THESIS

CONTROLS ON POST-FIRE EROSION AT THE HILLSLOPE SCALE, COLORADO FRONT RANGE

Submitted by

Joseph H. Pietraszek

Department of Forest, Rangeland, and Watershed Stewardship

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2006

COLORADO STATE UNIVERSITY

April 4, 2006

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JOSEPH H. PIETRASZEK ENTITLED CONTROLS ON POST-FIRE EROSION AT THE HILLSLOPE SCALE, COLORADO FRONT RANGE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

John D. Stednick

Jorge Ramirez

Lee MacDonald, Adviser

N. Thompson Hobbs, Department Head

ABSTRACT OF THESIS

CONTROLS ON POST-FIRE EROSION AT THE HILLSLOPE-SCALE, COLORADO FRONT RANGE

Post-fire erosion can have adverse affects on aquatic ecosystems and downstream resources. While several studies in the Colorado Front Range have documented increased erosion rates after wildfire, few studies have quantified the factors and processes that control post-fire erosion rates over time. The goal of this study was to quantify the key controls on hillslope-scale sediment yields at 10 fires of varying ages in the Colorado Front Range. Sediment yields were measured with sediment fences for 2-4 years to yield 31 fire years and 255 plot years of data. Independent variables such as percent cover, contributing area, slope, soil texture, aspect, and precipitation were measured and a series of regression models were developed to predict sediment yields. Rill incision rates were measured at 94 cross-sections in 14 swales at the 2002 Hayman and Schoonover fires, and these values were converted to a mass and compared to measured sediment yields.

Sediment yields were highly variable because short-duration, episodic summer thunderstorms were the primary mechanism for initiating overland flow and erosion. In the first two years after burning the mean sediment yield from high severity plots was 8.8 Mg ha^{-1} yr^{-1} (s.d.=7.6 Mg ha^{-1} yr^{-1}), or about two orders of magnitude above the estimated background rate. Sediment yields declined markedly by the third year after burning, but complete recovery was not evident at all high severity plots until the fifth year after burning. Sediment yields from the moderate and low severity plots were typically an order of magnitude less than the high severity plots. The differences with burn severity and the decline in sediment yields over time are attributed to the amount of residual cover and vegetative regrowth, as percent bare soil explained 58% of the variability in the logarithm of annual sediment yields. A 2-parameter model using percent bare soil and rainfall erosivity best predicted the validation dataset with a RMSE of 0.65 log (kg) units.

Topographic convergence was a key control on sediment yields at recent fires. At the 2002 Hayman fire, unit-area sediment yields were 3-4 times higher from convergent hillslopes (swales) than planar hillslopes, and 60-80% of the collected sediment from convergent hillslopes is attributed to rill erosion in the swale axes. An empirical model using contributing area times local slope explained 64% of the variability in rill incision rates. The results suggest that rill erosion in localized convergent zones is the primary sediment source for hillslope scale, post-fire erosion in the Colorado Front Range. The process-based understanding developed in this study can be used to predict post-fire erosion and guide post-fire rehabilitation programs in the Colorado Front Range.

Joseph H Pietraszek
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2006

ACKNOWLEDGEMENTS

I would first like to acknowledge the considerable time and effort that my academic advisor, Dr. Lee MacDonald, put forth to improve the quality and content of this thesis. I owe Dr. MacDonald a debt of gratitude for his support of my research and education at Colorado State University. I would also like to thank my other committee members, Dr. John Stednick and Dr. Jorge Ramirez, for their patience while waiting for me to finish writing.

Dr. Juan Benavides-Solorio collected the first 2 years of data presented in Chapter 2, then allowed me to continue monitoring his field sites when I began my research. Juan's generosity and helpful advice is sincerely appreciated. On a similar note, Daniella Rough allowed me to use her data from her control plots in the Hayman and Schoonover fires, and Zamir Libohova graciously allowed both Daniella and I to continue to monitor his plots in the Hayman fire. Many fellow colleagues helped in the field, including: Ben Snyder, Dan Woolley, Duncan Eccleston, Ethan Brown, Isaac Larsen, Joe Wagenbrenner, Jon Wagner, and Joey Willeke. Because of them I will always remember those brutal days shoveling sediment with fondness.

Finally, this research was made possible through grants funded through the United States Forest Service. Carl Chambers of the Arapaho-Roosevelt National Forest, and Steve Culver and Deborah Entwistle of the Pike-San Isabel National Forest were instrumental in providing access and valuable information.

TABLE OF CONTENTS

CONTROLS ON POST-FIRE EROSION AT THE HILLSLOPE SCALE, COLORADO FRONT RANGE

1. INTRODUCTION

In unburned forests, overland flow on hillslopes is rare because vegetation and litter protect the soil surface and facilitate the rapid infiltration of rainfall (e.g., Dunne and Leopold, 1978). Although wildfires are a natural disturbance to forested ecosystems (e.g., Agee, 1993), there is a dramatic decline in infiltration rates after a wildfire because the vegetative cover is removed and the soil structure is physically altered (e.g., Burch *et al*., 1989; Robichaud, 2000; Pierson *et al*., 2001; Martin and Moody, 2001). Decreased infiltration shifts the dominant runoff process from subsurface flow to infiltration-excess overland flow (Simanton *et al*., 1990; Robichaud and Waldrup, 1994). The combination of rainsplash and overland flow on soils with reduced aggregate stability and low surface cover can increase soil erosion rates by several orders of magnitude over background levels (e.g., Helvey, 1980; Inbar *et al*., 1998; Robichaud *et al*., 2000; Benavides-Solorio and MacDonald, 2001).

Over the past 100 years, fire suppression in the Colorado Front Range has altered natural fire patterns, particularly in ponderosa pine (*Pinus ponderosa*) and mixed conifer forests. This has led to increased fuel densities (Kaufmann *et al*., 2000; Kaufmann *et al*., 2001; Huckaby *et al*., 2001). As a result, modern wildfires may burn more intensely, leading to higher burn severities over larger areas than under pre-settlement conditions

(Romme *et al*., 2003). Post-fire flooding and erosion are a growing concern in the Colorado Front Range due to the increased risk of catastrophic wildfire and growing human populations in the low elevation forests that are prone to fire. Following the 1996 Buffalo Creek fire, for example, flooding and sedimentation caused two deaths and dramatically reduced the capacity of a reservoir that supplies drinking water to Denver (Agnew *et al*., 1997; Moody and Martin, 2001a).

Steep slopes, poorly aggregated soils, and high-intensity summer thunderstorms leave forested ecosystems in the Colorado Front Range particularly susceptible to erosion. High post-fire erosion rates have been attributed to the formation of a water repellent layer, loss of surface cover, and rainfall intensity (Moses, 1982; Morris and Moses, 1987; Moody and Martin, 2001a; Benavides-Solorio, 2003). Accelerated erosion rates appear to persist for 2-4 years after burning (Moody and Martin, 2001a; Benavides-Solorio, 2003), but there are a lack of data that extend from immediately after burning through hydrologic recovery.

Summer thunderstorms in the Colorado Front Range are episodic, short-duration events that are extremely variable over space and time (e.g., Gary, 1975). The variability in rainfall magnitude and occurrence has tremendous influence on post-fire erosion rates and can lead to large differences in sediment yields between plots with similar physical characteristics (Benavides-Solorio, 2003). Severe erosion from intense rainfall events at recent fires has been documented (Moody and Martin, 2001a; Benavides-Solorio, 2003), but the precise relationship between storm magnitude and post-fire erosion is largely unknown. Additional data are needed to document how the erosional response varies with storm magnitude, time since burning, fire severity, and other site characteristics.

There also are a lack of data on hillslope-scale erosion processes immediately after a high severity fire. At the Buffalo Creek fire, it was estimated that 80% of the eroded sediment in two 4-7 ha watersheds was derived from gully and channel erosion (Moody and Martin, 2001a). This suggests that concentrated overland flow in channels is the dominant erosion process in small basins. On convergent hillslopes or zero-order basins (termed swales in this study), overland flow concentrates in the swale axes and leads to the incision of small channels or rills. Similar incision processes have been observed on cultivated hillslopes (e.g., Slattery *et al*., 1994), and this incision is believed to cause the 2-3 fold difference in erosion rates between planar and convergent hillslopes or swales noted by Benavides-Solorio, 2003. However, the precise contribution of rill erosion to hillslope-scale sediment yields is not known. A more detailed understanding of erosion processes is needed to better predict post-fire erosion risk, and develop more effective post-fire rehabilitation treatments.

The results of this thesis are presented in two parts. Chapter 2 reports hillslope-scale sediment yields from 10 different fires of varying ages. Some portions of this study began in 2000 (Benavides-Solorio, 2003). This thesis adds data from four additional fires and two more years of data from the older fires. The complete dataset includes four fires that were monitored from a few weeks after burning through hydrologic recovery. This eliminates the need to substitute space for time and assuming comparability between fires of different ages. The specific objectives of this portion of the study were to: (1) define the dominant factors that control post-fire erosion rates over time, and (2) develop and test a series of models for predicting post-fire erosion rates in the Colorado Front Range.

Chapter 3 presents a more intensive study of hillslope-scale erosion processes immediately after two high severity wildfires. The objective was to quantify the role of rill incision on sediment yields after high severity wildfires. This includes measurements of rill incision rates at 94 cross-sections in 14 swales, and a comparison of sediment yields from planar hillslopes and swales. The results identify the primary sediment source areas on severely burned hillslopes. This information can help design more accurate erosion prediction models and more effective techniques to reduce post-fire erosion.

Taken together, the two chapters provide a much more explicit understanding of post-fire erosion processes in the Colorado Front Range. The models and process-based understanding can be used by land managers to develop more effective post-fire rehabilitation programs and evaluate longer-term management options. Future researchers can use this dataset to develop and validate complex, physically-based models.

1.2. REFERENCES

Agee, J.K., 1993. Fire ecology of Pacific Northwest forests. Island Press. Washington, D.C., 493 p.

Agnew, W., R.E. Labn, and M.V. Harding, 1997. Buffalo Creek, Colorado, fire and flood of 1996. *Land and Water* 41: 27-29.

Benavides-Solorio, J., 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. dissertation, Colorado State University, Fort Collins, CO, 218 p.

Benavides-Solorio, J., and L.H. MacDonald, 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* 15: 2931-2952.

Burch G.J., I.D. Moore, and J. Burns, 1989. Soil hydrophobic effects on infiltration and catchment runoff. *Hydrological Processes* 3: 211–222.

Dunne, T., and L.P. Leopold, 1978. Water in environmental planning. W.H. Freeman and Company. New York, NY, 818 p.

Gary, H.L., 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine zone: the status of our knowledge. USDA Forest Service Research Paper, RM-139. Fort Collins, CO, 32 p.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* 16: 627-634.

Huckaby, L. S., M. R. Kaufmann, J. M. Stoker, and P. J. Fornwalt. 2001. Landscape patterns of montane forest age structure relative to fire history at Cheesman Lake in the Colorado Front Range. In *Ponderosa pine ecosystems restoration and conservation: steps toward stewardship*, Vance, R.K., Edminster, C.B., Covington, W.W., and Blake, J.A., (eds.). USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-22. Fort Collins, CO, p. 19-27.

Inbar M., M. Tamir, and L. Wittenberg, 1998. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. *Geomorphology* 24: 17-33.

Kaufmann, M. R., L. S. Huckaby, and P. Gleason, 2000. Ponderosa pine in the Colorado Front Range: long historical fire and tree recruitment intervals and a case for landscape heterogeneity. In *Crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management,* Neuenschwander, L.F. (ed). University of Idaho and International Association of Wildland Fire. Moscow, ID, p. 153-160.

Kaufmann, M.R., P.J. Fornwalt, L.S. Huckaby, and J.M. Stoker, 2001. Ponderosa pine reconstruction: comparisons with historical data. In *Ponderosa pine ecosystems restoration and conservation: steps toward stewardship*, Vance, R.K., Edminster, C.B., Covington, W.W., and Blake, J.A., (eds.). USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-22. Fort Collins, CO, p. 19-27.

Martin, D.A., and J.A. Moody, 2001. Comparison of soil infiltration rates in burned and unburned mountainous watersheds. *Hydrological Processes* 15: 2893-2903.

Moody, J.A., and D.A. Martin, 2001a. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26: 1049-1070.

Moody, J.A., and D.A. Martin, 2001b. Post-fire rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes* 15: 2981-2993.

Morris, S.E., and T.A. Moses, 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* 77: 255-264.

Moses, T.A, 1982. Erosional response of hillslopes after forest fire in the Colorado Front Range. M.S. thesis, University of Colorado, Boulder, CO, 217 p.

Pierson, F.B., P.R. Robichaud, and K.E. Spaeth, 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrologic Processes* 15: 2905-2916.

Robichaud, P.R., T.A. Waldrop, 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resources Bulletin* 30: 27-34.

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. *Journal of Hydrology* 231: 220-229.

Robichaud, P.R., J.L. Beyers, and D.G. Neary, 2000. Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service, General Technical Report RM-GTR-63. Fort Collins, CO, 85 p.

Romme, W.H., T.T. Veblen, M.R. Kaufman, R. Sheriff, and C.M. Regan, 2003. Ecological effects of the Hayman fire. In *Hayman Fire Case Study*, Graham, R.T. (ed.). USDA Forest Service, General Technical Report RMRS-GTR-114. Fort Collins, CO, 396 p.

Simanton, J.R., G.D. Wingate, and M.A. Weltz, 1990. Runoff and sediment from a burned sagebrush community. USDA Forest Service General Technical Report RM-191. Fort Collins, CO, p.180-185.

Slattery, M.C., T.P. Burt, and J. Boardman, 1994. Rill erosion along the thalweg of a hillslope hollow: a case study from the Cotswold Hills, Central England. *Earth Surface Processes and Landforms* 19: 377-385.

2. MEASURING AND PREDICTING POST-FIRE EROSION AT THE HILLSLOPE SCALE, COLORADO FRONT RANGE

2.1. ABSTRACT

Post-fire erosion in the Colorado Front Range can have adverse effects on aquatic resources and property, but there are few data on the processes controlling post-fire erosion rates either immediately after burning or over time. Hillslope-scale erosion rates were measured with sediment fences on 10 fires of varying ages in the Colorado Front Range from 2000-2003, resulting in 255 plot years of data. Rainfall, ground cover, contributing area, slope, aspect, and soil texture were measured at each plot, and a series of empirical predictive models were developed.

Over 90% of the annual sediment yield was generated from summer convective thunderstorms from June to October. The mean sediment yield was 6.7 Mg ha^{-1} and 10.7 Mg ha^{-1} for all high severity plots in the first and second year after burning, respectively. Sediment yields declined markedly at most plots by the third summer after burning, as the mean value was just 0.57 Mg ha^{-1}. This decline is attributed to vegetative regrowth and the corresponding decrease in the amount of bare soil. Sediment yields from moderate and low severity plots were typically an order of magnitude lower than from high severity plots, and this difference also is attributed to higher amounts of litter and vegetative cover.

The best multivariate model had nine significant parameters and explained 83% of the variability in hillslope-scale sediment yields. Percent bare soil was the dominant independent variable with a partial R^2 of 0.58. A 2-parameter model using percent bare soil and rainfall erosivity had an R^2 of 0.63, and most accurately predicted the sediment yields for the validation dataset (RMSE=0.65 log units). The results provide a quantitative assessment of the different factors controlling post-fire erosion in the Colorado Front Range, recovery rates over time, and guidance for land managers.

2.2. INTRODUCTION

Wildfires are a natural disturbance in forested ecosystems in the western United States (e.g., Agee, 1993). In many forests, fire suppression has altered natural fire patterns and increased fuel densities (Agnew *et al*., 1997; Kaufman *et al.*, 2000; Kaufman *et al.*, 2001). As a result, modern wildfires may burn more intensely, leading to higher burn severities over larger areas than under pre-settlement conditions (Romme *et al*., 2003).

Wildfires alter the hydrologic regime by removing vegetation and altering the chemical (DeBano, 2000) and physical properties of soils (Kilinc, 1968; Wells *et al,* 1979; Wells, 1981; DeBano *et al.*, 1998). This results in decreased infiltration (Burch *et al*., 1989; Robichaud, 2000; Pierson *et al*., 2001) and increased overland flow (Simanton *et al*., 1990; Robichaud and Waldrup, 1994). The incineration of organic matter and fire-induced alterations to the soil structure results in decreased aggregate stability (Tiedemann *et al*., 1979; DeBano *et al.*, 1998).

The combined effect of rainsplash, increased overland flow, reduced aggregate stability, and reduced surface roughness can increase soil erosion rates by one or more orders of magnitude over background levels (e.g., Helvey, 1980; Wells, 1981; Morris and Moses, 1987; Robichaud *et al*., 2000; Benavides-Solorio and MacDonald, 2001; Moody and Martin, 2001a; Benavides-Solorio, 2003). Sedimentation of streams and reservoirs after wildfire can cause long-term degradation of water quality and aquatic ecosystems (e.g., Agnew *et al*., 1997).

Fire severity is an important control on post-fire erosion (e.g., Robichaud and Waldrup, 1994). Areas burned at high severity have more exposed bare soil (Wells *et al.*, 1979) and stronger soil water repellency (Huffman *et al.*, 2001) than areas burned at moderate or low severity. In moderate and low severity areas, the canopy cover remains at least partially intact and the resulting needlecast helps protect the soil surface and reduce post-fire erosion rates (Pannkuk and Robichaud, 2003). In the Colorado Front Range, erosion rates from plots burned at high severity are roughly an order of magnitude higher than erosion rates at plots burned at either moderate or low severities, and this has been attributed to the lower amount of ground cover in areas burned at high severity (Benavides-Solorio and MacDonald, 2005).

Ground cover limits soil erosion by preventing the detachment of soil particles by rainsplash, reducing overland flow velocities, and creating areas for sediment storage (e.g., McNabb and Swanson, 1990). The effect of ground cover on erosion rates is well established on mechanically disturbed soils (e.g., Brown and Norton, 1994), but few data are available for burned areas. Data on the change in ground cover over time are needed to predict post-fire erosion risks over time and design effective post-fire rehabilitation treatments.

In the Colorado Front Range, post-fire erosion is largely driven by convective summer thunderstorms (Moody and Martin, 2001b), which are extremely variable over space and time (Gary, 1975). Rain intensities of 10 mm hr^{-1} can initiate infiltration-excess overland flow from areas that recently burned at high severity. Beyond this threshold runoff and sediment yields increase sharply with increasing rainfall intensities (Moody and Martin 2001a; Kunze, 2003), but the exact relationship between rainfall and hillslope-scale sediment yields is poorly understood. Of particular concern is whether erosion rates increase linearly or nonlinearly with increasing rainfall intensities, and how the effect of a given rainfall varies over time as ground cover increases. Given the sporadic nature of summer thunderstorms and the spatial variability in sediment yields, data from multiple fires are needed to assess this relationship.

In 2000 a study was initiated at 48 plots on 6 fires of varying ages in the Colorado Front Range. Monitoring continued over 2 summers and one winter (Benavides-Solorio, 2003). In 2002 the study was expanded to include 47 plots from four additional fires, and data collection was continued through 2002 and 2003. This allowed sediment yields at four fires to be tracked from immediately after burning through hydrologic recovery. The overall goal was to develop a comprehensive understanding of the processes controlling hillslope scale post-fire erosion rates. The specific objectives of this study were to: (1) assess the relative importance of different site variables in controlling post-fire erosion rates; (2) quantify the reduction in post-fire sediment yields over time; and (3) develop and test models for predicting post-fire erosion.

2.3. METHODS

2.3.1. Site Descriptions

Hillslope-scale sediment yields were measured at 7 wildfires and 3 prescribed fires of varying ages in the Colorado Front Range from summer 2000 through summer 2003 (Table 1, Figure 1). Monitoring began in the first summer after burning at 6 fires. The remaining 4 fires were 1 to 6 years old at the beginning of the monitoring period (Table 1). For clarity, fires are also referred to as sites and individual sites within fires are termed plots. Hence the primary data set consists of results from 31 site years and 255 plot years.

The ten fires were between 2000 and 3500 m a.s.l. in the northern and central Colorado Front Range (Figure 1). Precipitation generally increases with elevation in the Colorado Front Range, and the estimated mean annual precipitation for the different study sites ranges from about 380 to 500 mm yr^{-1} (Hershfield, 1961; Gary 1975; Gary 1985). Precipitation falls mainly as snow in the winter, and as a mix of rain and snow in the spring and fall. Most of the precipitation in summer (defined here as 1 June to 31 October) comes in the form of short-duration, high-intensity convective rainstorms (Gary 1975).

The primary vegetation type was ponderosa pine (*Pinus ponderosa*) at lower elevations and lodgepole pine *(Pinus contorta*) at higher elevations. On north-facing slopes at lower elevations Douglas-fir (*Pseudotsuga menziesii*) was commonly intermixed with the ponderosa pine. Spruce-fir (*Picea-engelmanii-Abies lasiocarpa*) was the primary vegetation type in the relatively high elevation Bear Tracks fire.

Study plots were stratified into high, moderate, or low severity classes following the criteria developed by Wells *et al.* (1979) and applied by the USDA Forest Service (1995). In high severity plots the surface organic layer of the soil is completely burned and the color and structure of the mineral soil are physically altered. In moderate severity plots the organic layer is mostly consumed, but the mineral soil surface is not visibly altered. In low severity areas the organic layer is only scorched or partially consumed (USDA, 1995). Most of the study plots were in areas that had burned at high severity because these areas are of highest concern for post-fire erosion (Table 1).

2.3.2. Sediment Yields

Sediment fences (Robichaud and Brown, 2002) were used to measure sediment yields from 95 hillslope-scale plots. Forty-two plots were on planar hillslopes and 53 plots were in swales. For this study swales are defined as zero-order catchments with two converging hillslopes and a central axis. Generally the swales were unchanneled prior to burning (Libohova, 2004). Typically one fence was built perpendicular to the slope at each site, but in the larger swales two or three fences were built to increase the sediment storage capacity and reduce the risk of sediment loss by overtopping (Figure 2).

The sediment fences were constructed by hammering 5-15 pieces of 1-1.2 m long rebar about 0.5 m into the ground. Silt fence fabric was attached to the rebar and additional fabric was placed over the ground in front of the fence to facilitate the identification and removal of the captured sediment. The fences were constructed so that excess water or sediment flowed over the middle of the fence rather than around the edges. The eroded sediment was removed from each fence with a 20 L bucket and weighed to the nearest 1/4 kg. Fences were emptied each spring at the end of the snowmelt season and as needed during the summer thunderstorm season. An aggregated 1 kg sample was taken from the collected sediment to determine the gravimetric water content (Gardner, 1986), and the field-measured sediment weights were corrected for water content to yield a dry mass. The typical storage capacity of a single fence was about 1-2 Mg of dry sediment.

To the extent possible, the sediment was collected after individual storm events or sets of storms at the Bobcat, Hayman, and Schoonover fires. The sediment fences at most of the older and more remote sites were checked less frequently. Therefore the most complete data set consists of summer and winter sediment yields, and these were summed to obtain annual sediment yields for each site. The age of each fire was calculated to the nearest month for statistical analyses (e.g., a fire that burned in July would be 0.3 years old by October). For simplicity, the first year after burning refers to any fire that is less than 1 year old during the summer; the number of years corresponds to the number of summer rainfall seasons that the fire has experienced since burning.

2.3.3. Site Characteristics

Slopes were measured from the sediment fence to the ridgetop or topographic divide with a hand-held clinometer, except for twenty plots in the Hayman fire where the contributing area was surveyed with a total station. The mean slope at all plots was 31% (s.d.=11%), and the range was from 13% to 82%.

The contributing area at most plots was determined by surveying the perimeter with either a GPS or a total station, but the contributing areas of eight small plots (~100

m^2) in the Hayman fire were determined by measuring their lengths and widths with a flexible tape. The mean contributing area at all plots was 1440 m^2 (s.d.=1390 m^2) and the range was from 40 m^2 to 6630 m^2. The aspect was measured at the center or axis of each plot with a hand-held compass. Study plots were situated at all aspects, but the overall mean was 150° (s.d.=107°).

Soil textures ranged from very coarse sands to sandy loams, and soil types ranged from Typic Argicryolls to Ustic Haplocryalfs (E. Kelly, Colorado State University, pers. comm., 2002). The primary parent materials were schist, gneiss, and granite (Table 1).

2.3.4. Precipitation

Tipping-bucket rain gages were used to monitor rainfall. Multiple gages were used in the larger fires so that all plots were within approximately 1 km of a rain gage (Table 2). The resolution of the rain gages was either 0.20 mm or 0.25 mm, except for the Green Ridge gage in the Bobcat fire and the Squaw Mountain gage near the Bear Tracks fire, which had a resolution of 1.0 mm. For 2002 and 2003, the rainfall at the Bear Tracks fire was determined from the Squaw Mountain rain gage, which is approximately 15 km northeast of the Bear Tracks site. The Lower Flowers gage, which was approximately 8 km south of the Hourglass site, was used in place of the Hourglass gage after the Hourglass gage failed in late summer 2002.

Summer rainfall records were considered complete if the gage was operational for all but 7 days of the summer rainfall season (defined as 1 June-31 October). Over the four years of monitoring, 25 rain gages had a complete summer record, while fourteen rain gages had mechanical failures. In these cases the data from a nearby gage was substituted for the missing period of record, or the rainfall and sediment data were omitted from the analyses. Three rain gages occasionally recorded two tips in the same second, and these erroneous tips were individually identified and deleted.

Rainfall depth, duration, and maximum 30-minute intensity (I_{30}) were determined for each storm during the summer rainfall season. Precipitation events were considered discrete storms if they were separated by at least 60 minutes without any rainfall. Rainfall erosivities were calculated for each storm greater than 5 mm by multiplying the maximum I_{30} times the total kinetic energy (E_m) of the storm (Brown and Foster, 1987; Renard *et al*., 1997). E_m (MJ ha^{-1}) was calculated for each five-minute interval by:

$$E_m = 0.29 \times \left(1 - 0.72^{(-0.05I)}\right) \quad (1)$$

where I (mm hr^{-1}) is the 5-minute intensity. The total kinetic energy for each storm was the sum of the E_m values. Multiplying by the maximum I_{30} yielded the storm erosivity, and the erosivities for each storm were summed to obtain the total erosivity for each gage for the period of interest.

2.3.5. Soil Particle-size Analysis

Approximately 50 g of soil was collected from a depth of 0-5 cm at 5-10 locations within the contributing area of each site. These samples were aggregated, dried following Gardner (1986), and used to determine the soil texture at each site. The first step in the soil particle-size analysis was to remove the organic matter from each sample by heating for 6 hours at 400° C (Cambardella *et al*., 2001). Particles larger than 2 mm were separated by sieving and weighed. The particle-size distribution of the fraction finer than 2 mm was determined with the hydrometer method (Gee and Or, 2002). The coarse and fine fraction data were combined to calculate the percent of mass greater than 2 mm, and the size of the 84th, 50th, and 16th percentiles (D_{84}, D_{50}, and D_{16}, respectively) (Scott, 2000). The percent of sand, silt, and clay also were used to classify the soil texture.

