THE FLUX AND PARTICLE SIZE DISTRIBUTION OF SEDIMENT COLLECTED IN HILLSLOPE TRAPS AFTER A COLORADO WILDFIRE

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INTRODUCTION

Flooding and erosion following wildfires are well-recognized phenomena in montane areas of the western United States (e.g., Connaughton, 1935; Buck et al., 1948; Sartz, 1953; Cleveland, 1977; Swanson, 1981; White and Wells, 1984; Wells, 1986; Morris and Moses, 1987; McNabb and Swanson, 1990; Booker et al., 1993) and internationally (e.g., Atkinson, 1984; Ballais and Magagnosc, 1993; Andreu et al., 1994; Soler et al., 1994; Soto et al., 1994; Inbar et al., 1998; Prosser and Williams, 1998). The removal of duff, litter and the forest canopy along with the physical and chemical alteration of soil by fire change the erosional threshold of burned watersheds (McNabb and Swanson, 1990; Meyer and Wells, 1997; Moody and Martin, unpublished data). Hillslope erosion and transport processes include rainsplash (Foster, 1982; Moss and Green, 1983), sheetwash (Foster, 1982), rilling (Young and Wiersma, 1973; Mosley, 1974; Foster and Meyer, 1975), dry ravel (the transport of surface material by gravity and wind, not by flowing water; Krammes, 1960, 1965), and freeze-thaw action. The rates of these processes are altered when watersheds burn (Miller, 1994).

In this paper we report the results of hillslope erosion monitoring in the Spring Creek watershed southwest of Denver, Colorado following a wildfire in 1996. The hillslope sediment-flux measurements and particle-size analyses were part of a larger study to determine the storage and transport of sediment in two adjacent burned watersheds (Buffalo Creek and Spring Creek) that in a year contributed more than 30 times the average annual pre-fire flux of sediment to Strontia Springs Reservoir (Moody and Martin, unpublished data), a water supply reservoir serving Denver and Aurora, Colorado. The data provided by this study will contribute to a more detailed understanding of the movement and particle-size distribution of sediment in burned areas, which will help land mangers in their post-fire rehabilitation planning and implementation.

BACKGROUND

The Buffalo Creek Fire burned 4690 hectares of mainly ponderosa pine and Douglas-fir forest in May 1996 (Figure 1). Approximately 62% of the area burned was classified as high-intensity burn (Bruggink et al., 1998), based on the complete combustion of needles on burned trees and the consumption of litter and duff. On 12 July 1996, a rainstorm with an estimated intensity of 99 mm h^{-1} (Jarrett and Browning, unpublished data) followed by other less intense storms produced dramatic erosion and deposition in the Buffalo Creek and Spring Creek watersheds. Soils in the watersheds are decomposed granite derived from the Pike's Peak batholith and are classified as easily erodible due to the shallow depth to bedrock and hence the high runoff potential when thoroughly wet (Moore, 1992). The burned area is in mountainous terrain dominated by short-duration, high-intensity summer rainfall. Snow pack and spring snowmelt are minimal.

We evaluated hillslope erosion in Spring Creek watershed. The hillslopes in the Spring Creek watershed are steep, typically 30 º or greater. Spring Creek flows generally west to east, creating predominantly north- and south-facing hillslopes. The vegetation on the south-facing hillslopes is mostly ponderosa pine (*Pinus ponderosa*) with a small proportion of Rocky Mountain juniper (*Juniperus scopulorum*) and widely dispersed bunch grasses in the understory, whereas the vegetation on the north-facing slopes is generally Douglas-fir (*Pseudotsuga medezii*) with very little understory vegetation. Like much of the Colorado Front Range, both extensive grazing and active fire suppression for over 100 years have allowed tree densities to increase over historic densities in the pre-fire suppression era (Brown et al., 1999; Kaufmann et al., 2000a, 2000b). The increase in vegetation density affects fire behavior, the production of volatile organic compounds that may contribute to the water repellency of the soil, and the heat impulse to the soil (Miller, 1994). While pre-fire hillslope erosion rates are unknown for the Spring Creek watershed, typical annual fluxes for adjacent areas are 0.0-0.1 kg m^{-1} (Bovis, 1974; Morris and Moses, 1987; Welter, 1995).

