires.

5. Conclusions

Undisturbed forests have high infiltration rates and very low surface erosion rates. However, the unpaved roads used to access the forest have low infiltration rates and relatively high surface erosion rates. In drier areas most of the road-related runoff and sediment is unlikely to be delivered to the stream channel network, but as annual precipitation increases road-stream connectivity increases because of the greater travel distance of road runoff and the greater number of road crossings.

High-severity fires are of considerable concern to land managers because they can increase runoff and erosion rates by one or more orders of magnitude. The increases in runoff and erosion are due to the loss of the protective litter layer and subsequent soil sealing, the development of a water repellent layer at or near the soil surface, the disaggregation of soil particles due to the combustion of soil organic matter, and the high runoff velocities due to the loss of surface roughness. After high-severity fires in the Front Range of Colorado, surface runoff is generated by storm intensities of only 7-10 mm h^{-1}. This runoff is rapidly concentrated in topographically convergent areas, and the resultant rill and gully incision is the dominant source of sediment. Sediment yields from areas burned at high severity decline to near-background levels within 3-5 years after burning, and this is primarily attributed to the decline in percent bare soil over time. Runoff and erosion from areas burned at moderate and low severity are of much less concern because these values are commonly 5 or 10 times less than areas burned at high severity.

Rehabilitation treatments that immediately increase the amount of surface cover, such as mulching, significantly reduce post-fire sediment yields. Seeding generally does not increase revegetation rates and therefore is not effective in reducing post-fire sediment yields. Contour-felled log erosion barriers provide a limited amount of sediment storage, so this treatment is only effective in reducing sediment yields from small- to moderate-sized storms.

Over a millennial time scale, the amount of sediment delivered to streams from unpaved forest roads is equal to or greater than the amount of sediment that is delivered from high-severity wildfires. The chronic delivery of sediment from roads may be of greater significance to aquatic ecosystems than the pulsed delivery of sediment from high-severity wildfires, and forest managers should take steps to minimize road runoff and sediment delivery if downstream aquatic resources are being adversely affected.

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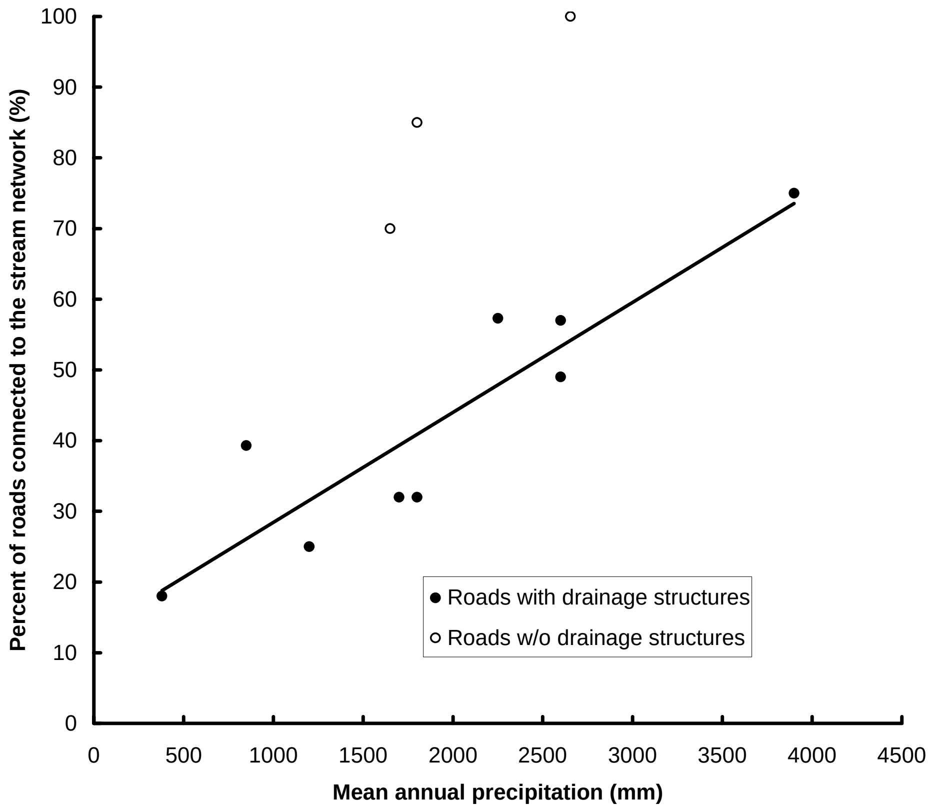

Figure 1. Percent of roads connected to the stream network versus mean annual precipitation for roads with and without engineered drainage structures. Regression line is for roads with engineered drainage structures (from Coe 2006).