2.3.6. Surface Cover

Percent surface cover was determined from point counts within the contributing area of each plot using a method similar to Parker (1951). The length of the contributing area from the sediment fence to the ridgetop was measured to estimate the number of horizontal transects that would be needed to obtain at least 100 sample points. Typically 5-10 equally spaced transects were established, and a flexible tape was laid across the plot at each transect. Surface cover was classified as bare soil, ash, live vegetation, litter, woody debris greater than 1 cm in diameter, rock (>5cm), tree, or moss at 1-2 m intervals from a randomly determined starting point. Percent ground cover was calculated by 100 minus the percent bare soil plus ash.

Surface cover was assessed in mid-summer at each plot in both 2000 and 2001 at the Bear Tracks, Bobcat, Crosier Mountain, Dadd Bennett, Hourglass, and Lower Flowers fires. In 2002 surface cover was measured in both the spring and fall for each plot in these six fires. Only one cover count was conducted in the Big Elk, Hayman, Hewlett Gulch, and Schoonover fires in 2002 because these plots were established after 1 July. In 2003 ground cover was assessed in the spring and fall at all sites. Spring and fall cover values were averaged to obtain the summer values used in the statistical analyses.

2.3.7. Statistical Analysis

Sediment yields were positively correlated with contributing area at the recent fires that produced large amounts of sediment. The spatial variability in rainfall intensities meant that this relationship was strongest for plots in close proximity (Figure 3). Given the dependence of sediment yields on contributing area, the sediment data were normalized by contributing area for most of the analyses. Mean sediment yields were calculated as an area-weighted average. Sediment yields were log-transformed to stabilize the variance and better approximate a normal distribution (Ott and Longnecker, 2001).

One-way ANOVA was used to test for differences in sediment yields, percent ground cover, and soil texture between fires. Univariate and multivariate regression analyses were used to assess the relationships between the independent variables and sediment yields. Twenty-five of the 255 plot years of data were omitted from the regression models due to overtopped fences or incomplete rainfall records.

The multivariate analysis included 13 independent variables, and a primary model was developed using Mallow's best C(p) model selection in the REG procedure in SAS (SAS Institute, 2001). Interaction terms were added to this primary model based on known physical interactions. Variables and interaction terms were included if they were significant at $p \leq 0.05$, but each component of a significant interaction term also was included to maintain a hierarchical framework regardless of their significance (P. Chapman, Colorado State University, pers. comm., 2004). A series of progressively simpler models were developed to determine the relative influence of key variables, and because simpler models are more likely to be used by researchers and land managers when detailed site data are not available.

The data set was randomly split in half with one half used to select and parameterize the models, and the other half used for validation. The fit of each model was evaluated during calibration and validation by calculating the sum of the squared errors (SSE) using equation 2 and the root mean square error (RMSE) using equation 3:

$$SSE = \sum (Y_{obs} - Y_{pred})^2 \quad (2)$$

$$RMSE = \sqrt{(Y_{obs} - Y_{pred})^2} \quad (3)$$

where Y_{obs} is the observed log-transformed sediment yield (kg m^{-2}), and Y_{pred} is the predicted log-transformed sediment yield (kg m^{-2}). The standard error of the prediction (SEP) was calculated for each model by:

$$SEP = \sqrt{\left(\frac{\sum (Y_{obs} - Y_{pred})^2}{n - p}\right)} \quad (4)$$

where n is the number of observations and p is the number of parameters (Salas and Smith, 1999).

2.4. RESULTS

2.4.1. Sediment Yields

Approximately 90-95% of the collected sediment was generated by summer rainfall events rather than the mix of snowmelt and frontal rainstorms that occur from 1 November to 31 May (Figure 4). An exact separation between rainfall and snowmelt is impossible because storms in the spring and fall often shift between rain and snow. Field observations showed that the rapid melt of a record spring snowfall on the Hayman fire did not generate any sediment. This suggests that the sediment that accumulated between November and May was most likely due to rainfall in the spring and fall rather than snowmelt. Data from the more intensively monitored sites indicate that approximately two-thirds of the annual sediment yield was generated between 1 July and 31 August.

The high severity plots in the first two years after burning yielded the most sediment (Figure 5). The mean sediment yield from high severity plots in the first year after burning was 6.7 Mg ha^{-1} (s.d.=6.6 Mg ha^{-1}) and 10.7 Mg ha^{-1} (s.d.=8.0 Mg ha^{-1}) in the second year after burning. The 40% increase in the second year after burning is largely due to the higher rainfall erosivities in the second summer after burning at the Bobcat, Schoonover, and Hayman fires, which together represent 57% of the study plots (Table 2). The first-year sediment yields also are low because 30% of the sediment fences in the Bobcat fire were overtopped by a large storm event in August 2000, and the fences on the Hayman fire were not established until after the first one or two moderate-sized storms. The Hewlett Gulch fire is the main exception to this trend, as the mean sediment yield dropped from 24.3 Mg ha^{-1} (s.d.=3.8 Mg ha^{-1}) in the first year after burning to only 0.18 Mg ha^{-1} (s.d.=0.056 Mg ha^{-1}) in the second year after burning. This difference is due to much lower rainfall amounts in the second year after burning. For all high severity plots, there was no significant difference between the sediment yields in the first and second year after burning (p=0.11).

In areas burned at high severity, sediment yields were highly variable between-plots in the first two years after burning (Figure 5). Sediment yields exceeded 10 Mg ha^{-1} at 38% of the plots, while 20% of the plots yielded less than 2 Mg ha^{-1}. In the larger fires the between plot variability often spanned 1-2 orders of magnitude. For example, in the second year after the Hayman fire sediment yields in the high severity plots ranged from 0.11 Mg ha^{-1} to 25.7 Mg ha^{-1}, or a factor of 200. In the second year after the Bobcat fire, the sediment yields from high severity plots ranged from 1.3 Mg ha^{-1} to 25.8 Mg ha^{-1}, or a factor of 20. For high severity plots, the median value was 26% lower than the mean in the first year after burning, and 12% lower than the mean in the second year after burning.

In the third year after burning the mean sediment yield for high severity plots dropped significantly to 0.58 Mg ha^{-1} (s.d.=2.9 Mg ha^{-1}), or just 5% of the mean value from the second year after burning (Figure 5). In the fourth year after burning the mean sediment yield showed a non-significant increase to 1.6 Mg ha^{-1} (s.d.=7.4 Mg ha^{-1}). This increase is due to the fact that sediment yields exceeded 10 Mg ha^{-1} on 3 of the 24 plots with fourth year data. Two very large storms in 2003 caused one fourth-year plot in the Bobcat fire to yield 34.3 Mg ha^{-1} yr^{-1}, which was the highest annual sediment yield recorded for any plot over the course of this study (Figure 5). The mean sediment yield for the other 21 plots was only 0.24 Mg ha^{-1} (s.d.=1.1 Mg ha^{-1}), or about 60% less than the mean value from the third year after burning. Because a few plots produced most of the sediment in the third and fourth years after burning, the median sediment yields were respectively only 14% and 5% of the mean value in these years.

By the fifth year after burning the mean sediment yield from the seven high severity plots was 0.26 Mg ha^{-1} (s.d=0.44 Mg ha^{-1}), and the maximum sediment yield was only 1.2 Mg ha^{-1} (Figure 5). From the sixth to the ninth year after burning no plot produced more than 0.1 Mg ha^{-1}, which is the approximate rate of sediment production from unburned forested areas in the Colorado Front Range (Gary, 1975; MacDonald and Stednick, 2003).

Sediment yields from the moderate severity plots were much lower than the high severity plots (Figures 4, 5). The mean sediment yield for plots burned at moderate severity in the first year after burning was 1.1 Mg ha^{-1} (s.d.= 1.1 Mg ha^{-1}), and this declined slightly to 0.90 Mg ha^{-1} (s.d.= 1.8 Mg ha^{-1}) in the second year after burning. The mean sediment yields from the moderate severity plots were significantly lower than the high severity plots in both the first and second years after burning ($p<0.001$). The sediment yields from the moderate severity plots also were skewed, but not as much as the high severity plots as the median sediment production in the first two years after burning was only 38% of the mean value. Sediment yields from the moderate severity plots rapidly declined to background levels, as only one of the twenty-six moderate severity plots had an annual sediment yield greater than 0.1 Mg ha^{-1} by the third year after burning (Figure 5).

For plots burned at low severity, the mean sediment yield in the first year after burning was only 0.51 Mg ha^{-1} (s.d.= 0.26 Mg ha^{-1}) (Figure 5). However, the sediment yields from low severity plots were not significantly lower than the moderate severity plots in either the first or second year after burning. Again the mean values were highly skewed because one plot yielded 7.0 Mg ha^{-1} and three plots produced 0.6-0.7 Mg ha^{-1} in the first two years after burning. Over the same period, the mean sediment yield from the other seven low severity plots was only 0.040 Mg ha^{-1} (s.d.=0.062 Mg ha^{-1}). By the third year after burning, the mean sediment yield from the low severity plots dropped to 0.030

Mg ha^{-1} (s.d= 0.044 Mg ha^{-1}). Only one of the twenty-eight low severity plots more than two years old exceeded the background sediment production rate of 0.1 Mg ha^{-1}.

The three prescribed fires generally produced less sediment than the wildfires, particularly for the plots that burned at high severity. The mean sediment yield for high severity plots in the Lower Flowers prescribed fire was 2.2 Mg ha^{-1} (s.d.=2.2 Mg ha^{-1}) in the first two years after burning, or just 24% of the mean value from the comparable plots in wildfires. By the fourth year after burning the highest sediment yield from a prescribed fire was only 0.5 Mg ha^{-1}, which is only 25% of the fourth-year mean value for the high severity plots in wildfires. Similarly, the plots burned at moderate severity in prescribed fires had a mean sediment yield of 0.68 Mg ha^{-1} (s.d.=1.3 Mg ha^{-1}) in the first two years after burning, or about half of the mean value from comparable plots in wildfires. For plots burned at low severity, there was little difference in sediment yields between prescribed and wild fires because sediment yields were so low from both.

2.4.2. Precipitation

Summer precipitation was highly variable between years, between fires, and even within fires. The mean summer rainfall over the four years of monitoring was 162 mm (s.d.=37 mm) (Table 2). The mean value in 2000 and 2001 was about 10% higher than the mean for all four years, while the mean value in 2002 was only 126 mm (s.d.=24 mm), or 78% of the overall mean. To some extent the variability between fires reflects differences in climate, as the Crosier Mountain site consistently had about 30% more rainfall than the nearby Bobcat fire. In most cases, however, these general tendencies were masked by the high variability over space and time. At the Bobcat fire in 2001, for example, total rainfall varied from 117 mm at the Green Ridge gage to 201 mm at the Snowtop gage, which was just 3 km west of the Green Ridge gage (Table 2).

Only 10% of the 1706 storms produced more than 5 mm of rain, and less than 4% of the storms had 10 mm or more of rain (Figure 6a). On average, there were approximately 9 storms per summer at each gage with 5 or more millimeters of rainfall, which is generally the minimum amount of rain needed to generate sediment from areas burned at high severity (Moody and Martin, 2001a; Benavides-Solorio, 2003). The number and magnitude of storms with at least 5 mm of rainfall were much more variable than the total summer rainfall. In the Dadd Bennett prescribed fire, for example, there were only two storms in 2002 with at least 5 mm of rain, but 9 storms in 2003. The maximum number of storms at least 5 mm of rainfall in one summer was 15 at the Lower Flowers fire in 2000, and the minimum number was 2.

Only 10% of the storms had a maximum thirty-minute intensity (I_{30}) greater than 10 mm hr^{-1} (Figure 6b), which is the approximate threshold for runoff generation in burned areas in the Colorado Front Range (Moody and Martin, 2001b; Kunze, 2003). On average, there were 5 storms per year at each rain gage with a maximum I_{30} greater than 10 mm hr^{-1}, but this number varied from 0 to 12 (Table 2). There were just 21 storms, or less than 2% of all events, with a maximum I_{30} of at least 25 mm hr^{-1}. Only 5 storms, or 0.5% of all events, had a maximum I_{30} greater than 40 mm hr^{-1}, which is approximately a 5-yr storm event in the Colorado Front Range (Hershfield, 1961). The highest I_{30} was 70 mm hr^{-1} at the Dadd Bennett fire in August 2000 (Table 2), and this storm has an estimated recurrence interval of about 35 years (Hershfield, 1961).

Rainfall erosivities were even more variable than summer rainfall and maximum storm I_{30}. The overall mean summer erosivity was 322 MJ mm ha^{-1} hr^{-1}, and the standard deviation is nearly as large (294 MJ mm ha^{-1} hr^{-1}). The annual mean varied by a factor of four, from 104 MJ mm ha^{-1} hr^{-1} in 2002 to 405 MJ mm ha^{-1} hr^{-1} in 2001 (Table 2). The maximum range for a single fire was from 12 to 1210 MJ mm ha^{-1} hr^{-1} at the Bobcat fire, or a factor of 100 (Table 2).

The total summer erosivity was typically controlled by only one or two large storms. At the Green Ridge gage in 2003, for example, 77% of the 1210 MJ mm ha^{-1} hr^{-1} was generated from just two convective storms in mid-June. The localized nature of the convective storms is evidenced by the fact that in 2003 the Snowtop gage in the Bobcat fire had a summer erosivity of only 124 MJ mm ha^{-1} hr^{-1}, even though this gage was only 3 km from the Green Ridge gage.

2.4.3. Effect of Rainfall on Sediment Yields

The storm-based data from the Hayman fire confirm that sediment production occurred when there was at least 5 mm of rainfall. However, in the spring and fall many storms with more than 5 mm of rain did not produce any sediment because they were low intensity, long duration events. For example, no measurable sediment was produced from a 5 hour, 14.7 mm rain event at the Hayman fire on 1 October 2002.

The maximum I_{30} and rainfall erosivity values yielded more consistent thresholds for sediment production than storm rainfall. In general, sediment production occurred when the I_{30} exceeded 8-10 mm hr^{-1}, which is similar to the threshold of 10 mm hr^{-1} identified after the Buffalo Creek (Moody and Martin, 2001b) and Bobcat (Kunze, 2003) fires. The 2003 data from the Hayman fire show that storm erosivities of approximately 20 MJ mm ha^{-1} hr^{-1} were sufficient to initiate sediment production. Figure 7 illustrates this erosivity threshold and the strong dependence of sediment production on storm erosivity for five storm events on three adjacent study areas in the Hayman fire. At the Upper Saloon Gulch (USG) South study area, the storm on 25 June 2003 had a rainfall erosivity of 21 MJ mm ha^{-1} hr^{-1} and the mean sediment yield for the three swales in this study area was 1.1 Mg ha^{-1} (s.d.=0.82 Mg ha^{-1}). Rainfall erosivities were less than 10 MJ mm ha^{-1} hr^{-1} at the adjacent USG North and USG East rain gages, and there was no sediment produced from the 13 swales in these two areas. Five other storms at the Hayman fire in 2003 had rainfall erosivities of 5-15 MJ mm ha^{-1} hr^{-1}, and none of these produced any sediment.

The data from the more intensively monitored Hayman and Bobcat fires show that storm-based sediment yields were strongly related to both maximum I_{30} and rainfall erosivity. The differences in sediment yields between fires and years means that these relationships are strongest for individual fires in the first two years after burnings. For example, rainfall erosivity explains 58% of the variability in sediment yields from swales in the Hayman fire for 2002 and 2003 (Figure 8), and maximum storm I_{30} and rainfall erosivity each explained 57% of the variability in storm-based sediment yields for swales in the Bobcat fire in 2001.

The exact effect of rainfall on sediment yields for larger storms was difficult to determine because: (1) there were few large storms at recent fires, and (2) there was considerable variability in sediment yields between adjacent plots when there was a large storm. For example, the 9 swales at USG North were separated by less than 0.5 km, but sediment yields from the 161 MJ mm ha^{-1} hr^{-1} storm on 11 August 2003 varied by a factor of four (Figure 8). For this storm the rainfall erosivities at the three gages in the USG study area varied from 48 to 240 MJ mm ha^{-1} hr^{-1}. Since the rain gages were about 2 km apart, the rainfall erosivity varied by 96 MJ mm ha^{-1} hr^{-1} per km. This rate suggests that the rainfall erosivity across the USG North study area varied by about 20%. Therefore some of the unexplained variability between plots can be attributed to the spatial variability of the storm events across a given study area.

2.4.4. Effect of Topographic Convergence on Sediment Yields

At the more recent fires, sediment yields were consistently higher from swales than planar hillslopes (Figure 8; Chapter 3). In the first 2 years after burning, the mean annual sediment yield from swales burned at high severity was 11.8 Mg ha^{-1} (s.d. = 7.8 Mg ha^{-1}) versus 3.9 Mg ha^{-1} (s.d. = 4.6 Mg ha^{-1}) from planar hillslopes, and this relatively large difference was highly significant ($p \leq 0.0001$). At the Hayman fire, the sediment yields from swales tended to increase more rapidly with rainfall erosivity than the sediment yields from planar hillslopes (Figure 8). An analysis of the data from all high severity plots less than two years old showed that the swales produced 3.3 times more sediment per unit of rainfall erosivity than the planar hillslopes.

The difference in sediment yields between swales and planar hillslopes was not significant for plots burned at moderate and low severity because of the limited sample sizes and high relative variability in sediment yields. For similar reasons, there was no significant difference in sediment yields between swales and planar hillslopes for the plots that were more than 2 years old.

2.4.5. Soil Texture

The soils in each fire were coarse textured, as all of the plots had between 40% and 60% sand and less than 5% clay (Figure 9). The percent silt was more variable, as this ranged from 1% at the Schoonover fire to 35% in the Jug Gulch and Bobcat Gulch areas of the Bobcat fire. The amount of coarse particles also was highly variable, as values ranged from 10% to 60% (Figure 9).

The soils derived from granite typically were coarser than the soils derived from metamorphic rocks. The coarsest soils were the granitic soils in the Hayman and Schoonover fires, as these had at least 50% gravel and less than 1% clay. The only other fire with very coarse soils was Hewlett Gulch, where the plots were on very steep talus slopes and almost 50% of the soil mass consisted of particles larger than 2 mm. Within the Bobcat fire, the granitic soils in the Green Ridge area were significantly coarser than the soils in Jug Gulch and Bobcat Gulch ($p=0.0008$) (Figure 9). The Bobcat fire was the only fire to exhibit significant variability in soil texture between study areas.

2.4.6. Surface Cover

The amount of surface cover generally decreased with increasing fire severity. For practical reasons it easier to focus on percent of bare soil, which is 100 minus the percent cover from all other sources, except for ash. Most of the plots that burned at high severity had over 90% bare soil in the first year after burning (Table 3). For the moderate severity plots the mean percent bare soil in the first year after burning was 59% (s.d.=15%), while the low severity plots had only 30% (s.d =11%) bare soil in the first year after burning. For plots less than 2 years old, there was significantly more bare soil on the high severity plots than the moderate and low severity plots, and the moderate severity plots had significantly more bare soil than the low severity plots.

The amount of bare soil declines nonlinearly with time since burning (Figure 10). On the high severity plots vegetative regrowth began within a few weeks after burning, but by the end of the second summer the mean percent bare soil was still 76% (s.d. = 17%) (Table 3). By the third summer after burning the mean percent soil in the high severity plots dropped to 37% (s.d.=19%). By five years after burning the mean percent bare soil in the high severity plots had declined to 18% (s.d.=10%). The data from the Hourglass fire indicate a continuing but much slower decline in percent bare soil from the sixth to the tenth year after burning (Figure 10).

Because the low and moderate severity plots had less exposed bare soil immediately after burning than the high severity plots, these plots approached background levels much more quickly (Figure 10). The moderate severity plots averaged just 32% (s.d =13%) bare soil by the second year after burning, and less than 20% bare soil by the third year after burning (Table 3). The mean percent bare soil was below 20% at the low severity plots by the second year after burning. Time since burning explains from 46% to 69% of the variability in percent bare soil when the data are stratified by fire severity (Figure 10), and the best-fit lines for the three fire severity classes are significantly different.

Most of the increase in ground cover in the high severity plots was due to vegetative regrowth. By the fourth year after burning live vegetation provided 54% cover while litter and needlecast accounted for just 22% of the surface cover. Litter and needlecast were much more important in the moderate and low severity plots, as these provided 38% of the surface cover in the first year after burning. After two years the ground cover in the plots burned at moderate severity averaged 42% needlecast or litter and 39% live vegetation. Similarly, after two years the surface cover in the low severity plots consisted of 41% needlecast or litter and 38% live vegetation.

The rate of vegetative recovery and the corresponding decline in percent bare soil varied between fires. In general, the plots situated on granitic parent material had the slowest recovery rates (Table 3). The highest percent bare soil in the second year after burning was at the Schoonover fire, where the soils are extremely coarse (Figure 9). In the third year after burning the high severity plots with granitic soils averaged 64% bare soil as compared to the overall mean of 37%. In the Bobcat Fire, the finer-textured soils in the Jug Gulch and Bobcat Gulch areas averaged only 20% bare soil in the third year after burning as compared to 59% for the coarse-textured granitic soils in the Green Ridge area. The slower regrowth on the plots with coarser-textured soils is consistent with the poorer water-holding capacity and excessive drainage of these soils.

2.4.7. Effect of Surface Cover on Sediment Yields

The amount of bare soil, or conversely total surface cover, is the primary control on post-fire erosion over time. When all the data are combined, percent bare soil explains 64% of the variability in unit area sediment yields (Figure 11). The relationship between percent bare soil and sediment yields is strongly non-linear as 87% of the total sediment yield was from plots with more than 60% bare soil (Figure 11). The mean sediment yield for these plots was 8.6 Mg ha^{-1} yr^{-1}, but the data were highly variable as the standard deviation was 7.5 Mg ha^{-1} yr^{-1} and the range was from 0.077 to 28.3 Mg ha^{-1} yr^{-1}. Sediment yields from plots with 40-60% bare soil had a large range (0.0071-34.3 Mg ha^{-1} yr^{-1}), but the mean value was only 3.1 Mg ha^{-1} (s.d.=7.9 Mg ha^{-1}). Plots with less than 36% bare soil generated very little sediment except in two cases when there was an exceptionally large storm event.

The effects of ground cover on sediment yields can be more specifically illustrated by comparing sediment yields over time from different areas in the Bobcat fire (Figure 12). In the first two years after burning the 13 plots burned at high severity averaged 77% bare soil and the mean sediment yield was 7.6 Mg ha^{-1} yr^{-1} (s.d.=6.4 Mg ha^{-1} yr^{-1}). By the third and fourth years after burning, the mean bare soil had dropped below 20% in the Bobcat and Jug Gulch study areas and the mean sediment yield declined to just 0.025 Mg ha^{-1} yr^{-1} (s.d.=0.031 Mg ha^{-1} yr^{-1}). Vegetative regrowth was much slower for three of the five plots in the Green Ridge area, as the mean percent bare soil in the fourth year after burning was still 42% for these three plots versus 19% for the other two plots. As a result of two large storms (56 mm hr^{-1} and 44 mm hr^{-1}) the mean annual sediment yield from the three relatively bare plots was 20.6 Mg ha^{-1} (s.d.=15.4 Mg ha^{-1}), and this was about 40 times the value of the two plots with more vegetation. This shows that plots with around 40% bare soil remain susceptible to high sediment yields during intense storm events, but very little sediment can be generated from plots with less than 20% bare soil.

2.4.8. Multivariate Regression Models

The first multivariate model considered all 13 independent variables but did not include interaction terms (Table 4). The resulting "primary model" used 8 independent variables to predict the logarithm of annual sediment production (log kg), and this had a R^2 of 0.76 and a root mean square error (RMSE) of 0.64 (Table 5). When the interaction terms were considered, the best model included six of the same primary variables, two interaction terms (bare soil*contributing area and bare soil*bare soil), and contributing area (Table 4). Time since burning and soil D_{16} became insignificant. This "interaction model" had a higher R^2 at 0.83 and a lower RMSE at 0.54 (Table 5).

Statistically, the R^2 will increase as more variables are included, but users may not have data for all of the variables in the complete models, so a key issue is the extent to which the models become weaker as fewer variables are included. Hence a series of progressively simpler models (1-4 parameter models) were developed. The best 4-parameter model included percent bare soil, summer rainfall erosivity, hillslope position, and soil D_{84}, and this had an R^2 of 0.72 and a RMSE of 0.68, which is only slightly worse than the primary model (Table 5).

The predictive capability of the models decreased by 4-14% as additional variables were removed. The 1-parameter bare soil model used only percent bare soil, but the R^2 value that was 0.58, or only 25% lower than the interaction model (Table 5).

While the R^2 decreased and the RMSE increased with progressively simpler models, there was not a comparable decreased in accuracy when the models were tested against the validation data. The RMSE for the validation data only varied from 0.65 to 0.73 log units, and the standard error of prediction (SEP) only varied from 0.65 to 0.74

log units (Table 5). The 3-parameter and 2-parameter models had the best performance against the validation data with RMSE values of 0.66 and 0.65, respectively.

Plots of the predicted versus observed values for the validation data set show that each model tended to over-predict low sediment yields and under-predict high sediment yields (Figure 13). The slopes of the regression lines indicate that this tendency was most severe in the simpler models, which generally were less accurate predictors of high sediment yields. The interaction model was the most accurate predictor of high sediment yields, but both the interaction model and the primary model were not able to accurately predict low sediment yields. Conversely, the 1- and 2-parameter models were relatively good at predicting low sediment yields (Figure 13). These trends show that percent bare soil is the dominant control on sediment yields at plots that are not producing much sediment, but many site variables affect the amount of sediment from plots that have a high percentage of bare soil and are more susceptible to high sediment yields.

The final model coefficients and statistics for each model were derived using the entire data set (n = 225) and the same predictive variables identified in model calibration. The significance and partial R^2 of each predictive variable illustrate the relative importance of percent bare soil compared to all of the other variables (Table 6). In each case percent bare soil had a partial R^2 of 0.58, and none of the other variables had a partial R^2 greater than 0.07. In the primary model, rainfall erosivity and the categorical variable of hillslope position were the second and third most important variables, although each had a partial R^2 of only 0.05. Other variables such as the soil D_{84}, average I_{30}, and time since burning were significant variables in either the primary or interaction model, but in each case the partial R^2 was less than 0.02 (Table 6). Aspect and soil D_{16}

were significant variables in the primary model during the initial model calibration, but these two variables were insignificant when the entire data set was used for model development (Table 6). Hence the primary model could be simplified by removing these two variables, but they are retained in Table 6 in order to maintain consistency with the model developed during calibration.