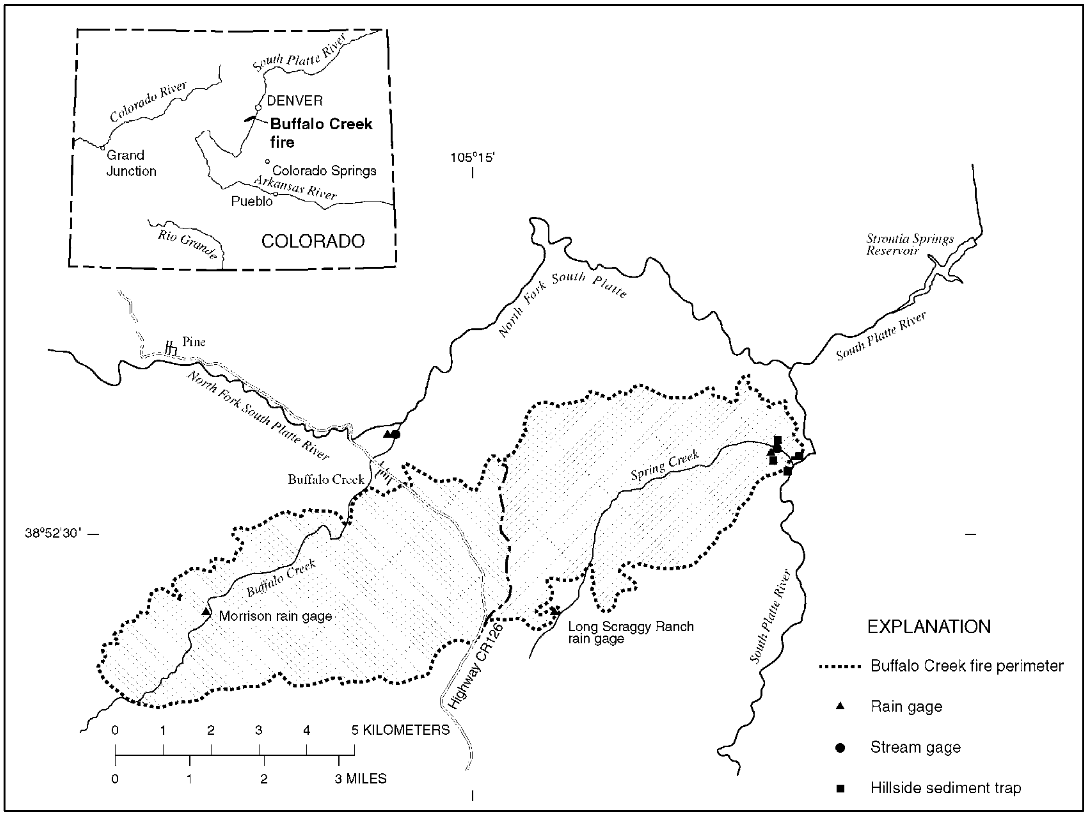

Figure 1 The Buffalo Creek Fire perimeter and the location of the hillslope sediment traps.

METHODS

We deployed sediment traps in interrill areas of severely burned and unburned hillslopes of the Spring Creek watershed. Traps were installed in the burned area on north-facing and south-facing hillslopes in 1997, one year after the wildfire, and in an unburned area on a north-facing and a south-facing hillslope in the second year after the wildfire. Four replicate traps were installed on each hillslope (south-facing, severely burned; north-facing, severely burned; south-facing, unburned; and north-facing, unburned). A sediment trap consisted of a trough constructed of PVC pipe with a 1-m x 0.1-m collection slot (Gerlach, 1967; Fitzhugh, 1992; Moody and Martin, unpublished data). Traps were installed perpendicular to the slope. A bucket collected sediment and water from the trough and additional buckets collected the water overflow from the trough. Metal edging enclosed the area of hillslope that contributed sediment to the trough. In 1997, the enclosures were of variable size averaging 10 m^2. Starting in 1998, the enclosures were reconfigured and standardized to 5 m^2 (1 m wide x 5 m long).

We collected sediment and water from the four replicate traps either after major storm events or as frequently as possible during the summer at all sites. Sediment from traps on the south-facing severely burned hillslope was also collected during the early spring and late fall to correspond to when rill-erosion measurements were made on the same hillslope. On the other hillslopes, sediment was allowed to accumulate throughout the winter until the first collection of the following summer. The four replicate samples collected at the end of each accumulation period constitute a group. Group averages for the median particle diameter, dispersion, and flux were computed using the four replicate samples. Seasonal means were computed as the means of the group averages and confidence limits were determined assuming that the group averages were statistically independent samples (Table 1). In addition, we took 5-cm diameter x 10-cm deep soil cores from the unburned, north- and south-facing hillslopes to characterize the particle-size distribution of the source of sediment collected in the hillslope traps.