Figure 2. Rill erosion after a 100-year rainstorm on the area burned at high severity in the 1996 Buffalo Creek fire in the Colorado Front Range. Photo by John Moody, USGS.

Figure 3. A contour felled log installed immediately after the Bobcat wildfire in the Colorado Front Range. The trench upslope of the log is created by excavating the soil and packing it against the log to prevent underflow (from Wagenbrenner et al. 2006).

Figure 4. A pair of sediment fences used for measuring hillslope-scale sediment yields after the June 2002 Hayman fire. The piles of sediment are the material captured and removed from the fences between July 2002 and early summer 2003. This area burned at high severity, and the slow recovery is evident from the small amount of vegative regrowth.

Figure 5. After a high-severity fire runoff can bypass of greatly exceed the capacity of a flume installed to measure discharge. Picture taken after the 1996 Buffalo Creek fire by John Moody, USGS.

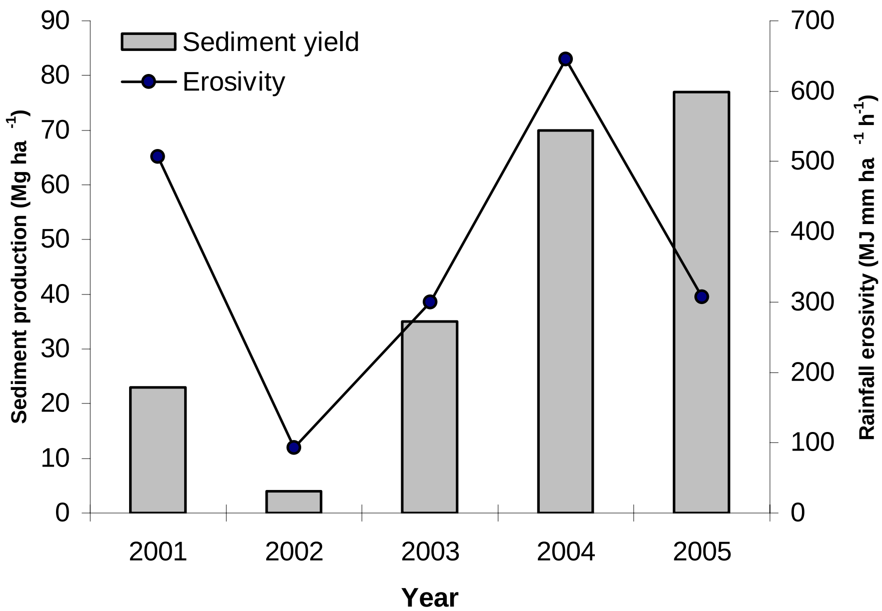

Figure 6. Mean annual sediment production and rainfall erosivity from 2001 to 2005 for 11 road segments along the Spring Creek road in the Upper South Platte River watershed in Colorado.