2.5. DISCUSSION

2.5.1. Rainfall Recurrence Intervals and Sediment Yields

Summer rainfall during the study period (2000-2003) was generally lower than the long-term average, but storm intensities were fairly representative of historic means in the Colorado Front Range. From 2000-2003 the mean summer rainfall at the Cheesman Reservoir and Drake, CO weather stations were only 76% and 70% of their historic averages, respectively (NOAA, 2004). At the same time, the mean annual maximum I_{30} at all fires was 25 mm hr^{-1}, which is equivalent to the 1-year 30-minute storm in the Colorado Front Range (Hershfield, 1961). The mean summer rainfall erosivities recorded during the four-year monitoring period also were roughly equal to the average annual rainfall erosivity of 340 MJ mm ha hr^{-1} (Renard et al., 1997). Three storms exceeded the 10-year, 30-minute storm of 50-55 mm hr^{-1} (Hershfield, 1961), but none of these occurred on a high severity fire that was less than 2 years old. The highest I_{30} on a recent high severity fire was 40 mm hr^{-1}, and this has a recurrence interval of about 5 years.

Similarly, the highest rainfall erosivities occurred on the older fires. Annual erosivities in the first and second summers after burning were below the estimated long-term mean at most of the primary study sites, including the Bobcat, Hayman, and Schoonover fires (Table 2) (Renard et al., 1997). The only recent fire with above-average rainfall erosivities in the first and second summer after burning was the Big Elk fire. Unfortunately accurate sediment yield data are not available from this fire because the sediment fences were overtopped at two of the three high severity plots.

This lack of very large storms, when coupled with the high spatial variability in sediment yields, makes it difficult to accurately determine the relationship between sediment yields and rainfall intensity for different amounts of surface cover. The data from this and other studies suggest a strongly non-linear relationship between rainfall intensity and sediment yields, particularly for the largest storms. Two months after the Buffalo Creek fire there was a rainstorm with a maximum I_{30} of 80 mm hr^{-1}, which has a recurrence interval of approximately 100 years. The hillslope sediment yields from this event were estimated to be 40-70 Mg ha^{-1} (Moody and Martin, 2001a). In the second summer after burning a storm on the Hayman fire had an I_{30} of 40 mm hr^{-1}, or half the intensity of the 1996 storm on Buffalo Creek. The mean sediment yield from this event was 11.3 Mg ha^{-1}, or just one-quarter of the estimated sediment yield at Buffalo Creek.

Most of the study plots were subjected only to storms with average intensities and erosivities, and this means that the measured sediment yields are representative of typical conditions in the Colorado Front Range. Therefore, the models developed in this study are best used to predict sediment yields from average rainfall conditions. More extreme storms generate much larger sediment yields, but the paucity of large storm events on recent high severity fires limits the accuracy of such predictions. The wide range of potential sediment yields means that future post-fire erosion models ideally should be probabilistic rather than deterministic.

2.5.2. Interactions Between Soils, Vegetation, and Sediment Yields

Under unburned conditions the ground cover on coarse, granitic soils is primarily needlecast and litter rather than live vegetation. In summer 2001 ground cover was measured on 23 plots that were later burned by the Hayman fire, and prior to the fire these plots had 88% ground cover. Two-thirds of this ground cover was needlecast and woody debris, 24% was live vegetation, and only 10% was bare soil (Libohova, 2004). The low percentage of live vegetation can be attributed to the deficit in summer rainfall relative to potential evapotranspiration, and the low water holding capacity of the coarse-textured soils (Moore, 1992). The low clay content also results in low nutrient storage capacity (Hillel, 1998).

Sediment yields on these plots were negligible prior to the Hayman fire (Libohova, 2004) because the needlecast and surface litter protect the soil surface and reduce overland flow velocities (e.g., McNabb and Swanson, 1990). Ponderosa pine needles, which are prevalent in the Colorado Front Range, create small debris dams and are particularly effective in reducing rill erosion (Pannkuk and Robichaud, 2003). The lack of rills or other erosional features confirms that there is little surface erosion on unburned hillslopes in the Colorado Front Range. Storms with exceptionally high rainfall intensities may initiate overland flow on unburned soils, but the large amount of litter and needlecast will help minimize surface erosion.

After a high severity fire live vegetation and surface litter are lacking and hillslope-scale sediment yields average 5-10 Mg ha^{-1} yr^{-1}. On finer-textured soils, such as those derived from gneiss and schist, vegetative re-growth is rapid and sediment yields decline to near background levels by the third summer after burning. On the coarser granitic soils, high sediment yields may persist for up to 5 years because vegetative regrowth is slower and there often are no nearby sources of surface litter, which is the principle source of ground cover under unburned conditions.

2.5.3. Analysis of the Multivariate Regression Models

The multivariate models showed that fire severity and time since burning had low partial R^2 values, even though these are very important controls on post-fire erosion (Morris and Moses, 1987; Inbar *et al*., 1998; Robichaud *et al*., 2000; Moody and Martin, 2001; Benavides-Solorio and MacDonald, 2001). The low partial R^2 values can be attributed to the fact that both of these variables are closely related to percent bare soil (Figure 10). If percent bare soil is excluded from the primary model, time since burning becomes the most important variable with a partial R^2 of 0.33, but the overall model R^2 drops from 0.76 to 0.66.

Rainfall erosivity was the second most important variable in the models, but a partial R^2 of 0.05 indicates that rainfall erosivity had relatively little influence relative to bare soil. At older fires rainfall erosivity is of little consequence because the high percentage of ground cover limits erosion regardless of storm energy. Even at fires less than two years old, however, rainfall erosivity explained just 8% of the variability in annual sediment yields. Total summer erosivity may have limited predictive power because the total erosivity from several small rain events may equal the erosivity value from one large storm, but the sediment production from the large storm probably will be much greater than the total sediment production from the smaller storms. As such, it is difficult to accurately characterize rainfall energy over an entire summer period.

Contributing area was an insignificant variable in the primary model because the older plots produced negligible amounts of sediment regardless of size. In the interaction model, contributing area was significant but had a negative coefficient, indicating that total sediment yields decreased with increasing contributing area. This counterintuitive result is probably due to the fact that many of the older plots, particularly those at the Hourglass fire, were quite large. Figure 3 clearly shows that when other factors are relatively constant, sediment yields from recently burned plots are strongly related to contributing area. A multivariate model for high severity plots less than two years old indicated that contributing area was the most important variable, and this had a partial R^2 of 0.32.

Plot slope was insignificant in the multivariate models even though slope is an important factor in most erosion models (Renard *et al*., 1997). Slope was the second most important variable when a model was developed for the high severity plots less than two years old, but the coefficient was negative. This negative correlation is partly due to the fact that swale slope tended to decrease as contributing area increased (R^2=0.05), and the largest swales had the highest sediment yields. The role of slope also may be limited because the slope at most plots ranged from only 20% to 40%. Within this range of values, slope may not be an important control on post-fire sediment yields because the lack of surface roughness allows for relatively high overland flow velocities regardless of slope. The low soil aggregate stability also implies that shear strength is easily overcome in these highly erodible soils (e.g., Hillel, 1998).

Soil texture had a greater effect on sediment yields than slope. Both the soil D_{84} and soil D_{16} were negatively and significantly related to sediment yields in the primary and interaction models. Finer-textured soils are expected to be more erodible because less shear stress is required to detach smaller particles (e.g., Elliot and Laflen, 1993). The relatively low partial R^2 values for the D_{84} and D_{16} (Table 6) may be due to the fact that all of the plots had relatively coarse soils (Figure 9).

A closer analysis of the modeling results indicates that only a few data points controlled the strength of some variables. Aspect is a prime example, as this variable was significant with the calibration dataset but was insignificant in the entire dataset. Removing 10 data points at random caused aspect to become insignificant, and average I_{30} to become significant. Even more important variables such as rainfall erosivity and hillslope position could become insignificant by randomly removing data points. For example, randomly removing 20 of the 117 data points from the calibration data set caused the partial R^2 values for rainfall erosivity to vary from less than 0.01 to 0.12. The same exercise showed that the partial R^2 values for percent bare soil fluctuated between 0.45 and 0.70.

The results show that the multivariate models can be sensitive to the calibration dataset, but percent bare soil is the dominant control on post-fire sediment yields over time. Percent bare soil is particularly useful because it can be readily quantified by field measurements or remote sensing techniques (Miller *et al*., 2003). Since the simpler models were nearly as accurate as the more complex models, land managers can simply use percent bare soil to obtain first-order estimates of post-fire sediment yields. The 2-parameter model may be the most useful model because it can be used to estimate the potential range of sediment yields for a given range of rainfall erosivity values.

2.5.4. Effect of Measurement Scale on Sediment Yields

Sediment yields generally decline with increasing catchment size due to increased areas of deposition and storage (e.g., Walling, 1983). However, data from different post-fire studies in the Colorado Front Range suggest that unit-area sediment yields may increase from the plot to the catchment scale. In the second summer after the Hayman fire, the mean sediment yield was 3.6 Mg ha^{-1} from 80 mm hr^{-1} of applied rainfall on 1 m^2 plots (Hughes, *in prep*.). At the hillslope plots, a 41 mm hr^{-1} rain event, or about 50% of the rainfall intensity applied on the small plots, resulted in a mean sediment yield of 11 Mg ha^{-1}, or three times the value from the plot scale. If all of the second-year data from the Hayman fire are normalized by area and rainfall intensity, the hillslope-scale sediment yields were three times higher than the sediment yields from the rainfall simulations.

Unit-area sediment yields from a 2.9 and a 4.6 ha catchment on the Hayman fire were higher than the hillslope-scale values. A storm with 22 mm of precipitation and a maximum I_{30} of 28.4 mm hr^{-1} generated a mean sediment yield of 18 Mg ha^{-1} (J. Wagenbrenner, USFS, unpublished data). At the hillslope scale, the sediment yields from storms with similar rainfall intensities produced less than 10 Mg ha^{-1}. In 2003 these small catchments produced approximately five times more sediment per unit of rainfall intensity than the hillslope plots and 13 times more sediment than the 1 m^2 plots. An 80 mm hr^{-1} rain event that is comparable to the rainfall applied on the 1 m^2 plots generated estimated sediment yields of at least 120 Mg ha^{-1} from two 4-7 ha catchments after the 1996 Buffalo Creek fire (Moody and Martin, 2001b), or 30-40 times the value measured from the small plots.

The increase in erosion rates from the plot to the hillslope scale may be attributed to a change in erosion process. On the 1 m^2 plots, sheetwash is the dominant erosion processes (Benavides-Solorio, 2003). At the hillslope scale, the concentration of overland flow in convergent areas induces rill erosion in the swale axes. Intensive surveys in the Hayman and Schoonover fires indicate that about 80% of the sediment yield from swales can be attributed to rill incision in the swale axes (Chapter 3). Incision in convergent zones remains the dominant erosion process at the small catchment and watershed scale, but with increasing scale the channels are larger and larger volumes of sediment can be eroded. Moody and Martin (2001a) estimated that approximately 80% of the eroded sediment from the two 4-7 ha catchments was generated from channel and gully incision, and only 20% was attributed to rill and sheetwash erosion on the hillslopes.

The lack of a decline in unit-area sediment yields from 1 m^2 to 7 ha is consistent with field observations at the Hayman fire. Sediment deposition on hillslopes and in low-order channels was minimal due to the relatively steep slopes and lack of roughness elements to slow overland flow and trap sediment. Aggradation was evident in the higher-order channels in the Hayman fire, and this shift from incision to deposition is probably controlled by channel slope (Moody and Martin, 2001a). At larger scales unit-area sediment yields probably decline because of deposition in the lower gradient downstream channels and the summer convective storms are limited in area and generally do not extend across larger catchments.

2.6. CONCLUSIONS

Sediment yields were measured over 1-4 years from 95 plots in seven wild and three prescribed fires in the Colorado Front Range. Over 90% of the annual sediment yield was generated between 1 June and 31 October, and the majority of this sediment resulted from high-intensity convective thunderstorms in July and August. Sediment production was typically generated from storms with more than 5 mm of total rainfall, rainfall intensities of at least 10 mm hr^{-1}, and rainfall erosivities greater than 20 MJ mm ha^{-1} hr^{-1}. On average there were about five storms per summer that exceeded these thresholds for sediment production, but this number may be low because the study period was dry compared to the long-term average.

The high severity plots at recent fires yielded the most sediment with a mean value of 8.8 Mg ha^{-1} yr^{-1}, or about two orders of magnitude higher than the estimated background rate. Variability in the amount and intensity of the summer rain events led to large differences in sediment yields between recent high severity plots (s.d.=7.6 Mg ha^{-1} yr^{-1}). Topographic convergence was another source of variability in the first two years after burning, as the swales produced about three times more sediment per unit area than the planar hillslopes.

The mean sediment yield from high severity plots dropped by an order of magnitude from the second to third year after burning. Over 70% of the plots produced lass than 0.2 Mg ha^{-1} in the third and fourth year after burning. Very little sediment was produced at any plot by the fifth year after burning, indicating that post-fire erosion rates returned to near-background levels in no more than five years.

The increase in ground cover was the dominant control on post-fire sediment yields. During the first two years after burning vegetative re-growth was slow and had little effect on sediment production. By the third year after burning approximately half of the plots had less than 40% bare soil, and sediment yields were virtually eliminated when the percent bare soil dropped below 35-40%. The recovery of ground vegetation was slower and sediment yields remained high on plots that had coarser soils.

The moderate and low severity plots yielded much less sediment than the high severity plots, and the recovery rates also were much more rapid. These results indicate that prescribed fires should minimize the amount of area that is burned at high severity, and that future post-fire rehabilitation should focus on treatments that immediately increase the amount of ground cover.

The most complete multivariate models explained 76%-83% of the variability in sediment yields and included 7 and 9 parameters, respectively. Progressively simpler models explained less of the variability, although a two-parameter model that included percent bare soil and rainfall erosivity still explained 63% of the variability in sediment yields. This two-parameter model best predicted the validation data set with a RMSE of 0.65. These models can be used by researchers and management agencies for predicting post-fire sediment yields in the Colorado Front Range.

2.7. REFERENCES

Agee, J.K., 1993. Fire ecology of Pacific Northwest forests. Island Press. Washington, D.C., 493 p.

Agnew, W., R.E. Labn, and M.V. Harding, 1997. Buffalo Creek, Colorado, fire and flood of 1996. *Land and Water* 41: 27-29.

Benavides-Solorio, J., 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. dissertation, Colorado State University, Fort Collins, CO, 218 p.

Benavides-Solorio, J., and L.H. MacDonald, 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* 15: 2931-2952.

Brown, L.C., and G.R. Foster, 1987. Storm erosivity using idealized intensity distributions. *Transactions of the American Society of Agricultural Engineers* 30: 379-386.

Brown, L.C., and L.D. Norton, 1994. Surface residue effects on soil erosion from ridges of different soils and formation. *Transactions of the American Society of Agricultural Engineers* 37: 1515-1524.

Burch G.J., I.D. Moore, and J. Burns, 1989. Soil hydrophobic effects on infiltration and catchment runoff. *Hydrological Processes* 3: 211-222.

Cambardella, C.A., A.M. Gajda, J.W. Doran, B.J. Wienhold, and T.A. Kettler, 2001. Estimation of particulate and total organic matter by weight loss-on-ignition. In *Assessment methods for soil carbon*, Lal, R., J.M. Kimble, R.F Folletr, and B.A. Stewart (eds.). Lewis Publishers. Boca Raton, FL, p. 349-359.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott, 1998. Fire's effects on ecosystems. John Wiley & Sons. New York, NY, 333 p.

DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* 231-232: 195-206.

Elliot, W.J., and J.M. Laflen, 1993. A process-based rill erosion model. *Transactions of the American Society of Agricultural Engineers* 36: 65-72.

Gardner, W.H., 1986. Water content. In *Methods of Soil Analysis: Part 1*, A. Klute (ed). American Society of Agronomy. Madison WI, p. 493-507.

Gary, H.L., 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine zone: the status of our knowledge. USDA Forest Service Research Paper, RM-139. Fort Collins, CO, 32 p.

Gary, H.L., 1985. A summary of research at the Manitou Experimental Forest in Colorado, 1937-1983. USDA Forest Service General Technical Report RM-116. Fort Collins, CO, 24 p.

Gee, G.W., and D. Orr, 2002. Particle-size analysis. In *Methods of Soil Analysis* Part 4, Dane, J.H., and G.C. Topp (eds.), Soil Science Society of America. Madison, WI, p. 255-293.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* 16: 627-634.

Hershfield, D.M., 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods of 1 to 100 years. Cooperative Studies Section, U.S. Weather Bureau, Washington, D.C., 70 p.

Hillel, D., 1998. Environmental soil physics. Academic Press. San Diego, CA, 771 p.

Huffman E.L., L.H. MacDonald, and J.D. Stednick, 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes* 15: 2877-2892.

Kaufmann, M.R., L.S. Huckaby, and P. Gleason. 2000. Ponderosa pine in the Colorado Front Range: long historical fire and tree recruitment intervals and a case for landscape heterogeneity. In *Crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management,* Neuenschwander, L.F. (ed). University of Idaho and International Association of Wildland Fire. Moscow, ID, p. 153-160.

Kaufmann, M.R., P.J. Fornwalt, L.S. Huckaby, and J.M. Stoker, 2001. Ponderosa pine reconstruction: comparisons with historical data. In *Ponderosa pine ecosystems restoration and conservation: steps toward stewardship*, Vance, R.K., C.B. Edminster, W.W Covington, and J.A. Blake (eds.). USDA Forest Service, Rocky Mountain Research Station Proceedings RMRS-P-22, Ogden, UT, p. 9-18.

Kilinc, M.Y., 1968. The effect of wildfire on soil properties. M.S. thesis, Colorado State University, Fort Collins, CO, 100 p.

Kunze, M., 2003. Streamflow and sediment yield following the 2000 Bobcat fire, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, 133 p.

Libohova, Z., 2004. Effects of thinning and a wildfire on sediment production rates, channel morphology, and water quality in the upper South Platte River watershed. M.S. thesis, Colorado State University, Fort Collins, CO, 260 p.

MacDonald, L.H., and J.D. Stednick, 2003. Forests and water: a state-of-the-art review for Colorado. Colorado Water Resources Research Institute, Completion Report No. 196: Fort Collins, CO, 65 p.

McNabb, D.H., and F.J. Swanson. 1990. Effects of fire on soil erosion. In *Natural and Prescribed Fire in Pacific Northwest Forests,* Walstad, J.D., S.R. Radosevich, and D.V. Swanson (eds). Corvallis, OR, p. 159-176.

Miller, J.D., J.W. Nyhan, and S.R. Yool, 2003. Modeling potential erosion due to the Cerro Grande Fire with a GIS-based implementation of the Revised Universal Soil Loss Equation. *International Journal of Wildland Fire* 12: 85-100.

Moody, J.A., and D.A. Martin, 2001a. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26: 1049-1070.

Moody, J.A., and D.A. Martin, 2001b. Post-fire rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes* 15: 2981-2993.

Moore, R., 1992. Soil Survey of the Pike National Forest, Eastern Part, Colorado, Parts of Douglas, El Paso, Jefferson, and Teller Counties. US Department of Agriculture, Forest Service and Soil Conservation Service. Fort Collins, CO, 143 p.

Morris, S.E., and T.A. Moses, 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* 77: 255-264.

National Oceanic and Atmospheric Administration (NOAA), National Climate Data Center, 2004. Retrieved 1 May 2004, from http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWDI~StnSrch.

Ott, R.L., and K. Longnecker, 2001. An introduction to statistical methods and data analysis. Duxbury Press. Pacific Grove, CA, 1152 p.

Pannkuk, C.D., and Robichaud, P.R., 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* 39: ESG 1-9.

Parker, K.W., 1951. A method for measuring trend in range condition on national forest ranges. U.S. Department of Agriculture, administrative report. Washington, D.C., 26 p.

Pierson, F.B., P.R. Robichaud, and P.E. Brown, 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological Processes* 15: 2905-2916.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, 1997. *Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).* USDA Agriculture Handbook 703. Washington D.C., 404 p.

Robichaud, P.R., T.A. Waldrop, 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resources Bulletin* 30: 27-34.

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. *Journal of Hydrology* 231: 220-229.

Robichaud, P.R., J.L. Beyers, and D.G. Neary, 2000. Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service General Technical Report RM-GTR-63. Fort Collins, CO, 85 p.

Robichaud, P.R., and R.E. Brown, 2002. Silt fences: an economical technique for measuring hillslope soil erosion. USDA Forest Service, General Technical Report RMRS-GTR-94. Fort Collins, CO, 24 p.

Romme, W.H., T.T. Veblen, M.R. Kaufman, R. Sheriff, and C.M. Regan, 2003. Ecological effects of the Hayman fire. In *Hayman Fire Case Study*, Graham, R.T. (ed.). USDA Forest Service General Technical Report RMRS-GTR-114. Fort Collins, CO, p. 181-203.

Salas, J., and F. Smith, 1999. Modeling watershed hydrology. Notes from CE/ER 524, Colorado State University, Fort Collins, CO.

SAS Institute, 2001. SAS software release 8.02. Cary, NC.

Scott, H.D., 2000. Soil physics, agricultural and environmental applications. Iowa State University Press. Ames, IA, 199 p.

Simanton, J.R., G.D. Wingate, and M.A. Weltz, 1990. Runoff and sediment from a burned sagebrush community. USDA Forest Service General Technical Report RM-191. Fort Collins, CO, p. 180-185.

Tiedemann, A.R., C.E. Conrad, J.H. Dietrich, J.W. Hornbeck, W.F., Megahan, L.A. Viereck, and D.D. Wade, 1979. Effects of fire on water: a state-of-knowledge review. USDA Forest Service General Technical Report WO-10. Washington, D.C., 28 p.

USDA Forest Service, 1995. Burned-area emergency rehabilitation assessment. Forest Service Handbook 2509.13-95-7. Washington, D.C., 18 p.

Wagenbrenner, J., 2003. Effectiveness of burned area emergency rehabilitation treatments, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, 193 p.

Walling, D.E., 1983. The sediment delivery problem. *Journal of Hydrology* 65: 209-237.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredrikson, E.C. Franklin, R.C. Froelich, and P.H. Dunn, 1979. Effects of fire on soil, a state-of knowledge review. USDA Forest Service General Technical Report WO-7. Washington, D.C., 34 p.

Wells, W.G., 1981. Some effects of brushfires on erosion processes in coastal Southern California. In *Erosion and Sediment Transport in Pacific Rim Steeplands*. IAHS Publication No. 132, p. 305-342.

Table 1. Characteristics of the ten fires monitored in this study. Year of monitoring relates to the age of the fire on 31 October; year 0 is the year in which the fire burned. *Indicates a prescribed fire.

					Number of sediment fences by severity			
Fire	Date burned	Years monitored	Primary parent material	Primary vegetation type	High	Moderate	Low	Total
Big Elk	August 2002	0.0-1.2	Gneiss/schist	Lodgepole pine	3	2	1	6
Hayman	June 2002	0.0-1.3	Granite	Ponderosa pine	31	1	0	32
Schoonover	May 2002	0.1-1.4	Granite	Ponderosa pine	6	0	0	6
Hewlett Gulch	April 2002	0.2-1.2	Gneiss/schist	Ponderosa pine	3	0	0	3
Bobcat	June 2000	0.0-3.3	Schist/granite	Ponderosa pine	13	2	1	16
Dadd Bennett*	January 2000	0.4-3.8	Gneiss	Ponderosa pine	0	3	2	5
Lower Flowers*	November 1999	0.6-3.9	Gneiss	Ponderosa pine	4	4	2	10
Crosier Mountain*	September 1998	0.5-5.1	Granite	Lodgepole Pine	4	1	0	5
Bear Tracks	June 1998	2.0-5.3	Granite	Subalpine fir	3	0	2	5
Hourglass	July 1994	5.9-9.3	Schist	Lodgepole pine	5	1	1	7
				Total	**72**	**14**	**9**	**95**

Table 2. Total rainfall, number of storms, rainfall intensities, and rainfall erosivities from 1 June to 31 October for each rain gage from 2000 to 2003. Values in bold indicate a complete summer record. - indicates no data.

		Total rain (mm)				Number of events with I_{30} $\geq$10 mm hr^{-1}				Maximum I_{30} (mm hr^{-1})				Mean I_{30} (mm hr^{-1}) for storms > 5 mm				Total erosivity (MJ mm ha^{-1} hr^{-1})			
Fire	Rain gage	2000	2001	2002	2003	2000	2001	2002	2003	2000	2001	2002	2003	2000	2001	2002	2003	2000	2001	2002	2003
Big Elk	Big Elk	-	-	-	**229**	-	-	-	**9**	-	-	-	**35**	-	-	-	**15**	-	-	-	**586**
Hayman	Brush Creek	-	-	131	**154**	-	-	3	**8**	-	-	24	**19**	-	-	11	**11**	-	-	141	**259**
	USG South	-	57	144	**152**	-	3	3	**7**	-	12	19	**33**	-	9	8	**11**	-	52	198	**231**
	USG North	-	-	77	**152**	-	-	1	**6**	-	-	10	**34**	-	-	6	**14**	-	-	25	**349**
	USG East	-	-	-	70	-	-	-	3	-	-	-	41	-	-	-	19	-	-	-	308
Schoonover	Schoonover	-	-	85	**138**	-	-	1	**7**	-	-	18	**23**	-	-	7	**13**	-	-	59	**241**
Hewlett Gulch	Hewlett Gulch	-	-	112	92	-	-	2	1	-	-	27	12	-	-	7	8	-	-	164	40
Bobcat	Snowtop	150	**201**	**116**	**119**	7	**8**	**2**	**3**	18	**26**	**13**	**22**	13	**14**	**7**	**12**	220	**303**	**55**	**124**
	Galuchie	129	**179**	**132**	141	1	**6**	**2**	5	18	**27**	**13**	34	13	**12**	**7**	14	193	**271**	**71**	375
	Green Ridge	115	**117**	**114**	**194**	1	**5**	**4**	**6**	12	**18**	**14**	**56**	7	**11**	**9**	**23**	63	**137**	**116**	**1210**
Dadd Bennett	Mom Gulch	**173**	**172**	**99**	**183**	**3**	**4**	**0**	**6**	**71**	**33**	**8**	**40**	**14**	**11**	**8**	**16**	**812**	**369**	**12**	**469**
Lower Flowers	Lower Flowers	**219**	**177**	**126**	**151**	**6**	**5**	**4**	**3**	**22**	**61**	**25**	**22**	**9**	**18**	**11**	**14**	**226**	**891**	**220**	**108**
Crosier Mountain	Crosier	**159**	**252**	**168**	213	**3**	**12**	**5**	6	**13**	**27**	**16**	100	**6**	**17**	**10**	28	**90**	**608**	**149**	-
Hourglass	Hourglass	**171**	**168**	56	76	**4**	**5**	4	2	**19**	**24**	17	15	**10**	**12**	14	12	**144**	**253**	84	65
	Mean	**181**	**181**	**7**	**7**	**4**	**6**	**3**	**5**	**31**	**31**	**15**	**36**	**10**	**14**	**9**	**16**	**318**	**405**	**104**	**397**
	S.D.	**26**	**40**	**3**	**3**	**1**	**3**	**2**	**2**	**27**	**14**	**6**	**23**	**3**	**3**	**2**	**5**	**334**	**259**	**74**	341

Table 3. Mean percent bare soil for high severity plots in each fire by year since burning. Standard deviations are shown in parentheses. *Indicates sets of data within the Bobcat fire. [#]Indicates plots on granitic soil. – indicates no data.