Table 1: Seasonal median particle diameter, dispersion, and flux of sediment collected in traps on hillslopes in the Spring Creek watershed

[A group consists of four replicate samples; dispersion is dimensionless; NA= not applicable; numbers following ± sign are 95 % confidence limits; [a] summer consists of 122 days in June, July, August, and September and includes 31 August 1997, [b] The flux of sediment overtopped the traps and so the summer 1997 total flux and the 31 August 1997 flux are minimum estimates; [c] winter consists of 243 days]

Location	Number of groups	D_{50} mm	Dispersion	Flux kg m^{-1}
North-facing, unburned, 12 cores, 10-cm deep	1	2.9	4.2	NA
South-facing, unburned, 12 cores, 10-cm deep	1	2.6	4.9	NA
North-facing, burned, hillslope traps:				
Summer[a,b] 1997	7	2.0 ± 0.7	5.9 ± 1.6	>5.9
31 August[b] 1997	1	3.3	3.9	>3.3
Winter[c] 1997-1998	1	1.3	NA	0.90
Summer 1998	4	3.4 ± 1.2	3.1 ± 0.9	0.30 ± 0.38
Winter 1998-1999	1	3.6	3.9	0.05
Summer 1999	2	4.1 ± 2.6	2.6 ± 1.9	0.10 ± 0.68
South-facing, burned, hillslope traps:				
Summer 1997	7	4.6 ± 1.2	4.1 ± 1.7	0.85 ± 0.18
31 August 1997	1	6.2	2.3	0.52
Winter 1997-1998	1	7.6	4.8	0.24
Summer 1998	4	6.0 ± 3.5	2.8 ± 0.8	0.15 ± 0.16
Winter 1998-1999	3	9.5 ± 7.3	1.9 ± 0.8	0.08 ± 0.10
Summer 1999	2	9.4 ± 6.4	2.0 ± 0.6	0.11 ± 0.43
North-facing, unburned, hillslope traps:				
Summer 1998	4	3.3 ± 0.9	2.8 ± 0.7	0.15 ± 0.10
Winter 1998-1999	1	4.6	2.6	0.06
Summer 1999	2	4.4 ± 6.4	2.5 ± 1.3	0.08 ± 0.29
South-facing, unburned, hillslope traps:				
Summer 1998	4	3.8 ± 0.4	2.2 ± 0.4	0.20 ± 0.18
Winter 1998-1999	1	3.9	2.4	0.05
Summer 1999	2	4.1 ± 3.2	2.1 ± 0.6	0.13 ± 0.22

Particle-Size Distribution: All of the sediment collected in the traps was processed in the laboratory. In the field, the total volume of water in the buckets was measured and recorded. If the water contained suspended sediment, the water was churned in a churn splitter (Meade and Stevens, 1990) and a 1-L water subsample taken to the laboratory. The sediment was dried at 105° C and weighed to determine mass. To determine the particle-size distribution, we sieved the dry sediment by whole phi (F) intervals (F = $-\log_2$ of the particle size diameter in mm; Krumbein, 1934). In addition, when sufficient dry sediment existed, a 1-gram subsample of the <0.063 mm particle size class was settled following the methods described by Guy (1969) to determine the silt (0.004-0.063 mm) and the clay (<0.004 mm) particle-size fractions. Also, we settled the water subsample and added the mass of the silt and clay to the mass of those particle-size classes determined from the settling of the dry sediment. We calculated the median particle diameter (D_{50}) and the dispersion (s) to characterize the particle-size distribution of the eroded sediment (Table 1). The dispersion is a dimensionless number (geometric standard deviation, s =vD_{84}/D_{16}, where D_{84} and D_{16} are the diameters at which 84 percent and 16 percent of the sediment are finer than the specified diameter; Inman, 1952) that measures the spread of the particle-size distribution and is equal to 1.0 for a distribution with only one particle-size class. Curves of the particle-size distribution were fit to the data using a cubic-spline program (R.F. Stallard, USGS, written communication) for the particle size data, and 95% confidence limits (Table 1) were computed using the Student-t distribution. Figures 2A and 2B show the curves for the three summer seasons during the study period.