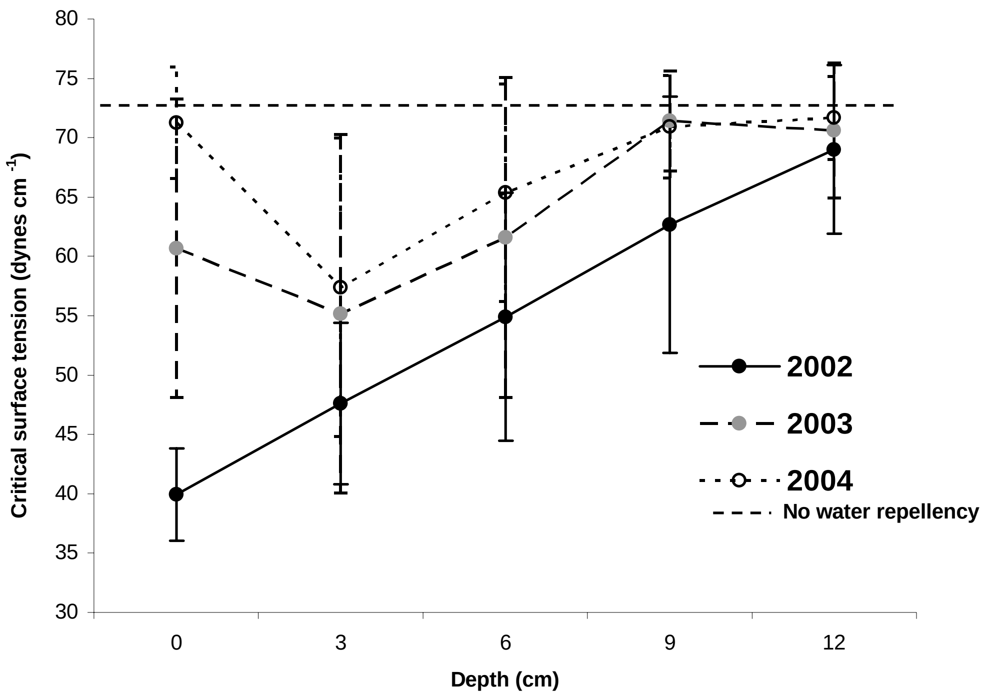

Figure 7. Mean soil water repellency over time at the Hayman fire using the CST procedure. Higher values indicate weaker soil water repellency, and the bars indicate one standard deviation.

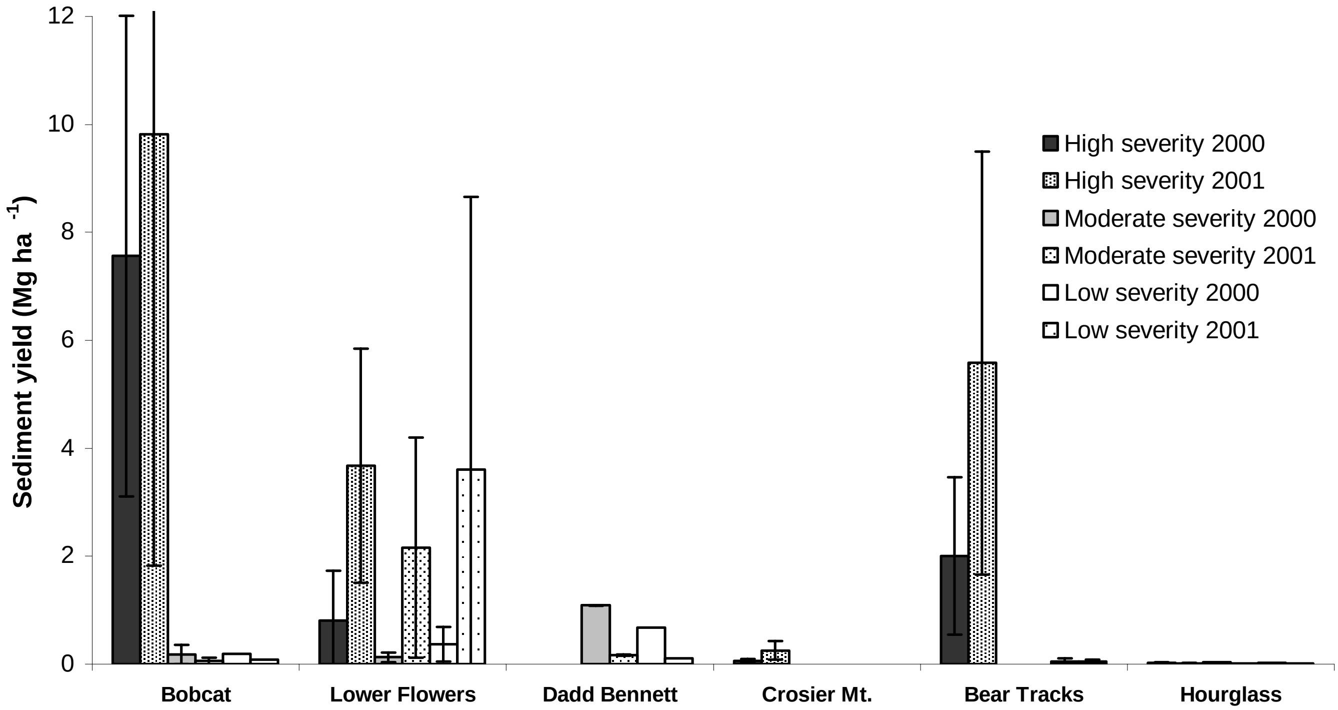

Figure 8. Sediment yields by burn severity for six Colorado fires for June-October 2000 and June-October 2001. Bars indicate one standard deviation.