	Years since burning									
Site	0-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0
Big Elk	87 (3)	82 (5)	-	-	-	-	-	-	-	-
Hayman[#]	90 (8)	84 (9)	-	-	-	-	-	-	-	-
Schoonover[#]	93 (2)	87 (2)	-	-	-	-	-	-	-	-
Hewlett	62 (9)	46 (13)	-	-	-	-	-	-	-	-
Jug Gulch and Bobcat Gulch*	92 (5)	57 (10)	29 (13)	12 (9)	-	-	-	-	-	-
Green Ridge*[#]	93 (5)	70 (12)	52 (12)	35 (15)	-	-	-	-	-	-
Lower Flowers	62 (2)	41 (8)	19 (13)	18 (6)	-	-	-	-	-	-
Crosier Mountain[#]	-	-	48 (8)	17 (8)	15 (7)	14 (8)	-	-	-	-
Bear Tracks[#]	-	-	68 (4)	41(2)	34 (6)	23 (4)	-	-	-	-
Hourglass	-	-	-	-	-	-	27 (14)	20 (9)	14 (5)	11 (6)
Mean	**86 (13)**	**76 (17)**	**37 (19)**	**21 (14)**	**26 (11)**	**19 (7)**	**27 (14)**	**20 (9)**	**14 (5)**	**11 (6)**

Table 4. List of the independent variables and the variables selected for each model. * indicates a discrete variable.

	Variables Selected					
Independent variables	**Primary model**	**Interaction model**	**4-parameter model**	**3-parameter model**	**2-parameter model**	**1-parameter model**
Bare soil (%)	X	X	X	X	X	X
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	X	X	X	X	X	
Hillslope position* (swales or planar)	X	X	X	X		
Soil D_{84} (mm)	X	X	X			
Soil D_{50} (mm)						
Soil D_{16} (mm)	X					
Contributing area (m^2)		X				
Fire severity*						
Time since burning (years)						
Summer rainfall (mm)						
Average I_{30} (mm hr^{-1})	X	X				
Aspect (degrees)	X	X				
Slope (%)						
Bare soil * Contributing area		X				
Bare soil * Erosivity						
Bare soil * Erosivity* Contributing area						
Bare soil * Bare soil		X				

Table 5. Calibration and validation statistics for the models developed to predict the logarithm of annual sediment production. RMSE is the root mean square error and SEP is the standard error of prediction.

	Calibration		Validation	
Model	**R^2**	**RMSE**	**RMSE**	**SEP**
Primary model	0.76	0.64	0.71	0.74
Interaction model	0.83	0.54	0.70	0.73
4-parameter model	0.72	0.68	0.73	0.75
3-parameter model	0.68	0.71	0.66	0.67
2-parameter model	0.63	0.76	0.65	0.65
1-parameter model	0.58	0.81	0.73	0.74

Table 6. Model coefficients and statistics derived from the entire data set (n=225).

Primary Model

Variable	Parameter estimate	p-value	Partial R^2
Intercept	0.83627	0.0023	--
Bare soil (%)	0.02678	<.0001	0.58
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	0.00111	<.0001	0.05
Hillslope position (swales, planar)	-0.52469	<.0001	0.05
Soil D_{84} (mm)	-0.02511	0.0299	0.04
Average I_{30} (mm hr^{-1})	0.01678	0.0072	0.01
Time since burning (years)	-0.08811	0.0017	0.01
Aspect (degrees)	0.00038711	0.3377	0.01
Soil D_{16} (mm)	-0.47342	0.4683	0.01

Interaction Model

Variable	Parameter estimate	p-value	Partial R^2
Intercept	-0.02813	0.9182	--
Bare soil (%)	0.04338	<.0001	0.58
Bare soil * Contributing area	0.00000566	<.0001	0.07
Bare soil * Bare soil	-0.00021162	0.0005	0.07
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	0.00109	<.0001	0.04
Aspect (degrees)	0.0008241	0.0339	0.02
Average I_{30} (mm hr^{-1})	0.01503	0.0017	0.01
Hillslope position (swales, planar)	-0.30172	0.0021	0.01
Soil D_{84} (mm)	-0.03895	<.0001	0.01
Contributing area (ha)	-1.3731	0.015	0.01

4-Parameter Model

Variable	Parameter estimate	p-value	Partial R^2
Intercept	0.61243	0.003	--
Bare soil (%)	0.03093	<.0001	0.58
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	0.00133	<.0001	0.05
Hillslope position (swales, planar)	-0.4916	<.0001	0.05
Soil D_{84} (mm)	-0.03367	0.001	0.04

3-Parameter Model

Variable	Parameter estimate	p-value	Partial R^2
Intercept	0.27335	0.1315	--
Bare soil (%)	0.03056	<.0001	0.58
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	0.00135	<.0001	0.05
Hillslope position (swales, planar)	-0.40751	<.0001	0.05

2-Parameter Model

Variable	Parameter estimate	p-value	Partial R^2
Intercept	-0.40067	<.0001	--
Bare soil (%)	0.03208	<.0001	0.58
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	0.00127	<.0001	0.05

1-Parameter Model

Variable	Parameter estimate	p-value	Partial R^2
Intercept	-0.03124	0.7173	--
Bare soil (%)	0.03184	<.0001	0.58

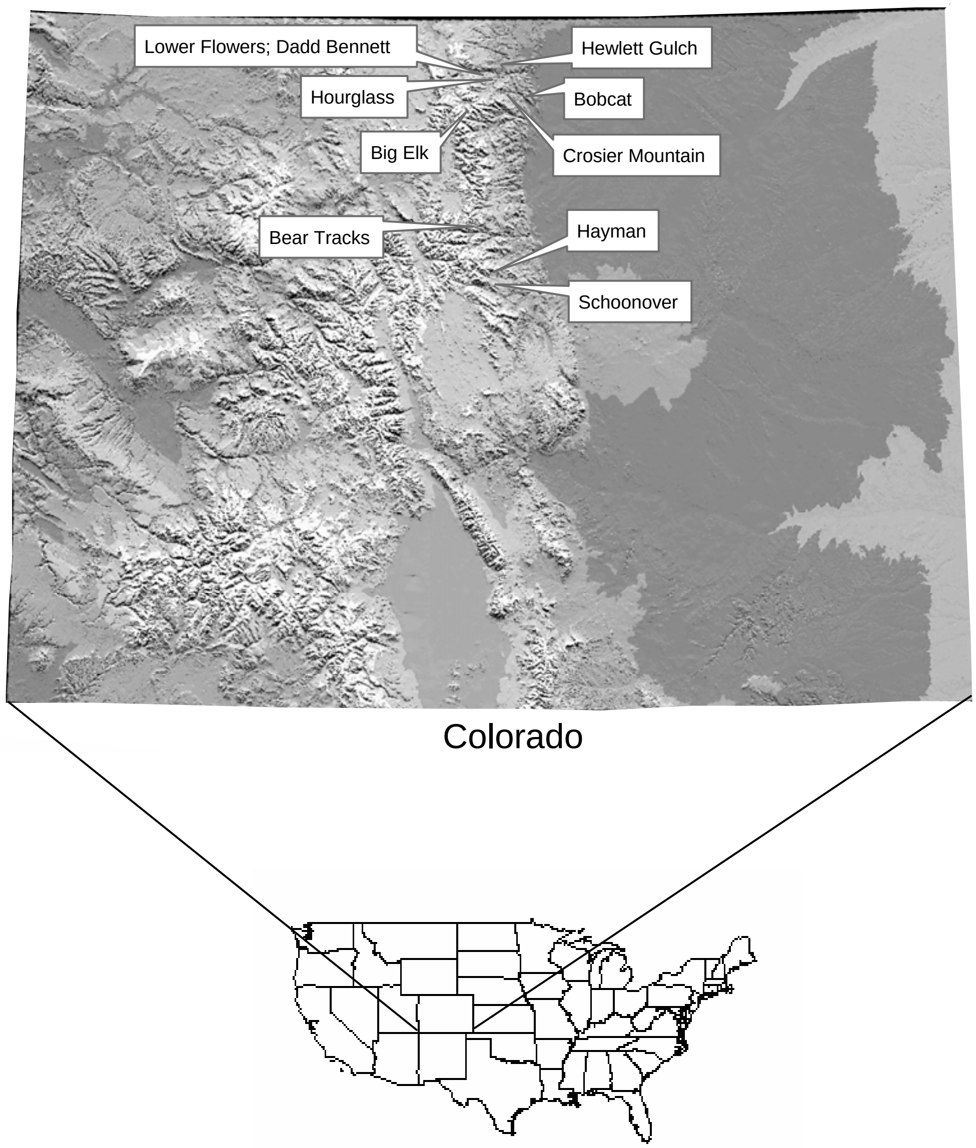

Figure 1. Location of the ten fires monitored in this study.

Figure 2. Two sediment fences in a swale in the Hayman fire. The lower fence is designed to capture any sediment that spills over the upper fence. Total storage capacity is about 2 Mg of wet sediment. The 20-L bucket in the upper fence is on the fabric apron laid in front of each fence.

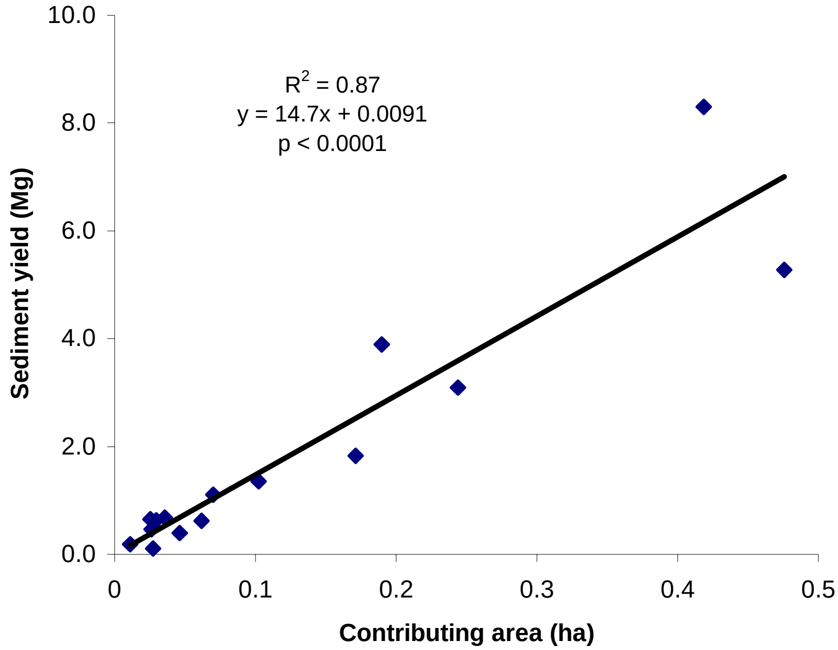

Figure 3. Relationship between contributing area and sediment yields in 2003 for the 15 plots on the north side of the Hayman fire.

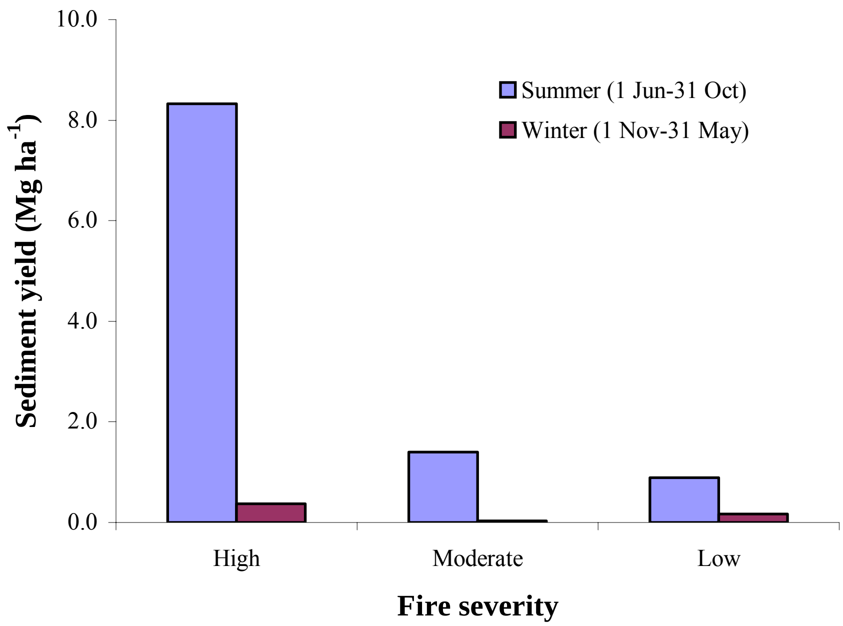

Figure 4. Sediment yields by fire severity for summer rainfall and winter snowmelt for all plots in the first two years after burning.

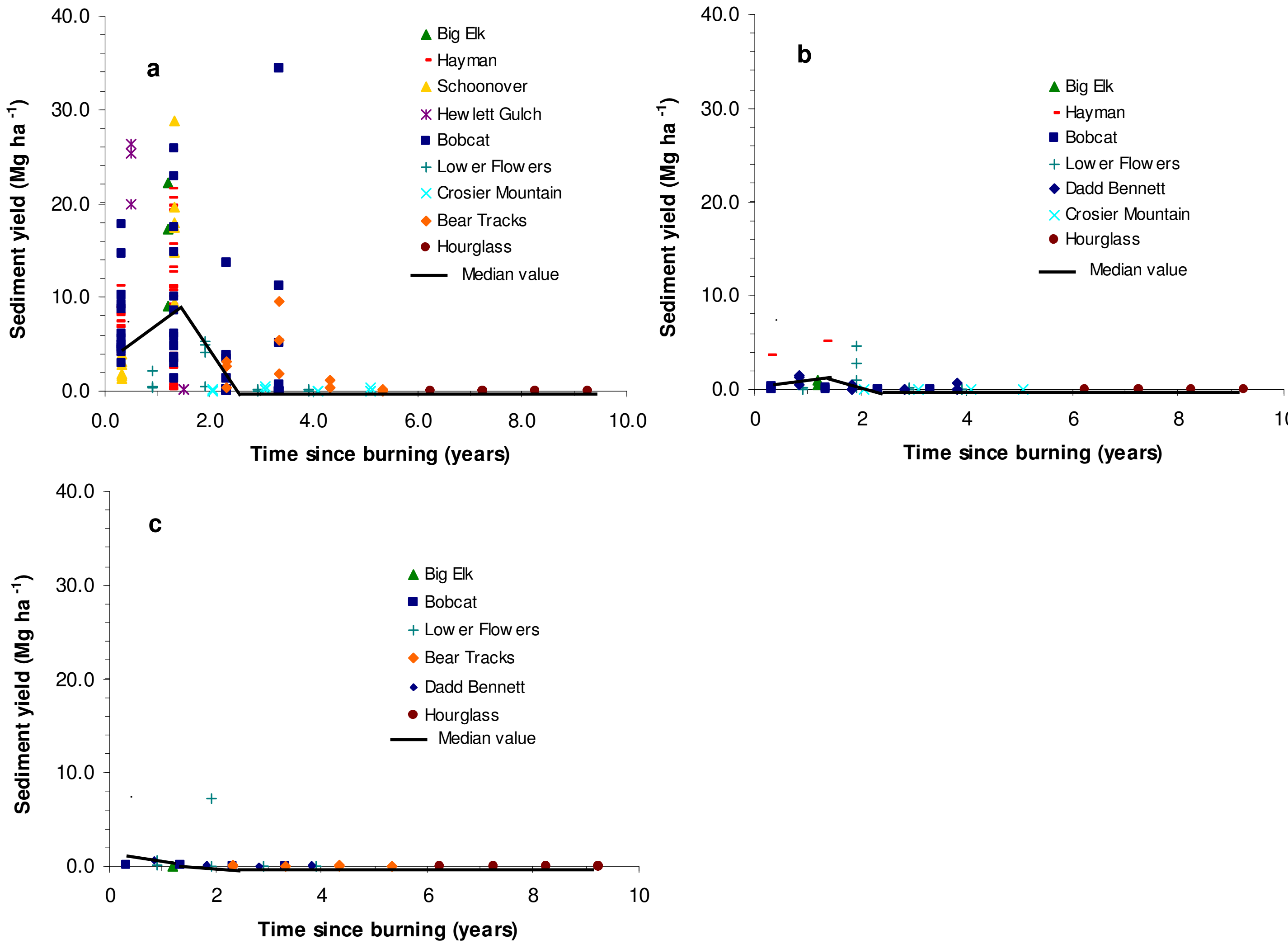

Figure 5. Annual sediment yields per unit area versus time since burning for (a) high, (b) moderate, and (c) low severity plots.

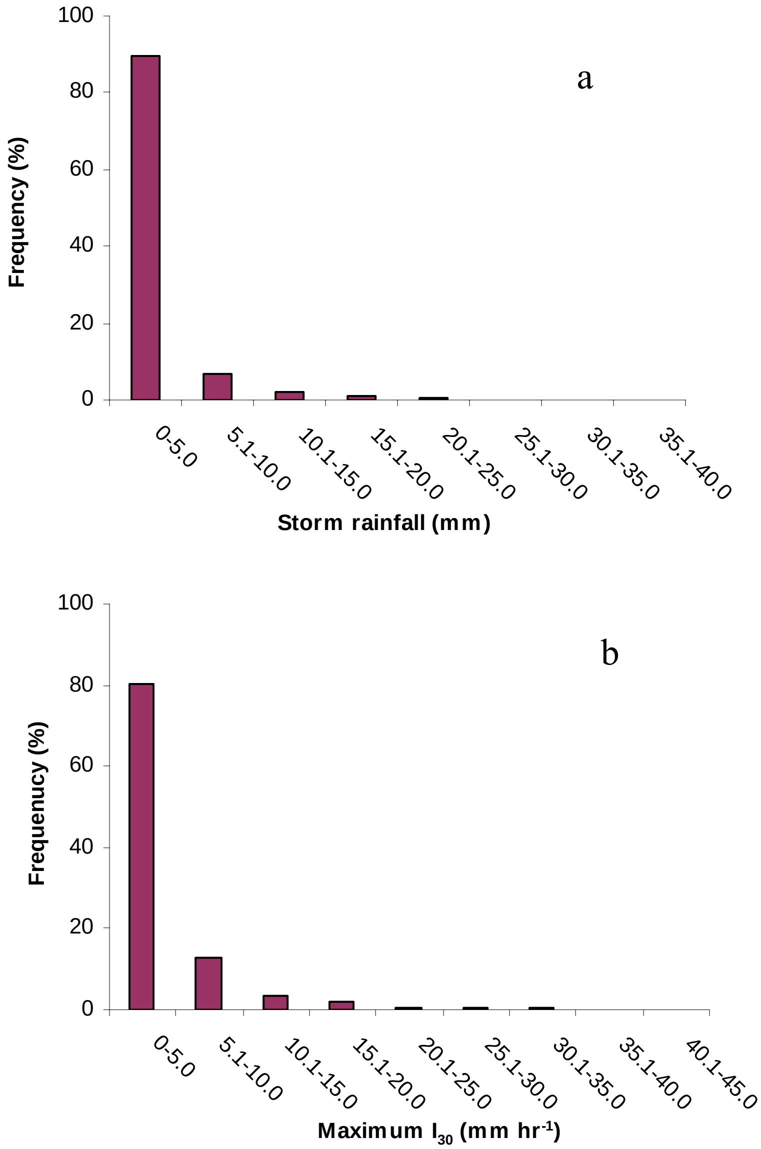

Figure 6. Frequency distribution of: (a) storm rainfall, and (b) maximum storm I_{30} for 1706 storms.

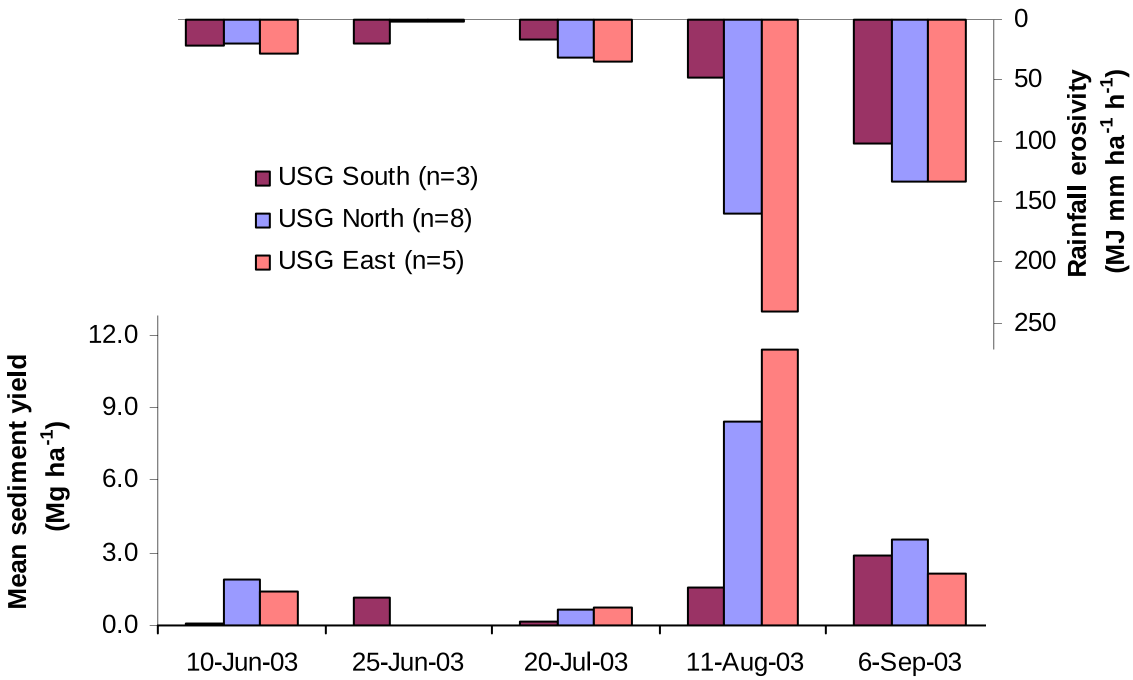

Figure 7. Rainfall erosivity and mean sediment yields in 2003 from 5 storms in 3 parts of the Upper Saloon Gulch (USG) area of the Hayman fire. The three rain gages are within 2 km of each other, and the numbers in parentheses represent the number of high severity plots associated with each rain gage.

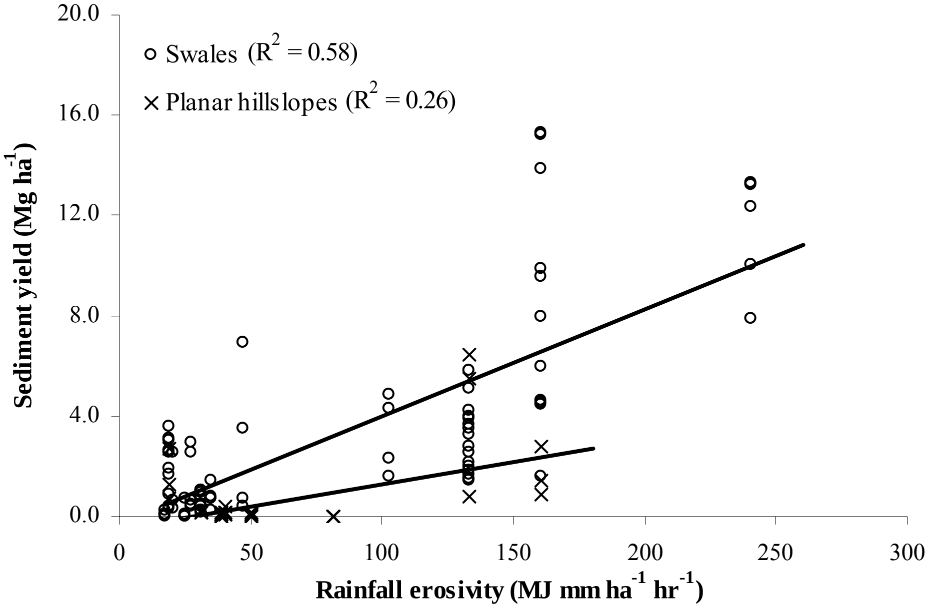

Figure 8. Sediment yields versus rainfall erosivity for swales and planar hillslopes in the Hayman fire for the five sediment-producing storms in 2003. The slopes of the regression lines are significantly different at p=0.01.