Sediment Flux: Sediment fluxes are reported for both the summer months (June-September) and for the winter months (October-May), based on the mass of sediment collected from the hillslope traps. Because we did not collect sediment after each storm, the data from each collection date represent the sediment moved by a variety of hillslope-transport processes. Even though we used bounded plots, we think that it is impossible to define the true contributing area from which sediment is eroded and later deposited in our hillslope sediment traps. Therefore, we chose to express our data as sediment flux rates, which we calculated as the mass of sediment transported across a unit contour (1 meter) per unit time (1 day). We multiplied the mass per bounded area by the length of the enclosure to yield mass per unit contour width and divided the result by the number of days in the accumulation period. Because sediment in the traps was not collected for the same time intervals each year, the sediment flux rate was multiplied by the number of days in the appropriate season (122 days for the summer season, 243 days for the winter season) to yield comparable seasonal fluxes (Table 1).

The 31 August 1997 storm: The storm of 31 August 1997 was notable for its greater rainfall intensity and sediment flux than any other storm during the study period. The storm lasted for about an hour, produced 48 mm of rain and had a 30-minute maximum intensity of 88 mm h^{-1}. We have reported the data separately for this date in Table 1 to highlight the episodic nature of hillslope erosion and because the rainfall intensities more closely match the intensity of the 12 July 1996 storm that produced the initial post-fire erosion in Spring Creek. The mass of sediment from the 31 August 1997 storm filled up and spilled over the hillslope traps on the north-facing, burned hillslope. Therefore, sediment fluxes for this date and for the whole 1997 summer season for the north-facing, burned hillslope can only be considered as minimum amounts.

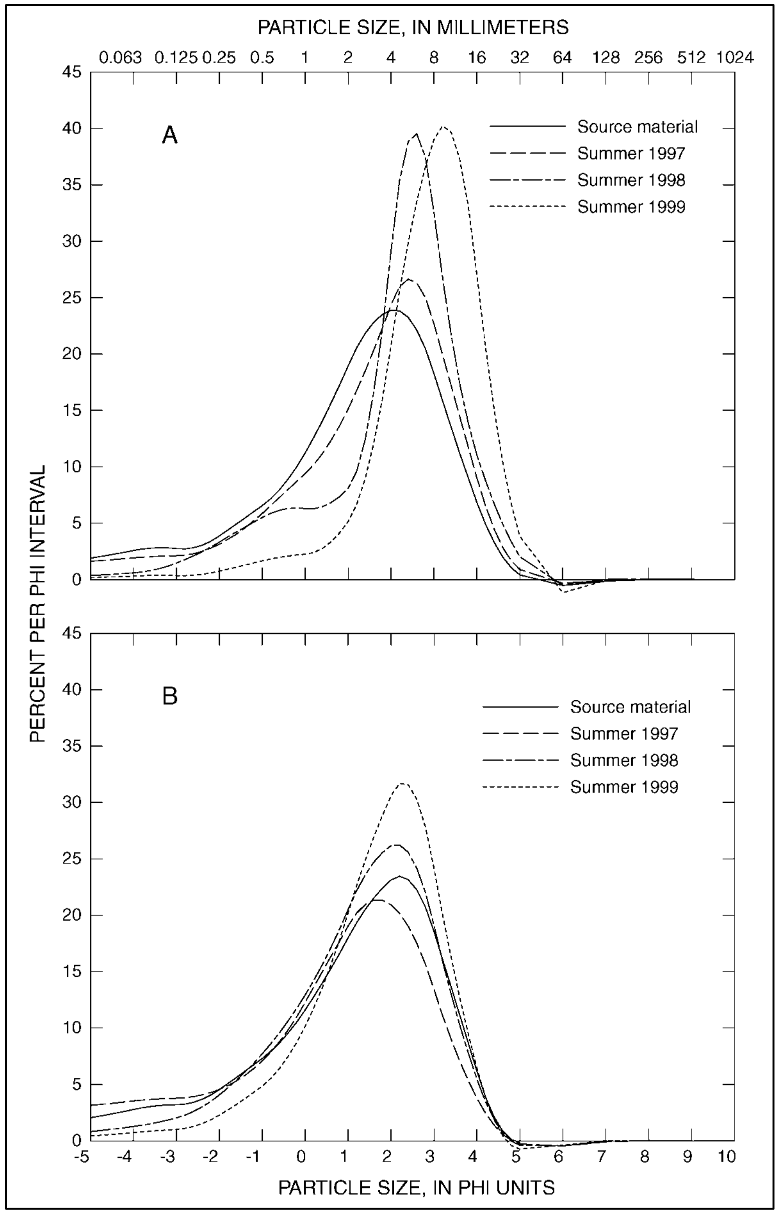

Figure 2.Particle-size distributions (summer only and source material) A. South-facing burned hillslope B. North-facing burned hillslope