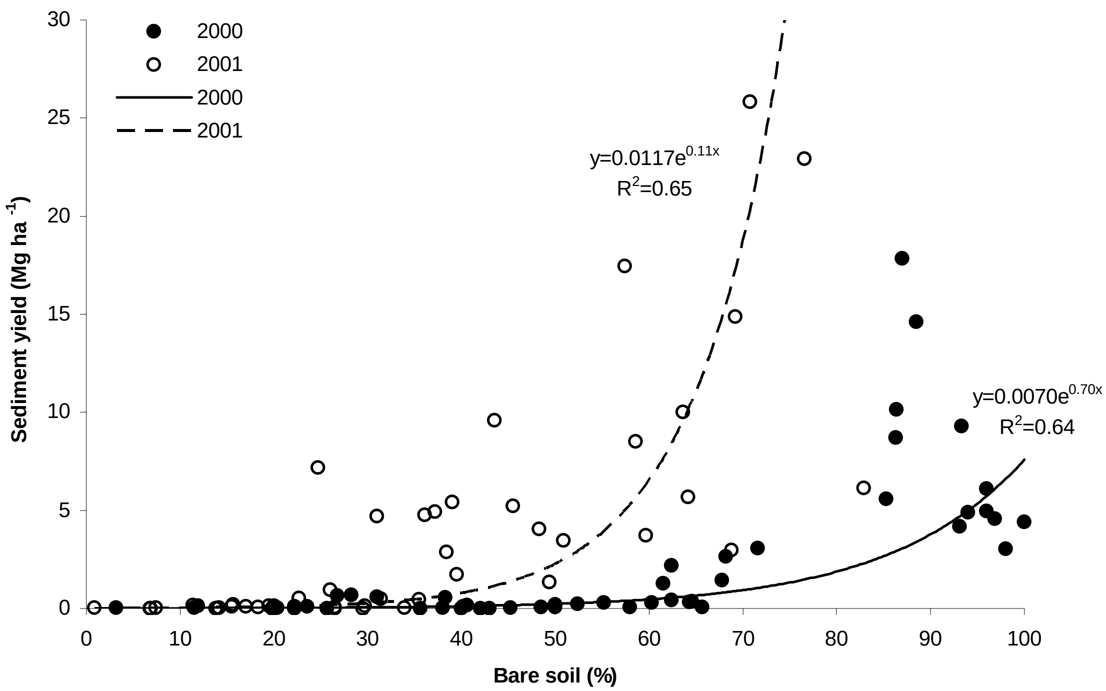

Figure 9. Relationship between percent bare soil and annual sediment production rates for the first and second year after burning. Data were collected from three wild and three prescribed fires in the Colorado Front Range.

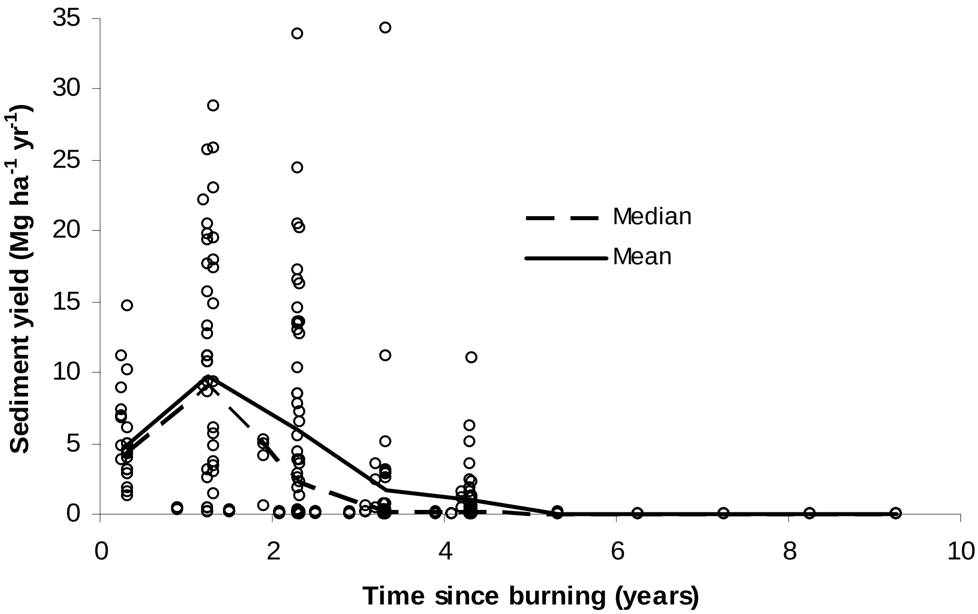

Figure 10. Annual sediment yields versus time since burning for six wildfires and three prescribed fires in the Colorado Front Range for high severity burns (from Pietraszek 2006).