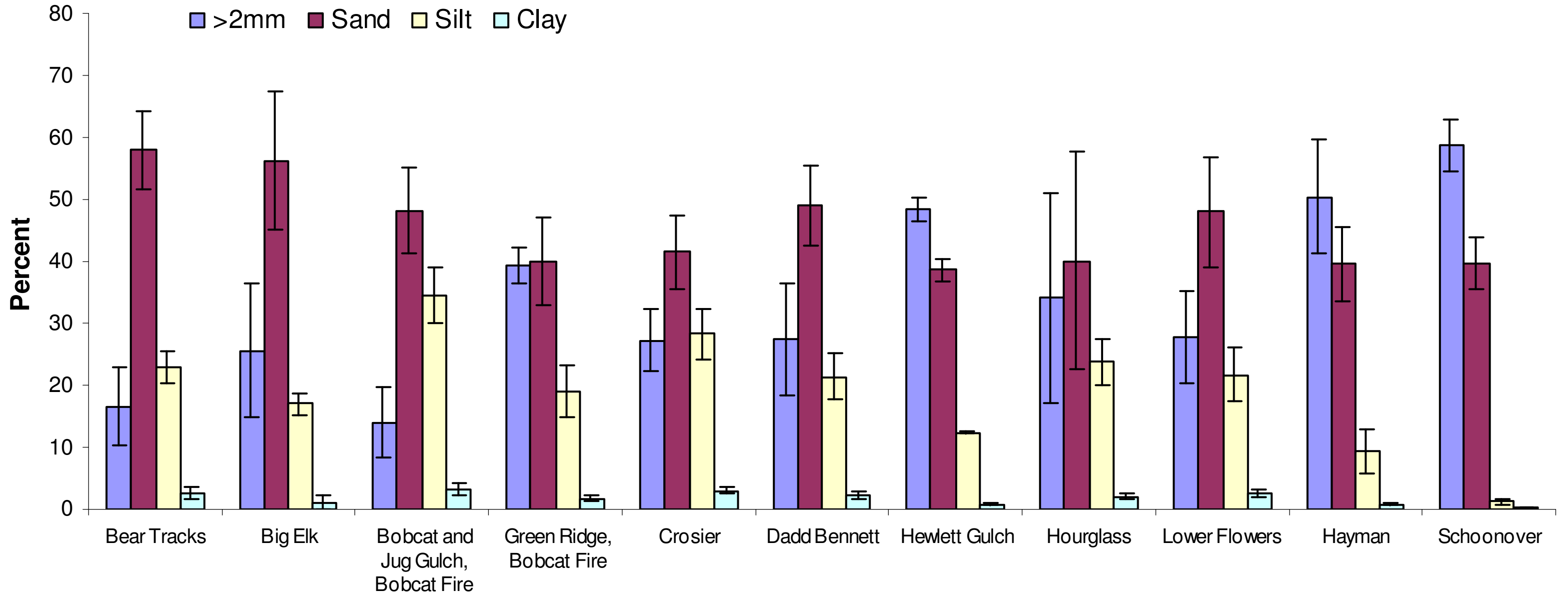

Figure 9. Mean percent of soil mass by particle-size class for each fire or study area. Bars indicate one standard deviation.

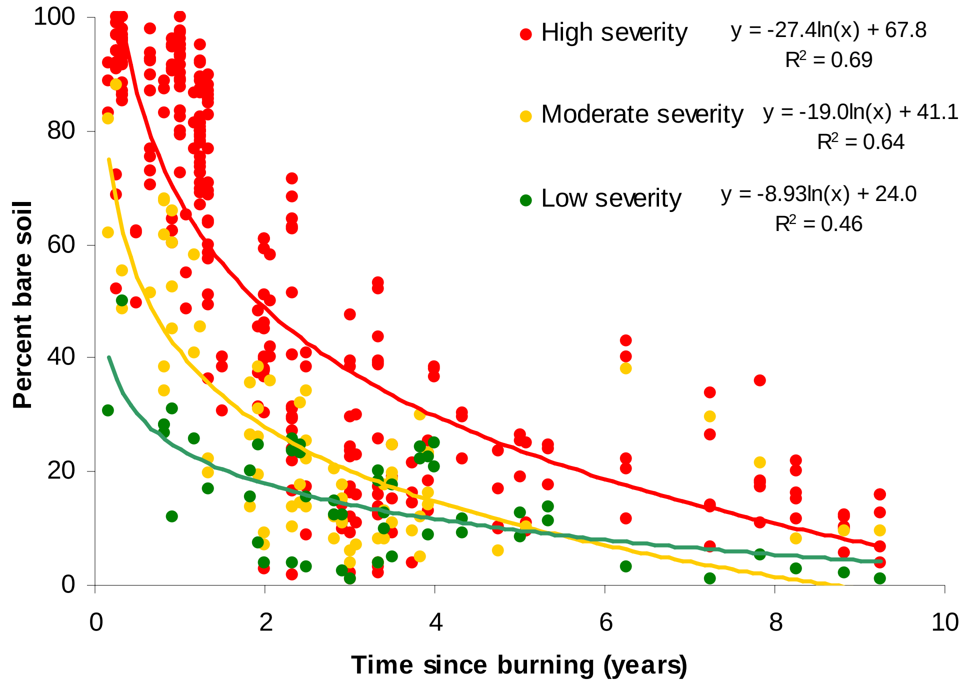

Figure 10. Percent bare soil for all plots by time since burning and fire severity.

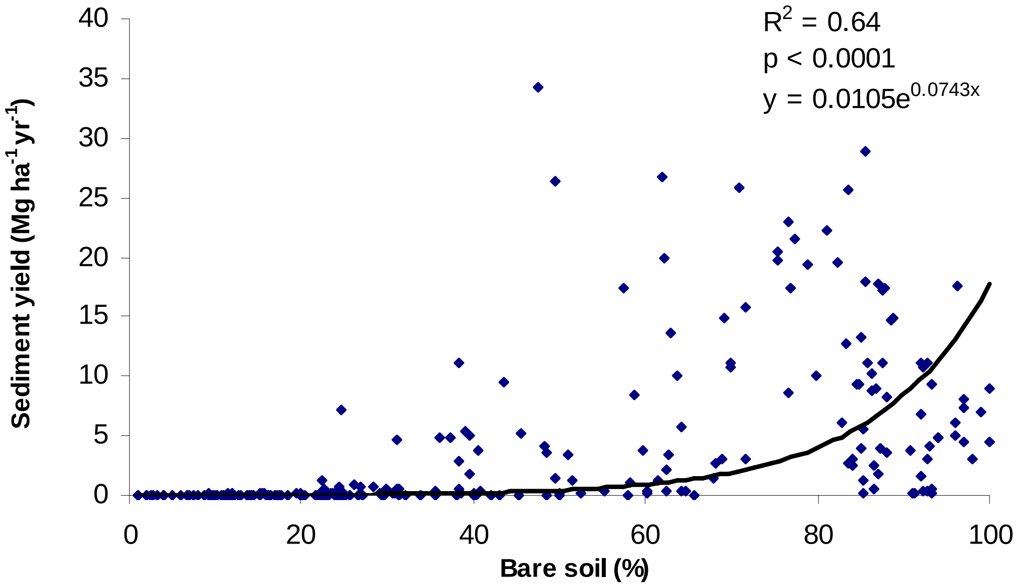

Figure 11. Annual sediment yields versus percent bare soil for all years and plots (n=255).

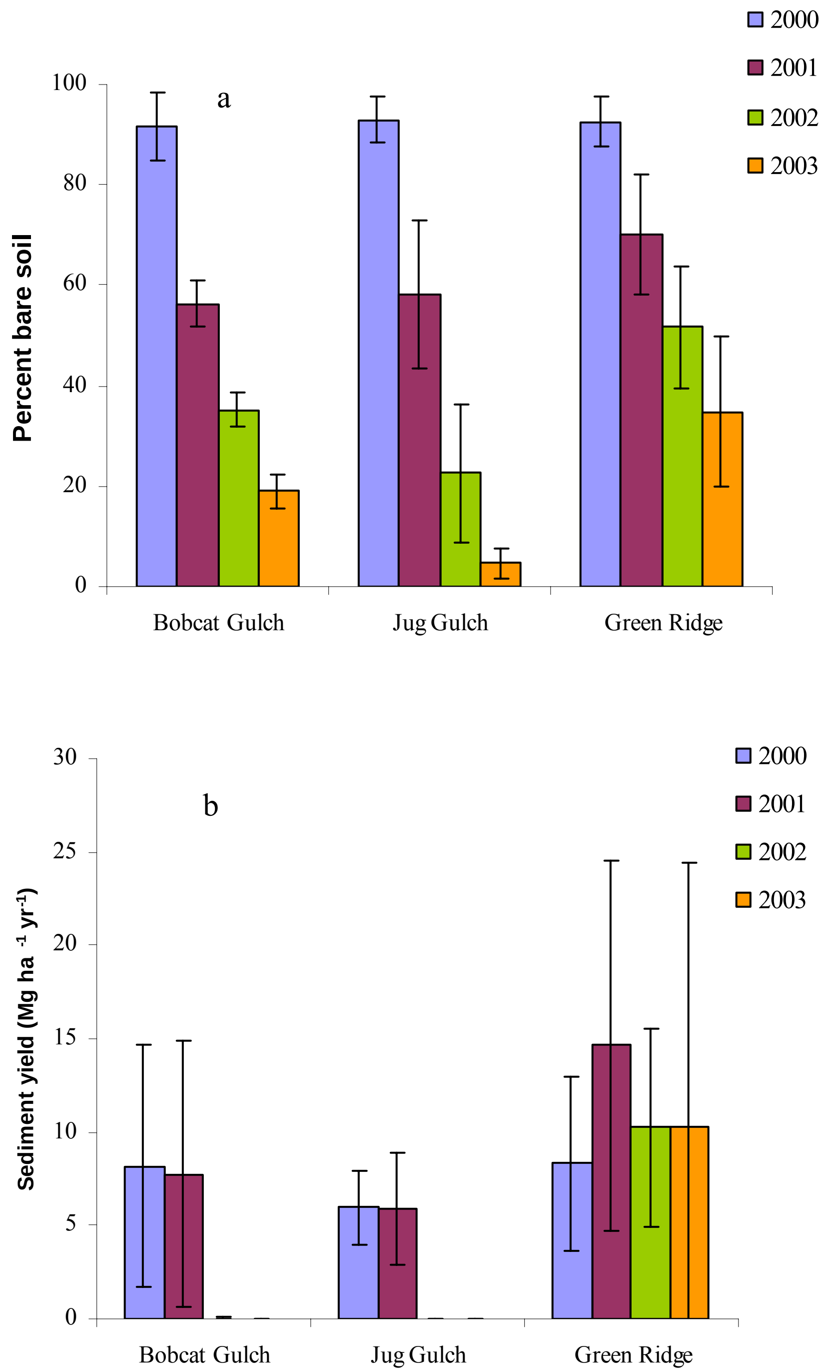

Figure 12. Mean percent bare soil (a) and sediment yields (b) over time for three study areas burned at high severity at the Bobcat fire. Bars indicate one standard deviation.

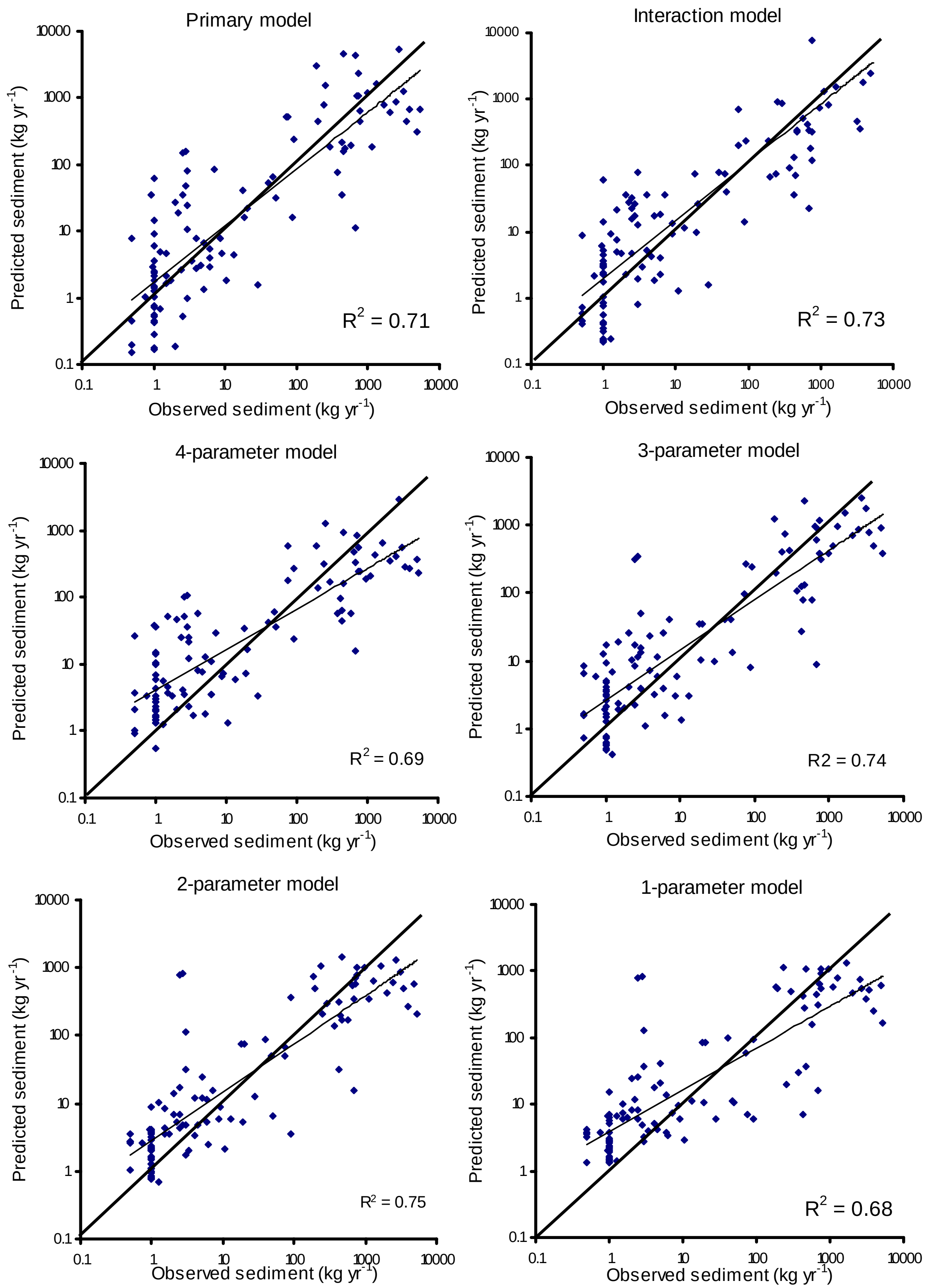

Figure 13. Predicted versus observed annual sediment yields for the validation data set for the six models listed in Tables 4 and 5.

3. HILLSLOPE AND RILL EROSION AFTER HIGH SEVERITY WILDFIRES, COLORADO FRONT RANGE

3.1. ABSTRACT

In the Colorado Front Range, hillslope-scale sediment yields can increase by two or more orders of magnitude after fire, but little is known about the dominant erosion processes or key sediment source areas on hillslopes. An important issue for land managers and designing post-fire treatments is whether most of the sediment is being eroded off hillslopes by sheetwash, or from convergent areas by rill incision. The two primary objectives of this study were to: (1) compare sediment yields from planar and convergent hillslopes ("swales"); and (2) determine the proportion of the swale sediment yields that can be attributed to rill incision in the swale axes. Sediment fences were used to measure sediment yields for either two or three years from 26 swales and 11 planar hillslopes that had burned at high severity in June 2002. Rill incision was measured after each storm in 14 swales. The incision rates were then compared to the sediment collected in the fences to determine the proportion of sediment derived from rill erosion.

The mean annual sediment yield during the three years of monitoring was 9.3 Mg ha^{-1} for the swales and only 2.7 Mg ha^{-1} for the planar hillslopes. On average, the estimated rill erosion in the swale axes accounted for 60% to 80% of the sediment collected in the sediment fences. Although rill incision rates were variable within and between swales, there was a strong relationship between the changes in rill incision and

the product of local slope and contributing area. These results indicate that the majority of sediment was derived from localized convergent zones that occupy less than 1% of the contributing area. This suggests that post-fire rehabilitation treatments must be designed to reduce rill incision if they are to successfully reduce hillslope-scale sediment yields.

3.2. INTRODUCTION

3.2.1. Background and Objectives

The large increases in soil erosion rates after high severity wildfires have been attributed to the breakdown of soil aggregates, loss of ground cover, decrease in infiltration, and increase in overland flow (Helvey, 1980; Moses, 1982; Morris and Moses, 1987; Inbar e*t al.*, 1998; Pierson *et al.,* 2001; Prosser and Williams, 1998; Robichaud et al., 2000; Benavides-Solorio and MacDonald, 2001; Moody and Martin, 2001a). In the Colorado Front Range fire suppression has increased ponderosa pine densities, thereby increasing the likelihood of high severity fires (Brown *et al*., 1999; Kaufmann *et al*., 2000; Huckaby *et al*., 2001; Romme *et al*., 2003). Post-fire erosion and sedimentation are a growing concern in much of the western United States due to expanding human populations and the adverse effects on water quality, infrastructure, and aquatic habitat (e.g., Agnew *et al*., 1997; Kunze, 2003).

Forested ecosystems in the Colorado Front Range are particularly susceptible to high post-fire erosion rates because of the frequency and intensity of summer thunderstorms. Rainfall intensities of only 10 mm hr^{-1} can initiate infiltration-excess overland flow on severely burned hillslopes, and recent studies indicate that there are typically about 5 to 10 storms per summer that exceed this threshold (Chapter 2). Runoff rates increase non-linearly with increasing storm magnitude, and the high runoff rates can cause severe rilling and channel erosion (Moody and Martin, 2001b; Kunze, 2003). After the 1996 Buffalo Creek fire, for example, unit-area runoff rates were estimated to reach 24 $m^3 s^{-1} km^{-2}$ as a result of a storm with a peak intensity of 90 mm hr^{-1} (Moody and Martin, 2001b).

The initial mechanisms for detaching and transporting soil particles on hillslopes are rainsplash and sheetwash (e.g., Knighton, 1998). The downslope accumulation and concentration of overland flow causes a shift in erosion processes from sheetwash to rill and gully erosion (e.g., Julien, 1995). Several studies in the Colorado Front Range have shown that the high surface runoff rates after high severity fires, when coupled with soil water repellency and the lack of vegetation, leads to concentrated overland flow and the incision of small channels or rills in previously unchannelled swales (Libohova, 2004; Moody and Martin, 2001b). These rills appear to have a large affect on hillslope-scale erosion rates, as unit-area sediment yields are 2-3 times higher from swales than planar hillslopes (Benavides-Solorio and MacDonald, 2005; Chapter 2). However, it is unclear whether the rills are a primary source of sediment, or just an efficient pathway for transporting the sediment generated by rainsplash and sheetwash down into the higher-order channels.

On cultivated hillslopes rill erosion has been shown to be the dominant source of sediment (Foster *et al*., 1984; Goevers and Poesen, 1988; Whiting *et al*., 2001; Valcarel *et. al.*, 2003). Rills that form in topographically convergent areas generate much more sediment than rills that form on planar hillslopes because of the increased shear stress resulting from the concentration of overland flow (Slattery *et al*., 1994; Davidson and Harrison, 1995).

Predicting rill erosion is difficult because cross-sectional areas and longitudinal profiles commonly are irregular, and this results in non-uniform flow velocities, depths, slopes, and shear stresses (Foster *et al.*, 1984). Particle detachment, D_r (g m^{-2} s^{-1}), occurs when the shear stress (τ) exceeds the minimum stress at which detachment occurs (τ_{crit}) (Foster and Meyer, 1972; Elliot and Laflen, 1993). Quantitatively,

$$D_r = K_r (\tau - \tau_{crit}) \qquad (1)$$

where K_r (s m^{-1}) is the rill erodibility factor. τ (Pa) is defined as:

$$\tau = \lambda RS \qquad (2)$$

where λ is the specific weight of water (g m^{-2} s^{-2}), R is the hydraulic radius (m), and S (m m^{-1}) is the slope of the energy grade line. The slope of the energy grade line is commonly approximated by the channel slope (Knighton, 1998). τ_{crit} is considered very small on slopes over 30% because a thin layer of overland flow is capable of detaching soil particles (e.g., Pannkuk and Robichaud, 2003). After wildfires τ_{crit} is further reduced due to the decline in soil aggregate stability and the loss of litter, woody debris, and live vegetative cover.

Unit stream power (Ω) also can be used to predict rill erosion (Nearing *et al.*, 1997), as the formula to calculate Ω simply replaces the hydraulic radius term in equation 2 with discharge per unit channel width, q (m^2 s^{-1}):

$$\Omega = \lambda qS \qquad (3)$$

where Ω is in W m^{-2}. A flume study on burned soils found that unit stream power was a better predictor of rill erosion than the shear stress equation (eq. 1) (Pannkuk and Robichaud, 2003).

Runoff should accumulate proportionally with area if rainfall intensity and infiltration are constant across a hillslope. Therefore contributing area can be used in place of either the hydraulic radius (R) or unit discharge (q). Similarly, contributing area times local slope is a surrogate for shear stress or unit stream power, and this can be used for predicting rill erosion. It follows that a model with slope*area can be used to predict post-fire sediment yields at the hillslope-scale if rill erosion in convergent zones is the dominant erosional process.

The objectives of this study were to: (1) compare sediment yields from planar and convergent hillslopes ("swales"); (2) measure rill erosion rates in swale axes; (3) compare the mass of sediment from rill erosion to the measured sediment yields; and (4) develop empirical models for predicting rill erosion rates from rainfall and site characteristics. The goal was to determine whether the majority of eroded sediment from burned hillslopes is derived from rill erosion in convergent areas, or by a combination of rainsplash and sheetwash across the entire hillslope. This information can be used to better understand hillslope erosion processes after burning, improve physically-based post-fire erosion models, and help design effective post-fire rehabilitation treatments.

3.2.2. Study Areas

Sediment yields were measured for the first three years after burning at two wildfires in the central Colorado Front Range (Figure 1). The Schoonover fire burned

1500 ha approximately 2 km southeast of Deckers, Colorado, in May 2002, and the Schoonover study area was in the northeastern portion of this fire. The Hayman fire burned over 55,000 ha in June 2002, and the Hayman study area was in the northeast corner of the fire approximately 10 km north of the Schoonover fire. The study sites in both fires were burned at high severity according to the criteria developed by Wells *et al.* (1979) and applied by the USDA Forest Service (1995). Prior to the fires ponderosa pine (*Pinus ponderosa*) was the dominant vegetation type.

The parent material is Precambrian granite that is part of the Pikes Peak batholith. The granite is heavily weathered due to multiple cycles of uplift and erosion. The most recent uplift and exposure was approximately 40 to 72 million years ago (Kent and Parker, 1980). Soils at both fires are poorly aggregated, coarse gravelly sandy loams ranging from Typic Ustorthents on south-facing slopes to Typic Cryorthents on north-facing slopes (Moore, 1992; Welter, 1995). The soils are typically 10-50 cm deep and very susceptible to water erosion if the surface cover is removed (Gary, 1975; Moore, 1992).

3.3. METHODS

3.3.1. Site Descriptions

Sediment yields were measured from 11 planar hillslopes (Figure 2a) and 26 convergent hillslopes or swales (Figure 2b) that were unchanneled prior to burning (Libohova, 2004). The 11 planar hillslopes and 20 of the 26 swales were in the Hayman fire; the remaining 6 swales were in the Schoonover fire (Table 1). Measurements began in July 2002 on 13 of the swales in the Hayman fire and all 6 swales in the Schoonover fire. The other 7 swales and 11 planar hillslopes were established in spring 2003. In this chapter a plot refers to a single swale or planar hillslope. The plots in the Hayman fire were grouped around 4 tipping bucket rain gages, and the term study site is used to refer to one of these groups of plots. The six swales at the Schoonover fire comprise just one study site as these were located around one recording rain gage.

3.3.2. Precipitation

The first tipping bucket rain gage in the Hayman fire was installed in June 2002, and three more were added in May 2003. The rain gage in the Schoonover fire was installed in June 2002. The resolution of the rain gages was either 0.20 mm or 0.25 mm.

Precipitation events were considered discrete storms if they were separated by at least 60 minutes with no rain. The depth, duration, and maximum 30-minute intensity (I_{30}) were determined for each storm during the summer rainfall season (1 June-31 October). Rainfall erosivities were calculated for each storm greater than 5 mm by multiplying the maximum I_{30} times the total kinetic energy (ΣE_m) of the storm (Renard *et al.*, 1997). The total kinetic energy was determined by dividing the storm into five-minute intervals, calculating the E_m (MJ ha^{-1}) for each five-minute interval (I_5) using equation 5, and summing the E_m values (Renard *et al.*, 1997):

$$E_m = 0.29 \times \left(1 - 0.72^{(-0.05 I_5)}\right) \quad (5)$$

The total summer erosivity was the sum of the calculated erosivity values for each storm larger than 5 mm.

3.3.3. Sediment Fences

Sediment fences (Robichaud and Brown, 2002) were used to trap the sediment eroded from each hillslope (Figure 2). The sediment fences were installed in either mid-summer 2002 or spring 2003, and sediment yields were measured through October 2004. The sediment fences were constructed by attaching 1-2 m wide geotextile fabric to 1.2 cm diameter rebar that was hammered about 0.5 m into the ground (http://www.fs.fed.us/insititute/middle_east/platte_pics/ silt_fence.htm). Two or three fences were used in the larger swales to increase the storage capacity and detention time, and thereby minimize the loss of sediment due to over-topping. The eroded sediment was manually removed after sediment-producing rain events and weighed to the nearest 1/4 kg. Subsamples of the eroded sediment were collected, aggregated, weighed, dried, and weighed again in order to determine gravimetric water content (Gardner, 1986). The sediment weights measured in the field were corrected by the measured water content to obtain a dry mass.

The contributing area above most of the sediment fences was determined by surveying the perimeter with either a Leica total station or a Trimble hand-held GPS unit. The contributing areas of the seven smallest plots (≤ 100 m^2) were determined by measuring the length and width with a tape measure. The mean contributing area of the swales was 1837 m^2 (s.d.=1543 m^2), and the range was from 110 to 6500 m^2 (Table 1). The planar hillslopes had a mean contributing area of 91 m^2 (s.d.=52 m^2) and a range of 35 m^2 to 220 m^2. The contributing areas of the planar plots were necessarily smaller to minimize lateral convergence and because these plots were purposefully situated at varying distances from a sharp ridge-top. More specifically, three sets of three planar plots were established at 10, 20, and 30 m from the ridge-top, respectively; one of these sets also included plots that extended 40 and 50 m from the ridge-top, respectively.

The average slope from the sediment fence to the drainage divide was measured with a clinometer or a total station. The mean slope of the planar plots was 36% (s.d.=6.3%), and the range was from 24% to 45%. The mean slope of the swale axes was 26% (s.d.=6.6%), and the range was from 18% to 41% (Table 1).

3.3.4. Rill Incision

The change in rill cross-sectional area is termed “rill incision”, which includes both the downcutting and widening of a rill. Rill incision rates were measured in 11 swales at the Hayman fire and 3 swales at the Schoonover fire using 4-12 cross-sections in the axis of each swale. Measurements were made from July 2002 to October 2004 (Table 1). The uppermost cross-sections were near the top of the swale where 2-5 smaller hillslope rills converged to form a larger, central rill in the swale axis. The lowest cross-section was placed near the sediment fence, but just above the pond that formed behind the sediment fence during storms. The other cross-sections typically were 2-10 m apart and placed to represent the variations in slope and rill morphology.