RESULTS AND DISCUSSION

The Particle-Size Distribution: For samples collected from the burned hillslopes, we measured coarser particle sizes in the summer of 1999 (D_{50}=4.1 mm for north-facing, D_{50}=9.4 mm for south-facing) than in the summer of 1997 or 1998 (Table 1), even though the maximum rainfall intensities decreased during the study period. We have two hypotheses to explain the shift to coarser particle sizes. The coarsening (Figure 3A) may be the result of a diminished supply of the finer-grained material. Some of the finer material was eroded from the watershed during the 1996 storms after the wildfire, as evidenced by post-flood deposits of ash and fine-grained sediment in Strontia Springs Reservoir and downstream of the Strontia Springs Reservoir dam, and during 1997 as evidenced by sediment collected in the hillslope traps (see 1997 dashed curve in Figure 2A). Alternatively, there may be a

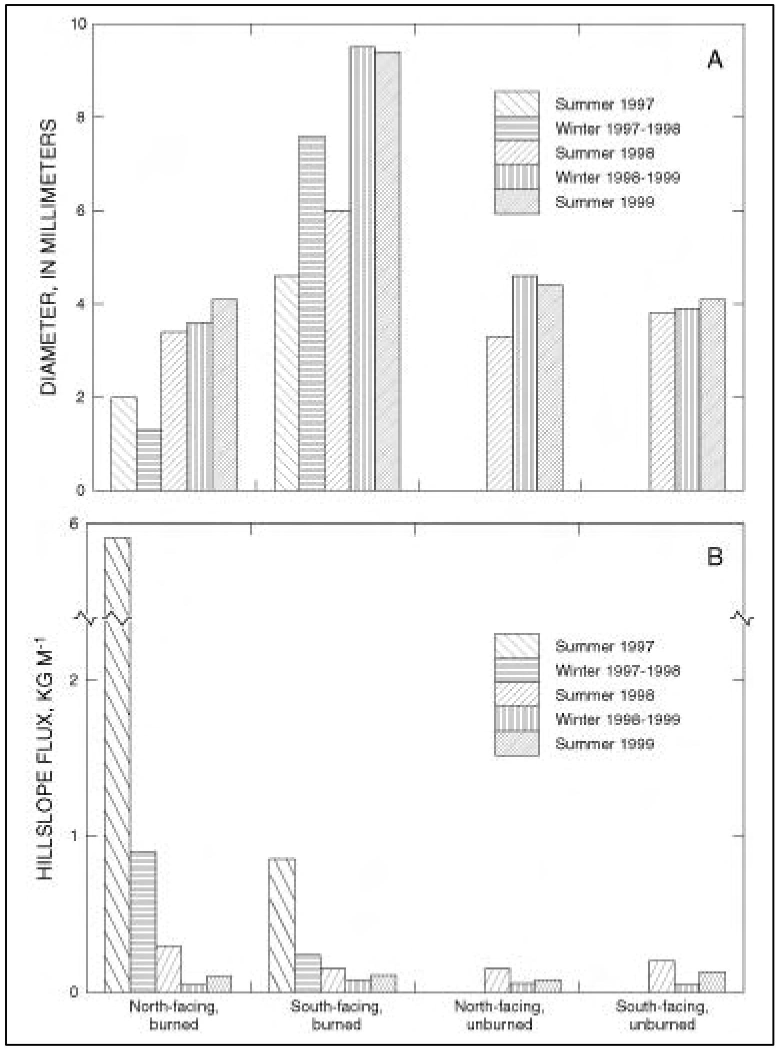

Figure 3. Seasonal change in median particle diameter and hillslope sediment flux in the Spring Creek watershed. A. Median particle diameter of eroded sediment collected in hillslope traps during summer (June-September, 122 days) and winter (October-May, 243 days) seasons. B. Hillslope flux for summer (June-September, 122 days) and winter (October-May, 243 days) seasons. Hillslope traps were not deployed in the unburned area until 1998.