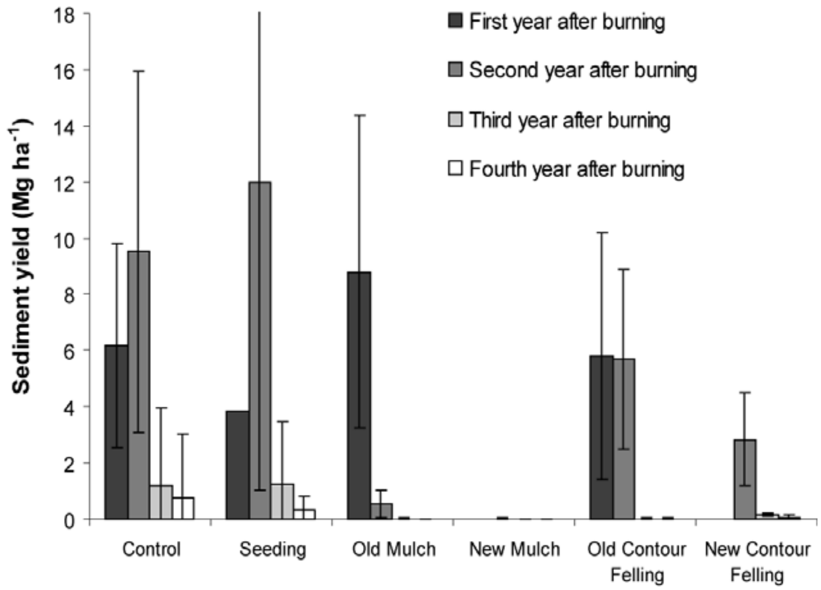

Figure 11. Annual sediment yields from treated and control hillslopes at the Bobcat fire. Old much and old contour felling refer to treatments that were applied before a very large storm that occurred two months after the fire. New mulch and new contour felling refer to treatments applied after this storm. Bars indicate one standard deviation.

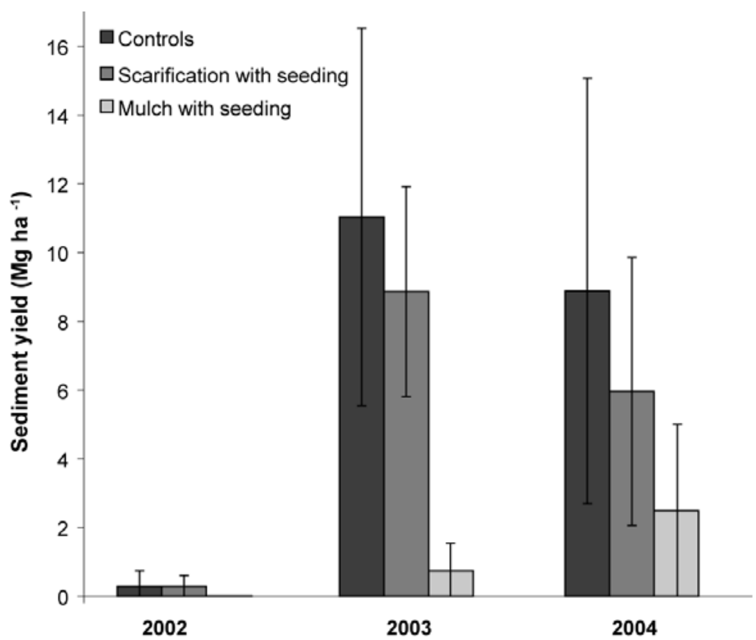

Figure 12. Mean annual sediment yields by year from eight untreated (control) hillslopes, four hillslopes treated by scarification and seeding, and four hillslopes treated by mulching and seeding. All sites were burned at high severity by the Hayman fire in the Colorado Front Range. Bars indicate one standard deviation.