At each cross-section an aluminum pin frame was placed on top of permanent rebar, and the depth in millimeters was measured at each of 22 pins spaced 5 cm apart (Figure 3). Cross-section measurements began in July 2002 on 6 swales in the Hayman fire and 3 swales in the Schoonover fire. In the Hayman fire there was at least one sediment-producing storm before the cross-sections were established, but there was no evidence of any surface runoff or rill incision at the Schoonover fire prior to the establishment of the cross-sections and sediment fences. In May 2003, 24 more cross-sections were established in 5 swales in the Hayman fire.

Rill incision was measured for seven storms at both the Hayman and Schoonover fires. In each case the change in cross-sectional area was due to a single rainstorm except for the final measurements in 2003, which represent the combined effect of at least two sediment-producing rainstorms. A set of rill measurements also were made after spring snowmelt in late May or early June of each year, but there was little cross-sectional change over the winter. Hence the spring measurements were used as the baseline for the subsequent summer rainstorm season.

Rill incision rates were multiplied by the length between successive cross-sections to calculate the volume of eroded sediment. For these calculations the sediment fence was used as the lowermost boundary, and uppermost boundary was where the central rill split into multiple hillslope rills. The calculated volumes from each rill segment were summed and multiplied by the mean soil bulk density to obtain the mass of sediment eroded from the central rill in each swale.

Soil bulk density was determined by taking five 310 cm^3 core samples from the central rill in each swale. These samples were dried and weighed, and the mean bulk density was calculated for each swale. There was surprisingly little variability between samples. The overall mean bulk density was 1.43 g cm^{-3} (s.d.=0.09 g cm^{-3}) in the Hayman fire and 1.39 g cm^{-3} (s.d.=0.07 g cm^{-3}) in the Schoonover fire (Table 1). The calculated mass of sediment eroded from each rill was summed for all swales, and then divided by the total amount of sediment collected from the sediment fences to determine the proportion of the measured sediment yield that can be attributed to rill incision for each storm event.

A digital elevation model (DEM) was created for 10 swales from detailed topographic surveys using a total station. The horizontal resolution of the DEMs was about 1 m and the vertical accuracy was approximately 0.02-0.05 m. The DEMs were used to determine the contributing area at each cross-section using the flow accumulation routine in ArcGIS (ESRI, 2004). The local slope at each of these cross-sections was measured directly with a 1-m long digital level. The storm precipitation variables, contributing area, local slope, and slope-area product were used as independent variables when developing a multivariate model for predicting rill incision at each cross-section. The regression analysis using slope and contributing area was limited to the 10 swales with topographic survey data.

Most of the swale sideslopes and approximately 40% of the planar plots had smaller, less-defined rills. These "hillslope rills" generally were much smaller than the central rill in the swale axes, and their location was not as clearly defined by the topography. The length, width, and depth of hillslope rills were measured in six swales and 4 planar hillslopes at the end of summer 2004. The six swales were chosen because they had large differences in their respective unit-area sediment yields, and the four planar hillslopes were chosen because these were the only planar plots with clearly-defined rills.

3.3.5. Ground Cover

The percent cover within the contributing area of each plot was measured using a systematic point count (Parker, 1951). The point count was conducted by classifying the surface cover at a minimum of 100 equally spaced points along 2-6 equally spaced transects across the contributing area. The cover classes were bare soil, ash, live vegetation, litter, woody debris (>1 cm diameter), rock (>5 cm diameter), tree, and moss. Ground cover was assessed once in July 2002 and in the spring and fall of 2003 and 2004.

3.3.6. Statistical Analysis

Sediment yields generally are presented in mass per unit area due to the strong relationship between sediment yields and contributing area (Chapter 2). Mean sediment yields were weighted by contributing area so that the smaller plots did not have a disproportionate influence. One-way ANOVA was used to test for statistical differences in sediment yields between fires, years, and topographic location (i.e., swales vs. planar hillslopes). Differences were considered significant at $\alpha = 0.05$. Regression coefficients were determined using the REG procedure in SAS (2001).

3.4. RESULTS

3.4.1. Precipitation

In 2002 there was only one large and one small sediment-producing storm at each fire (Table 2). Total rainfall was only 103 mm at the Hayman fire and 85 mm at the

Schoonover fire (Table 2). In 2003 there were four sediment-producing storms at the Hayman fire and six at the Schoonover fire. Total rainfall was at least 50% higher than in 2002. In 2004 total rainfall was 20-40% higher than in 2003, but there were only four sediment-producing events in the Hayman fire and two at the Schoonover fire. Long-term data from Cheesman Reservoir indicates that summer rainfall relative to the historic average was 56% lower in 2002, 28% lower in 2003, and 3% lower in 2004 (NOAA, 2004).

The sediment producing storms all occurred between 10 June and 9 September, and these generally were convective thunderstorms. The localized nature of the storms caused considerable spatial variability in rainfall amounts and intensities. The four rain gages in the Upper Saloon Gulch (USG) study sites in the Hayman fire were separated by less than 2 km, but rainfall intensities and erosivities typically varied by a factor of two or more between rain gages. For example, in 2003 the largest rainstorm had a maximum I_{30} of 40.8 mm hr^{-1} at the study site on the east side of USG (USG East). At USG South the maximum I_{30} was only 13.7 mm hr^{-1} for the same storm (Figure 4a). The rainfall erosivities for this event differed by up to a factor of six between the different rain gages (Figure 4b).

The rainstorms in the Hayman fire were typically larger and more intense than the storms in the Schoonover fire. In 2003 and 2004 the highest I_{30} at the Hayman fire was 41 mm hr^{-1} and 42 mm hr^{-1}, respectively. By comparison, the highest I_{30} at the Schoonover fire was 22.3 mm hr^{-1} in 2003 and 33.5 mm hr^{-1} in 2004 (Table 2). In terms of historic rainfall intensities in the central Colorado Front Range, a maximum I_{30} of 25 mm hr^{-1} has a 2-year recurrence interval, while a maximum I_{30} of 40 mm hr^{-1} has about a 5-year recurrence interval (Hershfield, 1961).

Summer erosivity values followed the same patterns over time and between fires as total rainfall and I_{30}, but the differences between years and sites were proportionally larger (Table 2). Summer erosivity values ranged from 59 MJ mm ha^{-1} hr^{-1} at the Schoonover fire in 2002 to 590 MJ mm ha^{-1} hr^{-1} at the Hayman fire in 2004. Rainfall erosivities were highly variable within the Hayman fire, as in 2004 rainfall erosivities ranged from 348 MJ mm ha^{-1} hr^{-1} at USG South to 590 MJ mm ha^{-1} hr^{-1} at the Brush Creek study site. Relative to the long-term mean (Renard et al., 1997), the mean summer erosivity from all of the study sites was 66% below average in 2002, 10% below average in 2003, and 26% above average in 2004.

3.4.2. Sediment Yields

The annual sediment yields from the swales were strongly related to both the contributing area (R^2=0.40; p<0.0001) and slope length (R^2=0.38; p=0.0001). Since the swales were much larger and produced much more sediment than the planar plots, the sediment yield data were normalized by contributing area to facilitate comparisons between plots, study sites, and fires.

Over 95% of the eroded sediment was generated from summer rainstorms between 1 June and 31 October (Chapter 2). Winter snowmelt produced virtually no sediment, as the rate of snowmelt was likely too slow to initiate infiltration-excess overland flow. In the first three summers after burning a rainfall intensity of 8-10 mm hr^{-1} or a rainfall erosivity of about 20 MJ mm ha^{-1} hr^{-1} was sufficient to generate overland flow and surface erosion (Table 2). This threshold of 8-10 mm hr^{-1} is similar to those identified after the Buffalo Creek (Moody and Martin, 2001b) and Bobcat (Kunze, 2003) fires.

Most of the annual sediment yield was usually generated from just one or two large storms (Table 2). In 2002 about 90% of the total sediment yield at the Hayman fire was generated by an 11-mm storm, and 96% of the total sediment yield at the Schoonover fire was generated by a 9-mm storm. In 2003 about half of the total sediment yield at each fire was generated by one storm. In 2004, one storm generated over 95% of the sediment yield at the Schoonover plots, while in the Hayman fire four storms produced almost equal amounts of sediment (Table 2).

Sediment yields were highly variable between years, particularly at the Schoonover fire. The lowest annual sediment yield at both fires was in 2002 because the plots were not established until the middle of the summer and there were no large storms (Table 2). The highest mean annual sediment yields were in 2003 when the swales in the Hayman fire produced 10.8 Mg ha^{-1} (s.d.=6.3 Mg ha^{-1}) and the swales in the Schoonover fire produced 16.7 Mg ha^{-1} (s.d.=6.4 Mg ha^{-1}). Mean sediment yields in 2004 were lower than in 2003 despite the increase in rainfall and total erosivity (Table 2).

Although the rainfall intensities and erosivities were lower at the Schoonover fire than at the Hayman fire, the mean sediment yield for the swales was 38% higher at Schoonover than at Hayman in 2003, and 15% higher in 2004 (Table 2). The high variability in sediment yields between swales meant that these differences were not significant in either year.

Annual sediment yields per unit area were 3-5 times higher from the swales than the planar hillslopes, and this difference was significant in both 2003 and 2004 (Table 2). On a storm-by-storm basis, the mean sediment yields from swales were 1.4 to 14 times higher than the mean sediment yields from the planar hillslopes (Table 2). The differences in sediment yields between planar hillslopes and swales were significant for each of the 8 sediment-producing storms in 2003 and 2004.

The between-plot variability in sediment yields was much greater for the planar hillslopes than the swales, as five of the planar plots produced most of the sediment while the remaining six planar plots produced very little sediment. Hence the coefficient of variation (CV) of the sediment yields from the planar hillslopes exceeded 100% in both 2003 and 2004 (Table 2). For example, in 2004 the mean annual sediment yield from the five highest yielding planar plots was 7.2 Mg ha^{-1} (s.d.=6.5 Mg ha^{-1}), or about 50 times the mean sediment yield from the remaining six plots (0.014 Mg ha^{-1};s.d.=0.013 Mg ha^{-1}). In contrast, the CV of the sediment yields from swales was 48% in 2003 and 64% in 2004. The minimum annual sediment yield for a swale was at least 3.0 Mg ha^{-1} in both 2003 and 2004.

In contrast to the swales, the unit area sediment yields from the planar hillslopes were not consistently related to contributing area (R^2=0.0002; p=0.95) or slope length (R^2=0.003; p=0.80). The planar plots that were 20 and 30 m long had the highest unit area sediment yields, while the lowest sediment yields per unit area were from the plots that were 40 and 50 m long (Figure 5). Sediment yields from the 10 m long plots were intermediate.

3.4.3. Controls on Sediment Yields

After normalizing by contributing area, the storm-based sediment yields were most strongly related to rainfall intensity and rainfall erosivity. Rainfall erosivity explains 60% of the variability in storm-based sediment yields for the swales in the Hayman fire in 2002 and 2003 (Figure 6). Unit area sediment yields were also significantly related to the maximum I_{30}, but this relationship was slightly weaker (R^2=0.51). For the Schoonover plots, rainfall erosivity explained just 17% of the storm-based variability in sediment yields. The poorer relationship for the Schoonover swales may be partly due to the fact that some swales were up to 1 km from the rain gage, so the rain gage may not have accurately characterized the rainfall at all plots. For the planar hillslopes, rainfall erosivity explained only 1% of the storm-based variability in sediment yields.

The spatial variability in storm rainfall resulted in a correspondingly high variability in storm-based sediment yields (Table 2). For example, the rainfall erosivity for the large storm on 11 August 2003 was 241 MJ mm ha^{-1} hr^{-1} at USG East (Figure 4), and the mean sediment yield from the four swales in this study site was 10.7 Mg ha^{-1} (s.d 2.5 Mg ha^{-1}). The erosivity for the same storm at USG South was 80% lower, and the mean sediment yield from the 3 swales in this study site was only 11% of the mean value from the swales at USG East (1.2 Mg ha^{-1}; s.d.=1.6 Mg ha^{-1}).

In the third summer after burning sediment yields were slightly lower despite higher rainfall erosivities (Table 2). This decline can be attributed to vegetative re-growth, as the annual sediment yields from the swales are significantly related to percent bare soil after normalizing for contributing area and rainfall erosivity (Figure 7). Other studies with a wider range of ground cover have shown that ground cover is the dominant control on post-fire erosion rates (Chapter 2; Benavides-Solorio and MacDonald, 2005).

3.4.4. Rill Incision

Rills formed in the central axis of each swale, on most swale sideslopes, and on four of the eleven planar hillslope plots. The so-called "hillslope rills" that formed on the swale sideslopes and planar hillslopes were typically about 5 m long and had cross-sectional areas of less than 50 cm^2. Although these rills were not as topographically confined as the rills in the central axes, they did not exhibit much lateral migration. Once formed, both the swale axes rills and hillslope rills persisted over the duration of the study.

The rills in the swale axes generally began within 10 to 30 m of the ridge-top. A few of swales had relatively wide and flat ridge-tops, and in these swales the central rill in the swale axis might form up to 100 meters from the ridge-top. The average length of the central rills was 59 m (s.d.=32 m), and the range was from 23 m to 127 m. Because storm runoff flowed over the sediment fences, these central rills usually continued for several hundred meters downslope, and eventually flowed into a lower-gradient depositional reach.

Over the study period net incision occurred in 92 of the 94 cross-sections. The mean incision rate over the entire monitoring period was 0.032 m^2 (s.d.=0.021 m^2), and the range was from –0.018 m^2 (negative values indicate net aggradation) to 0.12 m^2. Minor amounts of overbank and channel deposition were observed in approximately 5% of the cross-sections. Incision rates generally increased in the downstream direction, and each of the two cross-sections that aggraded slightly over the monitoring period were close to the top of a rill where incision rates were lowest. Net erosion occurred at all cross-sections with a contributing area of at least 100 m^2.

The increases in cross-sectional area occurred through a combination of downcutting and widening. At the end of the study there was a weak inverse relationship between contributing area and the rill width-to-depth ratio (Figure 8). The preponderance of vertical incision relative to widening implies that the rills became more confined as cross-sectional area increased.

Incision rates were highly variable between cross-sections, and sometimes varied by a factor of 2 or more between adjacent cross-sections. For example, the net incision at cross-section 2 in swale 17 in the Hayman fire was 0.024 m^2 (Figure 9a), or half of the measured value at cross-section 3 (Figure 9b). At some cross-sections much of the total increase in cross-sectional area occurred during a single storm. At cross-section 3 in swale 17, for example, 58% of the total incision occurred as a result of the 17 mm storm on 11 August 2003 (Figure 9b). The rate of incision was more constant between storms at cross-section 5, which was further downslope in swale 17 (Figure 9c). Cross-section 5 had the highest net incision rate of 0.074 m^2.

The highest incision rates often occurred as a result of the storms with the highest I_{30}'s and rainfall erosivities, but this was not always the case. At USG East, for example, the largest storm of the monitoring period (11 August 2003) caused the highest storm-based incision rates at 21 of the 29 cross-sections. However, the largest storm at USG North and in the Schoonover fire produced the highest incision rates at less than 20% of the cross-sections. Given the wide variability in incision rates, there was only a weak relationship between incision rates and rainfall erosivity (R^2=0.06) or I_{30} (R^2=0.06) when all the data were pooled.

Incision rates were most strongly related to topographic variables such as contributing area and slope. Contributing area explained 26% of the variability in rill incision between May 2003 and September 2004. Univariate analysis showed that local slope explained only 4% of the change in cross-sectional area, but contributing area times local slope explained 64% of the variability in rill incision (Figure 10).

The relative importance of contributing area and slope varied with contributing area. For cross-sections with a contributing area of at least 500 m^2, local slope explained 30% of the total change in cross-sectional area while contributing area explained just 2% of the total change. The implication is that contributing area is the most important control on rill incision rates across the entire data set, but local slope becomes a more important factor in the larger swales. For example, the highest incision rate was 0.12 m^2, and this cross-section had a contributing area of 2460 m^2 and a relatively high local slope of 32%. The next cross-section was 7 m downslope and this had a local slope of only 24%, and the net incision was 0.08 m^2, or 50% less. The two cross-sections with the largest contributing areas (>4000 m^2) had local slopes of only 11% and 8%, respectively, and the net incision at each was less than 0.05 m^2.

Slope and contributing area were much poorer predictors of incision rates at the cross-sections with contributing areas less than 500 m^2. In these cross-sections no more than 8% of the variability in incision rates could be explained by contributing area, local slope, or slope*area.

Minor aggradation occurred over each winter in about half of the cross-sections. The mean winter aggradation rate was 0.0014 $m^2 yr^{-1}$ (s.d.=0.0092), or just 3% of the mean incision rate. This aggradation was probably due to rill sideslope failures because 10-20% of all cross-sections became up to 10 cm wider and 5 cm shallower over the winter. In contrast to un-vegetated badlands (Schumm, 1956), this winter aggradation was not sufficient to completely fill in the rills.

3.4.5. Relationship Between Rill Incision and Sediment Yields

The calculated mass of rill erosion in the swale axes can account for most of the sediment captured in the sediment fences. In the Hayman fire, the calculated rill erosion was equal to 76% of the sediment yields measured from the swales, and rill erosion from the swales in the Schoonover fire could account for 63% of the measured sediment yields (Table 3; Figure 11).

For individual storm events, the ratio of the calculated rill erosion to the measured sediment yield varied from 0.38 to 1.59 for the swales in the Hayman fire; and 0.38 to 0.96 for the swales in the Schoonover fire (Table 3). At the Hayman fire, the ratio of rill erosion to sediment yields was substantially higher for the first one or two storms in each summer than the subsequent storms (Table 3). At the Schoonover fire the first storm in 2003 did have the highest ratio, but this was not true in 2004. Ratios were much more consistent at the Schoonover fire, as the values for 6 of the 7 storms ranged between 0.61 and 0.96.

The relative contribution of rill erosion tended to decrease as sediment yields increased. At the Hayman fire, rill erosion was equal to 89% of the sediment yield when sediment yields were less than 1000 kg. But when sediment yields exceeded 1000 kg, rill erosion could only account for 63% of the sediment yield. At the Schoonover fire, rill incision accounted for only 55% of the 5100 kg that was measured in swale 4 during the large storm on28 June 2004.

Although the ratio of rill erosion to sediment yields varied by storm and between swales, most comparisons show that rill erosion was the key control on sediment yields. For example, sediment yields from three adjacent swales in the middle Saloon Gulch (MSG) study site varied by a factor of three, but a detailed survey suggests that the observed differences in sediment yields are directly proportional to the differences in rill densities among these three swales (Table 4; Figure 12

The rill surveys on the planar plots further support the view that rill erosion is the principal source of sediment. In September 2004, hillslope rills were evident on four of the five planar plots that produced more than 1.0 Mg $ha^{-1}yr^{-1}$. There was no evidence of rilling on the other six planar plots, and sediment yields from each of these plots were less than 0.5 Mg ha^{-1} yr^{-1}. Sediment yields on the four planar plots with rills were strongly correlated with total rill area (R^2=0.57), and unit area sediment yields were strongly correlated with rill density (R^2=0.57).

When the data from the 6 swales and 4 planar plots that were surveyed are combined, sediment yields from 2003 to 2004 are strongly related to total rill area (Figure 13a). Similarly, the unit area sediment yields from 2003 to 2004 are strongly related to the measured rill density (Figure 13b). The sediment yields from the swales generally were much higher than the sediment yields from the planar hillslopes, and this can be explained by their higher percentage of rill area and higher rill densities. However, the two planar plots with the highest rill densities had unit-area sediment yields that were similar to the swales (Figure 13b).

3.5. DISCUSSION

3.5.1. Importance of Rill Erosion

Prior to the burning, the swales in the Hayman fire showed no evidence of overland flow, a central rill, or surface erosion (Libohova, 2004). The first rainstorms generated overland flow and a central rill was formed in each swale. The rills were connected to higher-order channels further downslope, indicating that the fire extended the channel network onto previously unchanelled hillslopes and greatly increased channel density.

The lack of deposition in the cross-sections indicates that the central rills were highly efficient at transporting the eroded sediment. The high efficiency can be attributed to the relatively steep slopes and lack of roughness elements, such as vegetation, to slow runoff and trap sediment. There also was very little deposition in the overbank areas adjacent to each rill. Sediment delivery ratios were not directly measured, but the results indicate that the vast majority of the sediment that was eroded from the central rills was delivered to the sediment fences. In the absence of a sediment fence, the eroded sediment would have been transported downslope to lower-gradient, higher-order channels.

Field observations indicate that rill erosion rates remained high in the steep, low-order channels downslope of the sediment fences. Studies after the 1996 Buffalo Creek fire indicated that approximately 80% of the sediment eroded from a 4 ha and 7 ha basin was derived from channel incision, and the majority of sediment came from 3rd and 4th order channels (Moody and Martin, 2001a). The central rills in this study would have been considered a first order or small second order channel in the Buffalo Creek study (J. Moody, USGS, 2004, pers. comm.). Therefore higher incision rates, and potentially unit-area sediment yields, may have been generated downslope of the sediment fences, provided the slopes remained high. Considerable aggradation was observed in lower-gradient, higher-order channels, and the transition between incision and deposition is believed to be controlled primarily by channel gradient (Moody and Martin, 2001a).

After the Buffalo Creek fire the amount of sediment derived from rill and sheetwash erosion was minimal, and these sources were roughly equal during a 100-yr storm that had a peak rainfall intensity of about 90 mm hr^{-1} (Moody and Martin 2001a). The implication is that the very high channel incision rates in the 3rd and 4th order channels overwhelmed any increase in sheetwash and rill erosion during this very large storm event. These results are not entirely consistent with the results of the present study, as Figure 11 shows a general decrease in the ratio of rill erosion to sediment yields as sediment yields (or storm size) increased. This suggests that proportionally more sediment is generated from sheetwash erosion during the larger storms, and rill erosion is a progressively less important source of sediment.

3.5.2. Controls on Rill Initiation

Rill initiation in the swale axes was controlled by slope, contributing area, and topographic convergence. Because the rills were connected to higher-order channels, the top of each rill can be viewed as a channel initiation point. When the slope of the swale axis was at least 15%, a contributing area of less than 100 m^2 often was sufficient to initiate a rill. Defining a slope-area threshold for rill initiation was difficult because of the variability in the amount of topographic convergence at the top of each swale. Nevertheless, it is clear that the channel initiation threshold was greatly reduced by burning since the swales were unchannelled immediately prior to burning. In western Oregon, channel initiation in unburned catchments requires a contributing area of roughly 10,000 m^2 at slopes of 15-30% (Montgomery and Dietrich, 1992).

The location and initiation point of the rills on the planar plots and swale sideslopes are much harder to predict. These hillslope rills appeared to form at almost random points on relatively planar hillslopes, so contributing area and local slope may not be useful indicators of where these rills may develop. Small topographic anomalies may be an important control on rill initiation, as this would affect flow accumulation and direction. Local variability in burn severity, soil depth, and soil water repellency are other possible controls, as each of these will influence infiltration, runoff rates, and local shear stress (e.g., Robichaud and Waldrup, 1994; Benavides-Solorio and MacDonald, 2001).

3.5.3. Rill Morphology

The first one or two sediment-producing events of each summer generally had the highest ratios of rill erosion to measured sediment yields (Table 3). This suggests that the sediment that was deposited in the bottom of the rill over the winter was easily detached and transported by the first major rainstorm. The lower ratios later in the summer suggest that rill erosion may have been reduced by armoring. However, sediment supply did not appear to be a limiting factor because most cross-sections continued to erode and bedrock was exposed in less than five percent of the cross-sections. This would suggest that sediment yields are limited by some combination of the critical shear stress and the transport capacity rather than sediment supply.

Twenty to twenty-five years would be needed to fill the rills given the mean winter aggradation rate of 0.0014 $m^2 yr^{-1}$ and the mean summer incision rate of 0.032 $m^2 yr^{-1}$. Ninety years would be necessary to fill the highest incision rate of 0.12 m^2. The historic fire recurrence interval in the central Colorado Front Range is approximately 50 years, but the recurrence interval of high severity fires is probably more than 100 years (Romme *et al.*, 2003). Since most erosion occurs following high severity fires (Chapter 2), the rills will probably fill in before the next high severity fire. The lack of rills prior to the Hayman and Schoonover fires further supports the assertion that the rills are likely to fill in before the next high severity fire (Libohova, 2004).

Given the infilling rates and the lack of erosional features on the swales before the Hayman fire, the effects of post-fire erosion on hillslopes do not appear to persist in time. However, the sediment eroded from the hillslopes remains in the low gradient channels for time periods that exceed the natural fire recurrence intervals (Moody and Martin, 2001a). Therefore, at the watershed scale, post-fire erosion appears to affect long-term landscape evolution patterns.

3.5.4. Soil Texture and Erosion Processes

The sediment production rates from the planar hillslopes in the Hayman fire were very low compared to most other sites in the Colorado Front Range that have been burned at high severity. The mean annual sediment yield from planar hillslopes in the first two years after the Bobcat fire was 4.9 Mg ha^{-1} (s.d =5.3 Mg ha^{-1}), or 80% more than the planar hillslopes in the Hayman fire (p=0.07) (Benavides-Solorio, 2003; Chapter 2). Since the total rainfall erosivity was 40% higher in the Hayman fire than the Bobcat fire the true difference in sediment yields is probably even larger. In contrast, a comparison of the mean sediment yields from swales in the Bobcat and Hayman fires showed no significant difference (p=0.59).

The higher sediment yield from the planar plots in the Bobcat fire may be attributed to the finer soil texture and greater susceptibility to sheetwash erosion. In the case of the swales, the lack of a significant difference in sediment yields may be due to a difference in topography, as the study areas in the Hayman and Schoonover fires are much more dissected than the study areas in the Bobcat fire. The swales in the Hayman fire tend to have steeper sideslopes and more sharply defined axes than the swales in the Bobcat fire. The greater topographic convergence and steeper slopes will help concentrate the overland flow and increase the shear stress in the swale axes. The higher shear stress may compensate for the coarser soils in the Hayman fire, and result in comparable sediment yields. On the planar hillslopes there is less concentrated runoff and less capability to transport the larger particles, so sediment yields will be lower in areas with coarse-textured soils, such as the Hayman and Schoonover fires.

3.5.5. Mitigating Post-fire Erosion

Post-fire rehabilitation treatments are often implemented after high severity fires to minimize erosion and reduce risk to downstream resources (Robichaud *et a*l., 2000).

Rehabilitation efforts after the Hayman fire included scarification and seeding, contour-felling, and different types of mulch (Robichaud *et al*., 2003). Straw mulch was the most effective treatment in reducing erosion (Wagenbrenner et al., in press; D. Rough, CSU, unpublished data). Eleven rill cross-sections were installed in two swales that were treated with straw mulch in the Hayman fire. On average these cross-sections incised by just 0.006 m^2 from 2002 to 2004, or 20% of the mean value for the untreated swales in the Hayman fire.