preferential transport of coarser material with time after the fire, possibly by the dry ravel process. The decrease in the dispersion with time (Table 1) on both the north-facing and south-facing burned hillslopes during the summer seasons may be an indication of the increase in importance of the dry ravel. In this climate, dry ravel is mainly triggered by wind and disturbance by fauna (lizards, snakes, crickets, grasshoppers, and mice, all of which we inadvertently caught in our hillslope erosion traps). We observed that as the surface of both the unburned hillslopes and burned hillslopes became dry, it became increasingly difficult to walk on the surface. Coarse-grained material (>4 mm diameter) acted as ball bearings while the fine-grained material was more cohesive and had hardened. In agricultural areas, Young and Onstad (1976) also found that sand-sized material was enriched in eroded material in interrill areas, but this result differs from the findings of Meyer et al. (1975), Monke et al. (1977), and Alberts et al. (1980).

The eroded sediment from the south-facing, burned hillslope was coarser during each season than the sediment from the north-facing burned slope (Table 1 and Figure 3A). The relative coarseness of the eroded sediment from the burned south-facing hillslope compared to the north-facing burned hillslopes and the unburned hillslopes may be a reflection of both the hillslope vegetation cover and the prior removal of fine-grained sediment discussed above. As the south-facing, burned slope is recovering, there has been a regrowth of the bunch grasses that existed before the wildfire. Even under unburned conditions, bare hillslopes are exposed between the bunch grasses. Field observations suggest that these bare spots are more susceptible to dry ravel and disturbance than are vegetated hillslopes. The previous loss of the fine-grained material would reduce the soil cohesion and allow more coarse-grained material to erode. In contrast, the north-facing, burned hillslopes have developed a dense cover of herbaceous vegetation (including creeping dogbane, *Apocynum androsaemifolium*, sugarbowl, *Clematis hirsutissima*, and leafy spurge, *Euphorbia esula*) as they have recovered during the three years of our study. Based on observations of the north-facing, unburned hillslopes, it is clear that before the fire the north-facing hillslopes had very little understory vegetation because of competition for light and nutrients under the closed, mainly Douglas-fir canopy. The thick vegetation cover on the recovering north-facing, burned hillslopes may be stabilizing the coarser-grained material.

Sediment flux: The pattern of sediment flux was similar on burned and unburned hillslopes beginning in the summer of 1998 (Figure 3B). By the summer of 1999, all four hillslopes have similar sediment fluxes. The flux of sediment from the north-facing, burned hillslope was greater than from the south-facing, burned hillslope through the summer of 1998. We hypothesize that the pre-fire vegetation density on the north-facing slope may account for this behavior. The fuel loading on the north-facing hillslopes (mainly densely spaced Douglas-fir with a thick duff layer) was greater than the south-facing hillslope and the burned north-facing soils were more water-repellent (Jeff Bruggink, USFS, written communication; for a more complete discussion of fire-induced water repellency see DeBano, 1969; Debano et al., 1977; Giovannini et al., 1983). The greater water repellency on the north-facing burned hillslopes probably created greater runoff that, in turn, caused greater erosion. Also, the thick litter and duff layer on the north-facing hillslopes could have held sediment that is easily mobilized once the litter and duff were burned off (P.M. Wohlgemuth, USFS, written communication). As herbaceous groundcover grows, the sediment is increasingly stabilized.

CONCLUSIONS

We found that the flux of sediment decreased and the median diameter of eroded sediment increased from burned hillslopes in Spring Creek watershed during the three years following the Buffalo Creek Fire. It took three years for fluxes of sediment from burned hillslopes to return to rates of unburned hillslopes, which and is within the range (3-9 years) of other studies of burned areas in other soils and terrains (Rowe et al., 1949, 1954; Doehring, 1968; Brown, 1972; Wells et al., 1979; Laird and Harvey, 1986; Wells, 1986; Potyondy and Hardy, 1994). In addition, the sediment fluxes that we have documented during the first three years after the wildfire are comparable to values, 2.9-4.0 kg m^{-1}, measured by Morris and Moses (1987) for another Colorado Front Range wildfire. Although fluxes from the burned hillslopes appear to have returned to rates in unburned areas, as of August 2000 considerable sediment was stored in tributaries and in the main channel of Spring Creek. This stored sediment may be a long-term supply of sediment to the downstream water-supply reservoir or it may be stabilized by riparian vegetation until another erosional cycle is initiated by wildfire or another disturbance (Moody and Martin, unpublished data). We are continuing to monitor hillslope fluxes and stored channel sediment to provide data to support land management decisions.

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