Much of the straw mulch was transported from sideslopes into the swale axes. This resultant increase in surface roughness reduced overland flow velocities and rill incision rates. The largest storms produced only small amounts of fine sediment in the sediment fences. The coarser particles tended to be trapped in the rill behind small piles of mulch. In one case this sediment caused a net aggradation of 0.07 m^2, which is more than double the mean incision rate from the untreated swales.

The results from this study indicate that large amounts of sediment are eroded from the axes of convergent hillslopes or swales. It is relatively easy to predict the location of the central rill because swale axes are obvious landscape features, which represent less than 1% of the total hillslope area. A post-fire rehabilitation treatment such as straw mulching is successful because the mulch protects the soil surface, reduces rainsplash and sheetwash erosion on planar hillslopes, and lowers flow velocities and reduces rill erosion in swale axes.

3.6. CONCLUSIONS

Virtually all of the sediment was generated from short-duration, high-intensity summer thunderstorms that were highly variable in space and time. Little sediment was produced until rainfall intensities exceeded 10 mm hr^{-1}, or rainfall erosivities exceeded 20 MJ mm ha^{-1} hr^{-1}. The largest storm events yielded most of the sediment, as 60% of the sediment produced over the three-year study was generated from just 5 storms.

Mean sediment yields from convergent hillslopes or swales were 13.3 Mg ha^{-1} yr^{-1}, or 3.7 times higher than the mean sediment yield from planar hillslopes. Sediment yields on planar hillslopes were essentially bimodal because the mean sediment yield from five of the eleven planar plots was 6.0 Mg ha^{-1} yr^{-1} (s.d.=5.7 mg ha^{-1}), while the remaining six plots yielded only 0.18 Mg ha^{-1} yr^{-1} (s.d.=0.19 mg ha^{-1}). In comparison, each of the swales produced at least 3.0 Mg $ha^{-1}yr^{-1}$.

Rills formed in the axes of the swales during the first runoff event and continued to incise and widen over first three summers after burning. Cross-section measurements indicate that rill erosion in the swale axes can account for about 60-80% of the sediment captured in the sediment fences. On planar plots, sediment yields were strongly related to rill density (R^2=0.50). This suggests that rill erosion is the dominant erosion process on burned hillslopes in the Colorado Front Range. Net incision at individual cross-sections varied from -0.018 to 0.12 m^2, and 64% of this variability was explained by contributing area times local slope. This is consistent with other erosion studies, as contributing area is a surrogate for the amount of runoff and local slope controls the amount of energy available to detach and transport sediment.

The rills that contribute much of the eroded sediment after wildfires occur in well-defined, localized convergent zones that occupy less than 1% of the total hillslope area. To be effective, post-fire rehabilitation treatments need to reduce erosion in these convergent zones, and this can best be done by minimizing the amount, concentration, and velocity of overland flow. Straw mulch is particularly effective in reducing post-fire erosion rates because it increases surface roughness in the swale axes, and this reduces overland flow velocities and limits rill incision.

3.7. REFERENCES

Agnew, W., R.E. Labn, and M.V. Harding, 1997. Buffalo Creek, Colorado, fire and flood of 1996. *Land and Water* 41: 27-29.

Benavides-Solorio, J., 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. dissertation, Colorado State University, Fort Collins, CO, 218 p.

Benavides-Solorio, J., and L.H. MacDonald, 2005. Measurement and prediction of post-fire erosion at the hillslope-scale, Colorado Front Range. *International Journal of Wildland Fire* 14: 1-18.

Brown, P.M., M.R. Kaufmann, and W.D. Shepperd, 1999. Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. *Landscape Ecology* 14: 513-532.

Davidson, D.A. and D.J. Harrison, 1995. The nature, causes, and implications of water erosion on arable land in Scotland. *Soil Use and Management* 11: 63-58.

Elliot, W.J., and J.M. Laflen, 1993. A process-based rill erosion model. *Transactions of the American Society of Agricultural Engineers* 36: 65-72.

ESRI, 2004. ArcGIS software release 8.0. Redlands, CA.

Foster, G. R., and L.D. Meyer, 1972. A closed-form soil erosion equation for upland areas. In *Sedimentation Symposium to Honor Professor Hans Albert Einstein*, H.W. Shen, (ed.). Colorado State University, Fort Collins, CO, p. 121-129.

Foster, G.R., L.F. Huggins, and L.D. Meyer, 1984. A laboratory study of rill hydraulics 2, shear stress relationships. *Transactions of the American Society of Agricultural Engineers* 27: 797-804.

Gardner, W.H., 1986. Water content. In *Methods of Soil Analysis: Part 1*, A. Klute (ed). American Society of Agronomy. Madison WI, p. 493-507.

Gary, H.L., 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine zone: the status of our knowledge. USDA Forest Service Research Paper, RM-139. Fort Collins, CO, 32 p.

Goevers, G. and J. Poessen, 1988. Assessment of the interill and rill contributions to total soil loss from an upland field plot. *Geomorphology* 1: 343-354.

Hack, J.T., 1965. Geomorphology of the Shenandoah Valley Virginia and West Virginia and origin of the residual ore deposits. U.S. Geological Survey Professional Paper 484. Washington, D.C., 84 p.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* 16: 627-634.

Hershfield, D.M., 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods of 1 to 100 years. Cooperative Studies Section, U.S. Weather Bureau, Washington, D.C., 70 p.

Huckaby, L.S., M.R. Kaufmann, J.M. Stoker, and P.J. Fornwalt, 2001. Landscape patterns of montane forest age structure relative to fire history at Cheesman Lake in the Colorado Front Range. USDA Forest Service, Rocky Mountain Research Station Proceedings RMRS-P-22. Fort Collins, CO, p.19-27.

Inbar, M., M. Tamir, and L. Wittenberg, 1998. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. *Geomorphology* 24: 17–33.

Julien, P.Y., 1995. Erosion and Sedimentation. Cambridge University Press. Cambridge, England, 280 p.

Kaufmann, M.R., L.S. Huckaby, and P. Gleason, 2000. Ponderosa pine in the Colorado Front Range: long historical fire and tree recruitment intervals and a case for landscape heterogeneity. In *Crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management,* Neuenschwander, L.F. (ed). University of Idaho and International Association of Wildland Fire. Moscow, ID, p. 153-160.

Kent, H.C., and K.W. Parker, 1980. Colorado geology. Rocky Mountain Association of Geologists. Denver, CO, 258 p.

Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. London Press. New York, New York, 383 p.

Kunze, M., 2003. Streamflow and sediment yield following the 2000 Bobcat fire, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, 133 p.

Libohova, Z., 2004. Effects of thinning and a wildfire on sediment production rates, channel morphology, and water quality in the upper South Platte River watershed. M.S. thesis, Colorado State University, Fort Collins, CO, 260 p.

Montgomery, D.R., and W.E. Dietrich, 1992. Channel initiation and the problem of landscape scale. *Science* 255: 826-830.

Moody, J.A., and D.A. Martin, 2001a. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26: 1049-1070.

Moody, J.A., and D.A. Martin, 2001b. Post-fire rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes* 15: 2981-2993.

Moore, R., 1992. Soil Survey of the Pike National Forest, Eastern Part, Colorado, Parts of Douglas, El Paso, Jefferson, and Teller Counties. US Department of Agriculture, Forest Service and Soil Conservation Service. Fort Collins, CO, 143 p.

Morris, S.E., and T.A. Moses, 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* 77: 255-264.

Moses, T.A., 1982. Erosional response of hillslopes after forest fire in the Colorado Front Range. M.S. thesis, University of Colorado, Boulder, CO, 217 p.

National Oceanic and Atmospheric Administration (NOAA), National Climate Data Center, 2004. Retrieved 1 May 2004, from http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWDI~StnSrch.

Nearing, M.A., L.D. Norton, D.A. Bulgakov, G.A. Larionov, L.T. West, and K.M. Dontsova, 1997. Hydraulics and erosion in eroding rills. *Water Resources Research* 33: 865–876.

Pannkuk, C.D., and Robichaud, P.R., 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* 39: ESG 1-9.

Parker, K.W., 1951. A method for measuring trend in range condition on national forest ranges. U.S. Department of Agriculture, administrative report. Washington, D.C., 26 p.

Pierson F.B., P.R. Robichaud, and K.E. Spaeth, 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological Processes* 15: 2905-2916.

Prosser, I.P., and L. Williams, 1998. The effect of wildfire on runoff and erosion in native Eucalyptus forest. *Hydrological Processes* 12: 251-265.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agriculture Handbook 703. Washington D.C., 404 p.

Robichaud, P.R., and T.A. Waldrop, 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resources Bulletin* 30: 27-34.

Robichaud, P.R., J.L. Beyers, and D.G. Neary, 2000. Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service General Technical Report RM-GTR-63. Fort Collins, CO, 85 p.

Robichaud, P.R., and R.E. Brown, 2002. Silt fences: an economical technique for measuring hillslope soil erosion. USDA Forest Service, General Technical Report RMRS-GTR-94. Fort Collins, CO, 24 p.

Robichaud, P.R., L.H MacDonald, J. Freeouf, D. Neary, D. Martin, and L. Ashmun, 2003. Post-fire rehabilitation of the Hayman fire. In *Hayman Fire Case Study*, R.T Graham (ed.). USDA Forest Service General Technical Report RMRS-GTR-114. Fort Collins, CO, p. 181-203.

Romme, W.H., T.T. Veblen, M.R. Kaufman, R. Sheriff, and C.M. Regan, 2003. Ecological effects of the Hayman fire. In *Hayman Fire Case Study*, R.T. Graham (ed.). USDA Forest Service General Technical Report RMRS-GTR-114. Fort Collins, CO, p. 181-203.

SAS Institute, 2001. SAS software release 8.02. Cary, NC.

Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands of Perth Amboy, New Jersey. *Geological Society of America Bulletin* 67: 597-646.

Slattery, M.C., T.P. Burt, and J. Boardman, 1994. Rill erosion along the thalweg of a hillslope hollow: a case study from the Cotswold Hills, Central England. *Earth Surface Processes and Landforms* 19: 377-385.

Tonkin, P.J., and L.R. Basher, 1990. Soil-stratigraphic techniques in the study of soil and landform evolution across the Southern Alps, New Zealand. *Geomorphology* 3: 197-205.

Valcarel, M., M.T. Taboada, A. Paz, and J. Dafonte, 2003. Ephemeral gully erosion in northwestern Spain. *Catena* 50: 199-216.

USDA Forest Service, 1995. Burned-area emergency rehabilitation assessment. Forest Service Handbook 2509.13-95-7. Washington, D.C., 18 p.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredrikson, E.C. Franklin, R.C. Froelich, and P.H. Dunn, 1979. Effects of fire on soil, a state-of knowledge review. USDA Forest Service General Technical Report WO-7. Washington, D.C., 34 p.

Welter, S.P, 1995. Topographic influences on soil erosion and soil development in hollows of the Rampart Range. Ph.D. dissertation, University of Colorado, Boulder, CO, 219 p.

Whiting, P.J., E.C. Bonniwell, and G. Matisoff, 2001. Depth and aerial extent of sheet and rill erosion based on radionuclides in soils and suspended sediment. *Geology* 12: 1131-1134.

Table 1. Site characteristics at the Hayman and Schoonover fires. Numbers in parentheses are standard deviations. n/a indicates not applicable.

	Hayman fire		**Schoonover fire**		
	Planar hillslopes	Swales	Planar hillslopes	Swales	Overall mean or total
Number of sites	11	20	0	6	37
Mean contributing area (m^2)	91 (52)	1771 (1760)	n/a	1936 (704)	1331 (1523)
Mean slope (%)	36 (6.4)	24 (6.6)	n/a	36 (3.4)	29 (7.7)
Swales with cross-sections	n/a	11	n/a	3	14
Number of cross-sections	n/a	71	n/a	23	94
Mean soil bulk density ($g\ cm^{-3}$)	n/a	1.43 (0.09)	n/a	1.39 (0.07)	1.42 (0.08)

Table 2. Rainfall, maximum I_{30}, and sediment yields for the sediment producing storms from 2003-2004 for: (a) Hayman fire, and (b) Schoonover fire. Totals are from all storms, and the values in parentheses are standard deviations.

a.

			Precipitation			Sediment yields (Mg ha^{-1})	
Year	Storm no.	Date	Rainfall (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})	Swales (n=20)	Planar hillslopes (n=11)
2002	1	21 July	10.9	21.8	62	6.2 (2.3)	n/a
	2	30 August	4.0	8.1	6	0.12 (0.22)	n/a
		Totals	**102.9**	**n/a**	**169**	**7.0 (2.2)**	**n/a**
2003	3	10 June	7.7 (0.7)	13.8 (2.2)	25 (6)	0.91 (1.3)	0.47 (0.79)
	4	19 July	10.3 (1.7)	16.0 (3.4)	33 (13)	0.44 (0.42)	0.087 (0.75)
	5	11 August	17.1 (5.9)	26.3 (13.0)	122 (97)	6.4 (4.8)	0.45 (0.88)
	6	6 September	45.3 (3.9)	24.1 (6.8)	113 (25)	2.9 (1.3)	1.2 (2.4)
		Totals	**158.8 (6.2)**	**n/a**	**324 (95)**	**10.8 (6.3)**	**2.2 (4.0)**
2004	7	10 June	13.1 (4.7)	23.0 (7.9)	79 (61)	3.7 (2.0)	0.54 (1.1)
	8	28 June	37.4 (15.8)	22.0 (7.8)	114 (53)	2.0 (3.2)	1.4 (2.1)
	9	26 July	50.6 (4.9)	36.6 (6.0)	256 (64)	2.4 (3.1)	0.88 (1.9)
	10	8 September	17.1 (6.5)	15.3 (3.4)	44 (7)	1.3 (1.5)	0.33 (0.64)
		Totals	**218.6 (34)**	**n/a**	**469 (127)**	**9.4 (8.3)**	**3.1 (5.5)**

b.

			Precipitation			Sediment yields (Mg ha^{-1})
Year	Storm no.	Date	Rainfall (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})	Swales (n=20)
2002	1	21 August	9.1	17.8	36	2.3 (0.95)
	2	10 September	14.7	5.6	11	0.11 (0.11)
		Totals	**84.8**	**n/a**	**59**	**2.4 (1.0)**
2003	3	24 June	12.2	22.9	64	2.7 (1.1)
	4	2 August	8.6	17.3	40	8.0 (4.7)
	5	5 August	4.8	8.6	9	0.17 (0.12)
	6	15 August	7.1	13.2	22	2.1 (1.3)
	7	20 August	5.6	11.2	15	1.6 (1.2)
	8	9 September	23.9	14.5	62	2.1 (0.79)
		Totals	**138.4**	**n/a**	**241**	**16.7 (6.4)**
2004	9	25 June	17.8	33.5	149	9.6 (6.1)
	10	29 July	11.9	14.7	32	1.0 (0.51)
		Totals	**168.0**	**n/a**	**271**	**10.6 (6.5)**

Table 3. Mean ratios of calculated rill erosion to measured sediment yields for each sediment-producing storm on the Hayman and Schoonover fires, 2002-2004. Totals represent the total mass of eroded sediment divided by the total incision measured between 2002 and 2004.

Hayman fire (14 swales)

	14-Jun-03	20-Jul-03	12-Aug-03	6-Sep-03	16-Jun-04	28-Jun-04	26-Jul-04	8-Sep-04	Total
Mean	1.59	1.53	0.80	0.50	1.00	0.38	0.47	0.76	0.76
s.d.	0.82	0.99	0.27	0.26	0.25	0.36	0.17	0.68	0.68

Schoonover fire (3 swales)

	23-Aug-02	24-Jun-03	2-Aug-03	20-Aug-03	9-Sep-03	28-Jun-04	29-Jul-04	Total
Mean	0.79	0.77	0.62	0.38	0.61	0.61	0.96	0.63
s.d.	0.19	0.22	0.13	0.26	0.29	0.19	0.48	0.29

Table 4. Site characteristics, sediment yields, and rill data for 3 swales in middle Saloon Gulch (MSG) in the Hayman fire 2003-2004.

	MSG1	**MSG2**	**MSG3**
Contributing area (m^2)	463	261	256
Axis slope (%)	24	27	29
Total sediment yield (Mg)	1.0	1.1	1.5
Total unit area sediment yield (Mg ha^{-1})	22	42	56
Length of rill in swale axis (m)	20	21	27
Average rill incision (m^2)	0.024	0.019	0.023
Eroded rill volume (m^3)	0.65	0.46	0.69
Total length of hillslope rills (m)	21	32	33
Total area of all rills (m^2)	8.6	8.9	10.5
Rill area/contributing area (m^2 m^{-2})	0.019	0.033	0.041

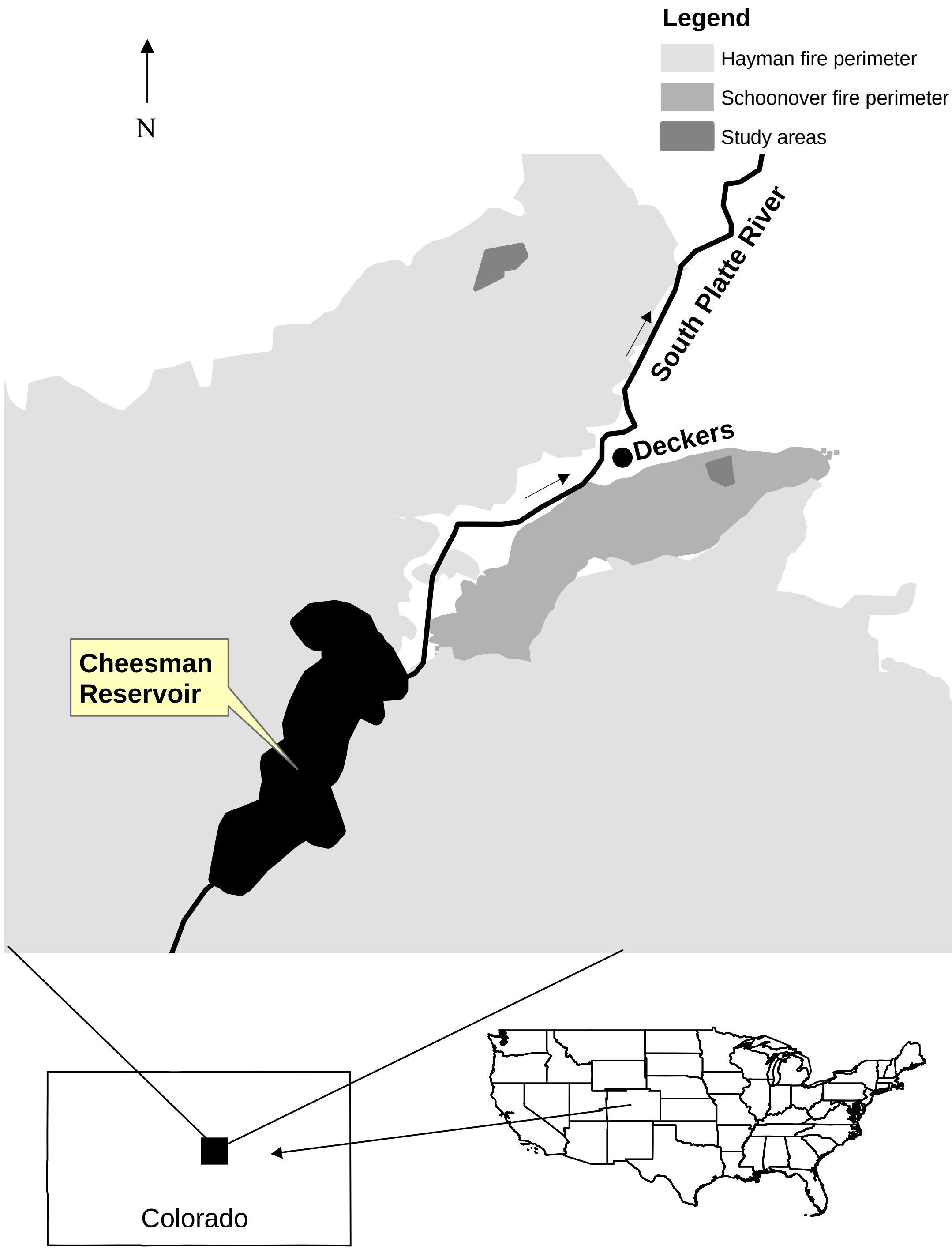

Figure 1. Location of the study areas in the Hayman and Schoonover fires, respectively.

Figure 2. Sediment fence on: (a) a planar hillslope in the Hayman fire in September 2003, fifteen months after burning: and (b) a convergent swale in the Schoonover fire in September 2002, three months after burning.

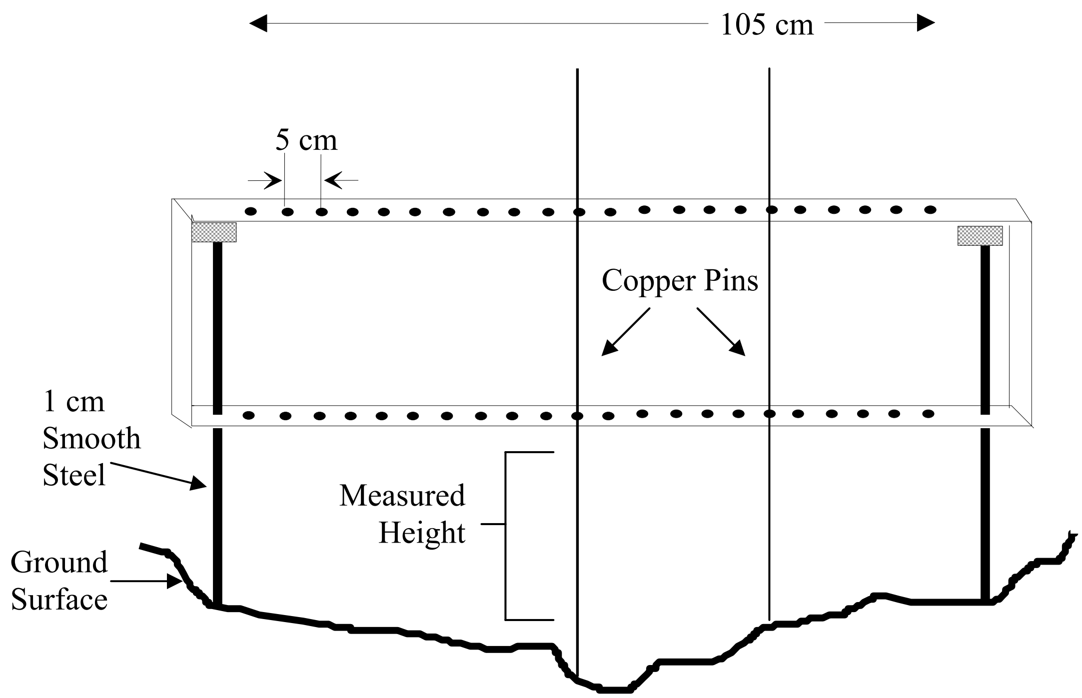

Figure 3. Schematic of the aluminum pin-frame used to measure rill cross-sections.

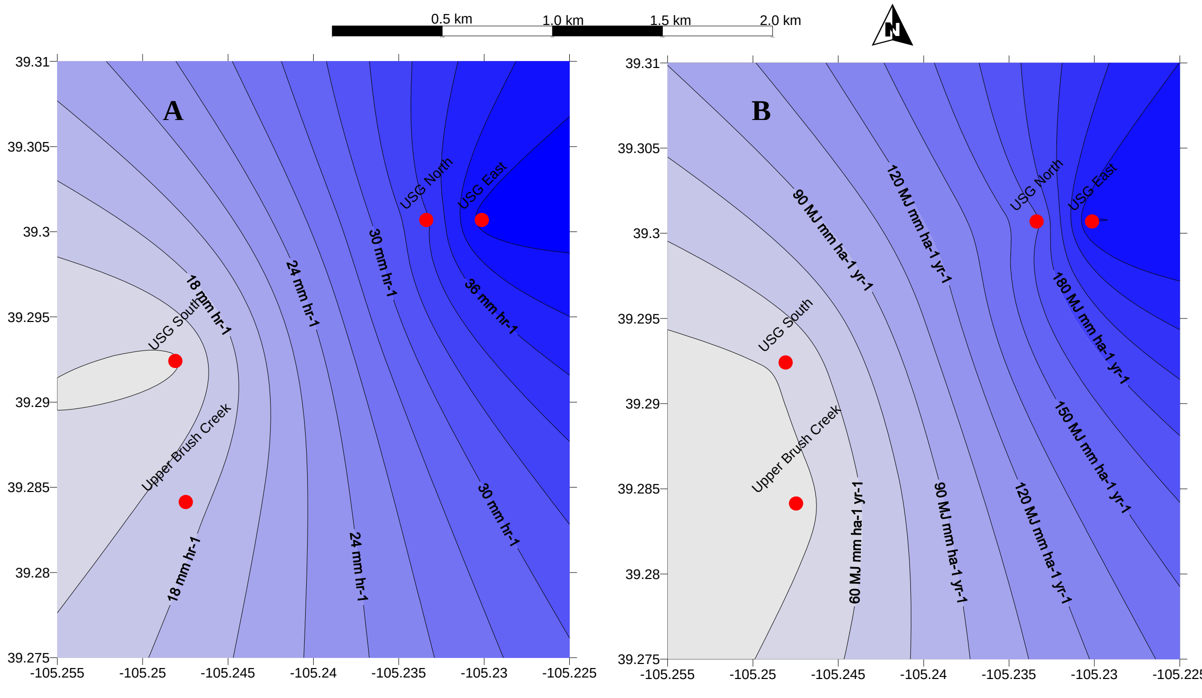

Figure 4. Isohyets of (a) maximum thirty-minute intensities, and (b) rainfall erosivities for a rainstorm on 11 August 2003 in the Hayman fire. The isohyets were developed using data from four recording rain gages (red circles).

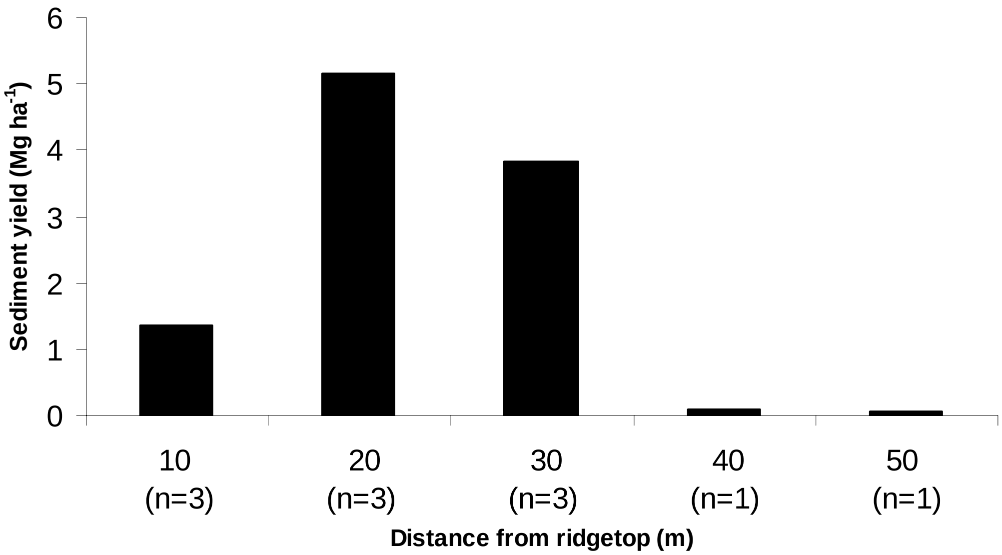

Figure 5. Sediment yields per unit area for 2003-2004 versus distance from the ridgetop for the 11 planar plots in the Hayman fire.

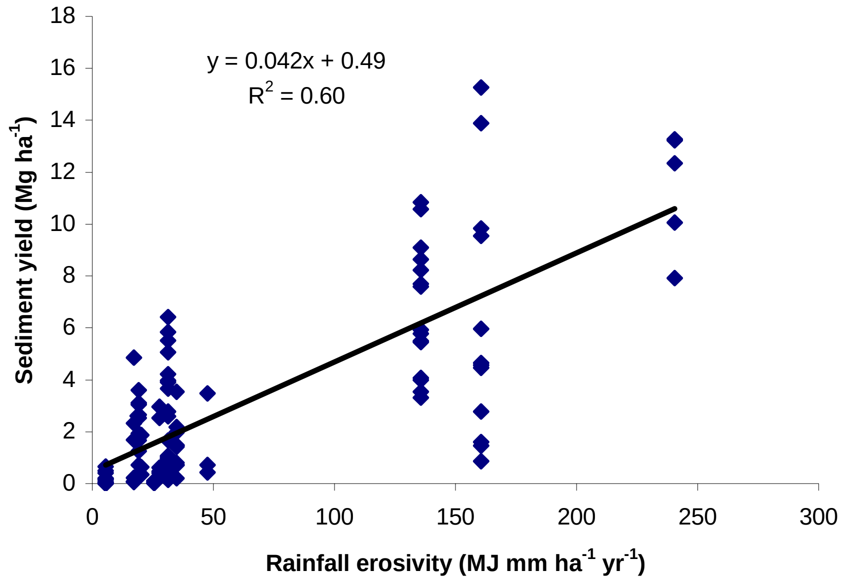

Figure 6. Storm-based sediment yields from 2002 and 2003 for the 20 swales in the Hayman fire versus rainfall erosivity.

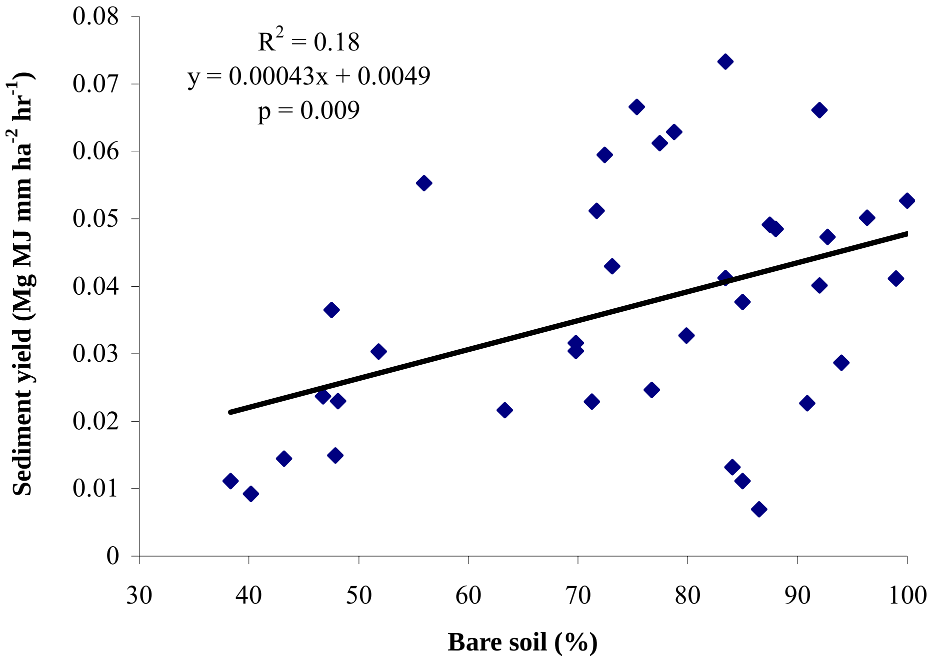

Figure 7. Annual sediment yields from 2002 to 2004 versus percent bare soil for the 15 swales in the Hayman fire. The sediment yields are normalized by contributing area and rainfall erosivity.

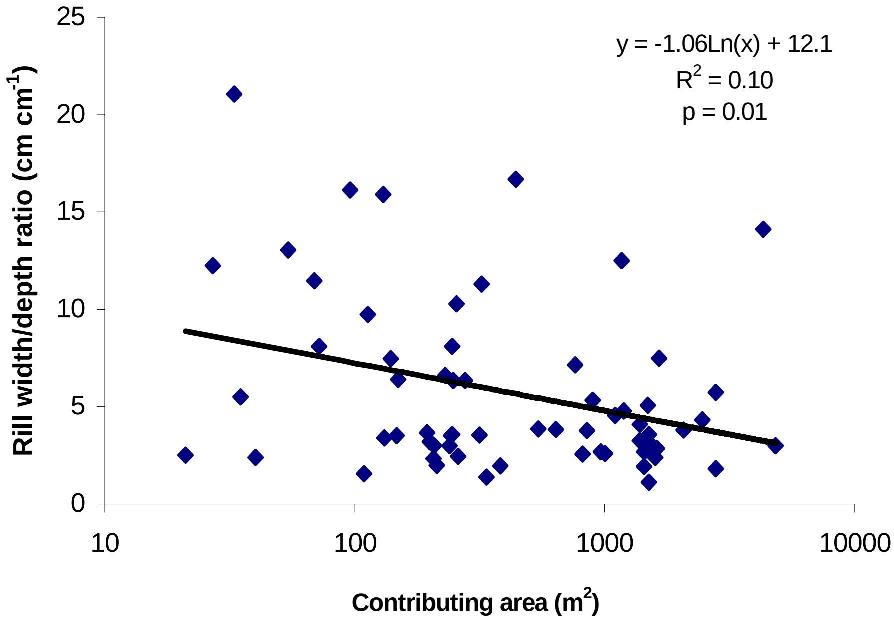

Figure 8. Contributing area versus the width-to-depth ratio at the end of the monitoring period for each of the 94 cross-sections.

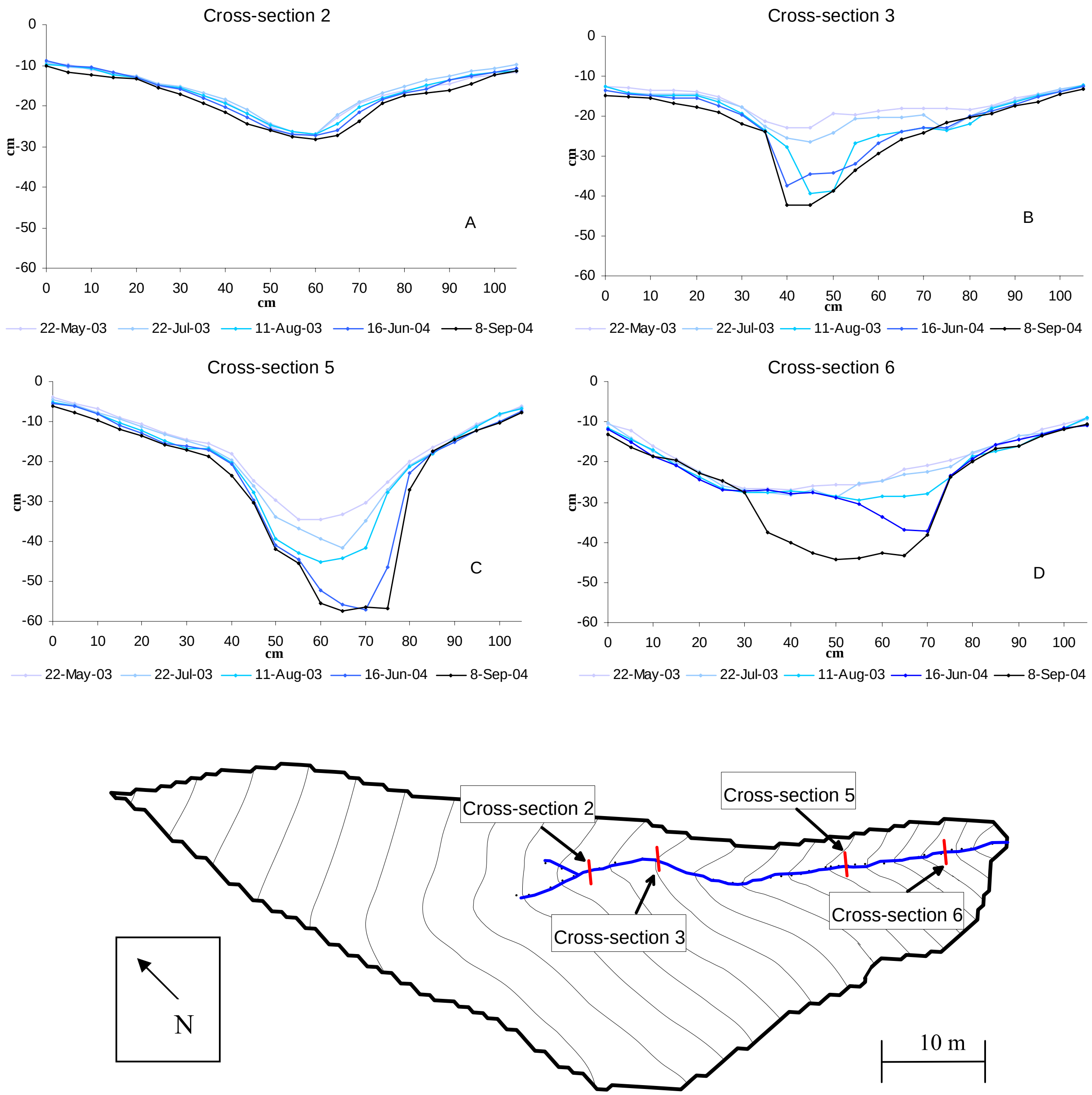

Figure 9. Changes in rill cross-sections over time for four different cross-sections in swale 17 in the Hayman fire. The contour interval on the site map is 1 m.

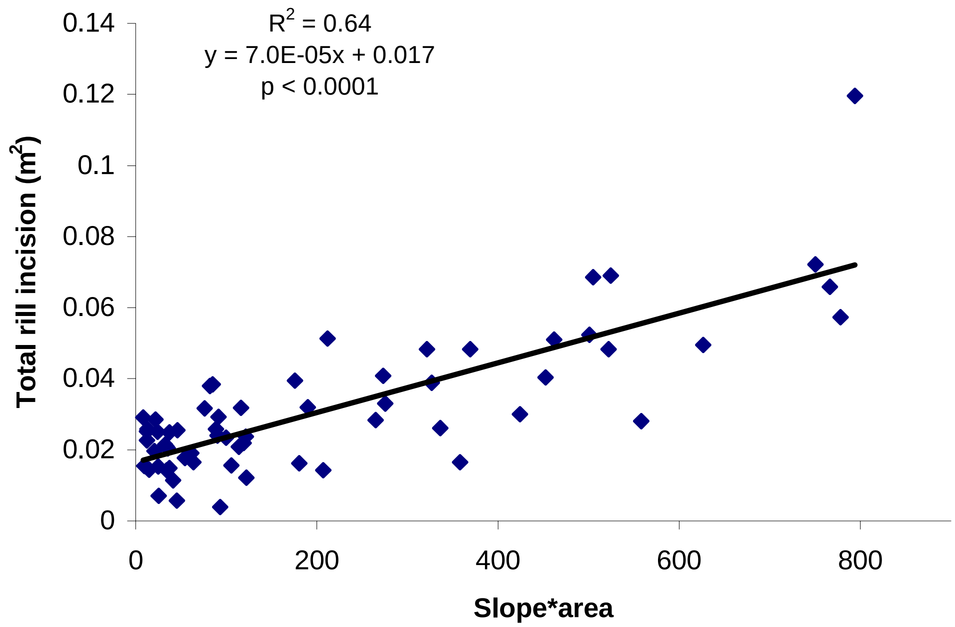

Figure 10. Relationship between contributing area*local slope and change in rill cross-sectional area for the 63 cross-sections in 14 swales at the Hayman and Schoonover fires.

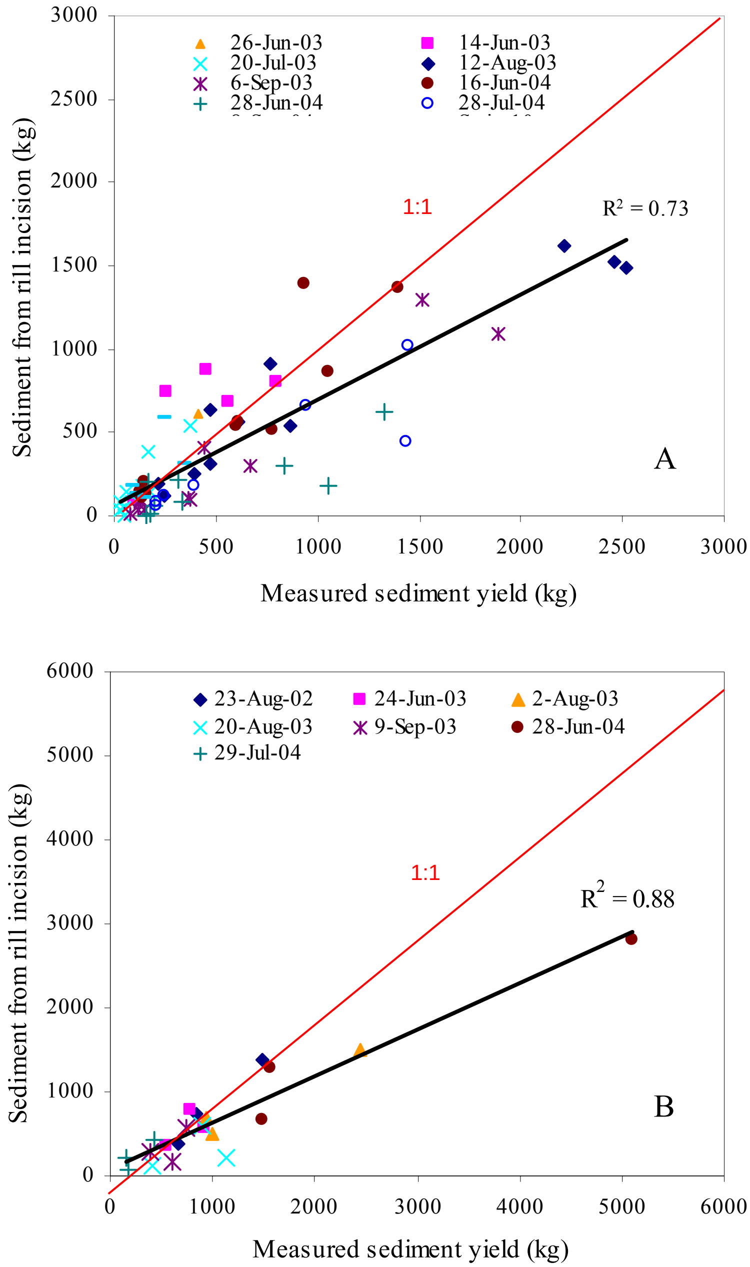

Figure 11. Calculated mass of sediment derived from rill erosion vs. measured sediment yields for the swales in the: (a) Hayman fire and (b) Schoonover fire.

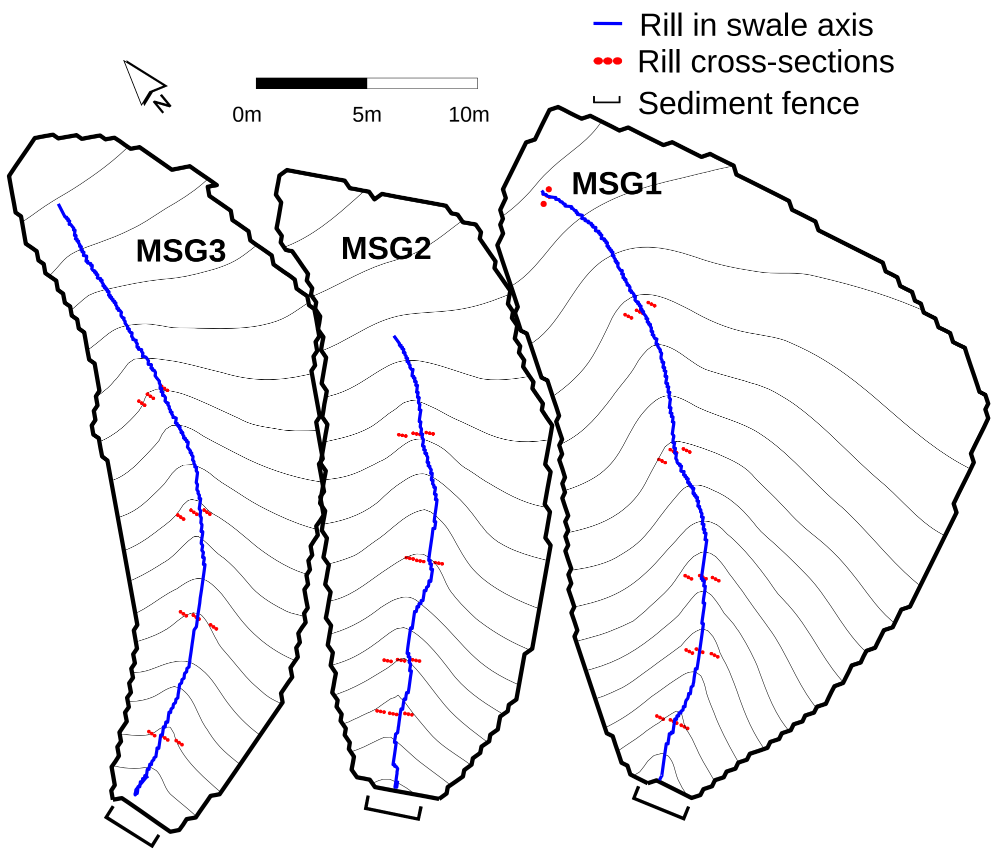

Figure 12. Map of the three adjacent swales in the middle Saloon Gulch (MSG) study site in the Hayman fire. Contour interval is 0.5 m.

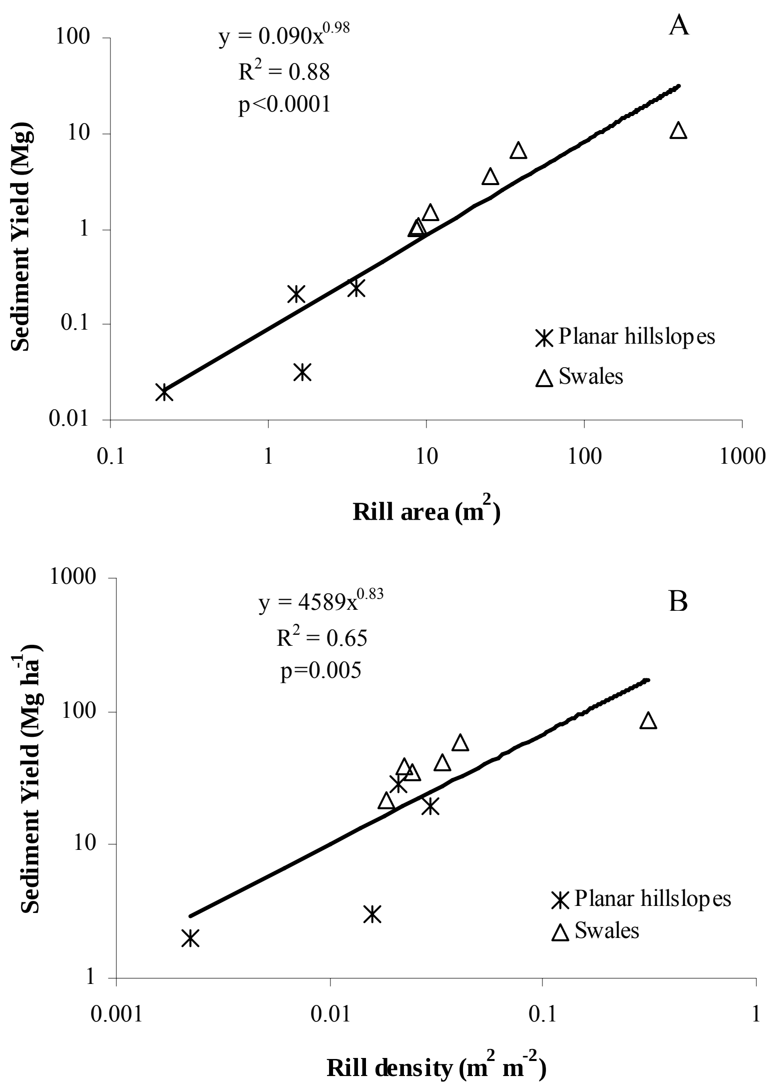

Figure 13. Total sediment yields versus rill area (A) and unit-area sediment yields versus rill density (B).

4. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The results from this study corroborate the other studies in the western United States that show post-fire erosion rates to be orders of magnitude higher than background levels (e.g., Helvey, 1980; Wells, 1981; Morris and Moses, 1987; DeBano *et al*., 1998; Prosser and Williams, 1998; Robichaud *et al*., 2000; Moody and Martin, 2001; Benavides-Solorio and MacDonald, 2005). The objective of this study, however, was not to document the increase in erosion rates after fires, but to define the key processes and controls on post-fire erosion rates from different sites over time. Chapter 2 described the factors controlling sediment yields over time, while Chapter 3 investigated the magnitude and importance of rill erosion following two high severity wildfires.

A unique strength of this study is the very large dataset that was available for the analyses. Chapter 2 was based on 4 years of data from 10 fires, or 225 plot years of data. This meant that the data set could be split into calibration and validation data for model development, and allowed for meaningful inferences with respect to the various factors affecting post-fire erosion. The primary controlling factors, such as bare soil and rainfall intensity, had been identified in previous studies with much smaller sample sizes (e.g., Morris and Moses, 1987; Moody and Martin, 2001), but this study was able to quantify the relative importance of these factors and a much wider set of other variables. The results document the influence of other factors such as hillslope position and soil texture, as well as the small effect of seemingly critical variables such as slope and contributing area.

The large dataset was critical in quantifying the wide variability between plots and fires. For example, in the fourth summer after the Bobcat fire, only one of the sixteen plots produced a substantial amount of sediment. This one plot was important because it showed that high sediment yields could persist into the fourth summer after burning, if a plot has low bare soil and is subjected to intense rainfall. The data from the other fifteen plots at the Bobcat fire, and similar aged plots at other fires, showed that this site could be identified as a relatively rare situation.

The variability between plots was a consistent theme, and the work presented in Chapter 3 was developed in response to the observed difference in sediment yields between planar and convergent hillslopes at the Bobcat fire (Benavides-Solorio, 2003). Many sub-sections in both chapters were used to explain other unforeseen sources of variability.

An inherent problem with field-based, observational studies is that many variables are difficult to measure precisely. The episodic, localized nature of the summer thunderstorms was difficult to quantify. Variability in sediment yields within a fire was often unexplained because rainfall was measured with just one rain gage. Even at fires with multiple gages, the rain gage density was not sufficiently able to completely characterize the spatial variability in rainfall.

Delineating contributing areas also was problematic, in that the drainage divides often flattened near the crest rather than being defined with sharp ridges. The flattened ridgetops probably did not contribute much sediment, but were included in the contributing area. Since the flattened areas could be several hundred square meters or more, they represent a potentially significant error or bias.

Nevertheless, the overall trends and understanding are sound. The empirical models developed in Chapters 2 and 3 can be used by land managers to predict post-fire erosion both immediately after burning and over time. Because the models were developed for the Colorado Front Range, their applicability to other areas is not known. However, the general principles and processes defined in this study should be observed in other areas, even though the absolute numbers may change.

4.1. FUTURE RESEARCH

One pressing need for future research is to test the models developed in this study against data from other regions. This recalibration would allow the models to be used in other areas, and help confirm the overall validity of the results developed in the present study. The data from the present study also should be used to validate physically-based erosion models such as WEPP, RULSE, and ERMiT. Improved modeling capabilities could prove particularly useful in the future as global climate change may affect temperature, precipitation, and wildfire patterns in the western United States.

The present study has helped to document many of the key processes and controls on post-fire erosion in the Colorado Front Range, but some processes remain poorly understood. In particular, the relative influence of soil hydrophobicity versus soil sealing in controlling runoff rates needs to be addressed. The factors affecting vegetative regrowth over time also could be more rigorously evaluated, particularly as they relate to soil moisture and nutrient availability.

It also would be helpful to assess the role of hillslope convergence on a continuous scale rather than classifying hillslopes into two discrete classes (convergent vs. planar). This information would collectively help in the development of an accurate, physically based, hillslope-scale model for predicting post-fire runoff and erosion for the Colorado Front Range. Ultimately, the increased understanding of hillslope erosion rates that has been developed in this study should help lead to improved hillslope- and basin-scale models for use in Colorado and other regions.

4.2. REFERENCES

Benavides-Solorio, J., 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. dissertation, Colorado State University, Fort Collins, CO, 218 p.

Benavides-Solorio, J., and L.H. MacDonald, 2005. Measurement and prediction of post-fire erosion at the hillslope-scale, Colorado Front Range. *International Journal of Wildland Fire* 14: 1-18.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott, 1998. Fire's effects on ecosystems. John Wiley & Sons. New York, NY, 333 p.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* 16: 627-634.

Moody, J.A., and D.A. Martin, 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26: 1049-1070.

Morris, S.E., and T.A. Moses, 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* 77: 255-264.

Prosser, I.P., and L. Williams, 1998. The effect of wildfire on runoff and erosion in native Eucalyptus forest. *Hydrological Processes* 12: 251-265.

Robichaud, P.R., J.L. Beyers, and D.G. Neary, 2000. Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service General Technical Report RM-GTR-63. Fort Collins, CO, 85 p.

Wells, W.G., 1981. Some effects of brushfires on erosion processes in coastal Southern California. In *Erosion and Sediment Transport in Pacific Rim Steeplands*. IAHS Publication No. 132, p. 305-342.